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Edited by Roshan Paul





# Denim

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# Denim

# Manufacture, Finishing and Applications

Edited by

Roshan Paul



The Textile Institute



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# Preface

In the history of textiles, no other fabric has received such a wide acceptance as denim and it is the fabric of generations, worn by people of all classes and ages. It has an undisputed position in the fashion industry and its ability to adapt creatively to the fashion trends through its unique washing effects is incredible. Denim is a hard wearing cotton twill fabric, traditionally woven with indigo dyed warp and white filling yarns. Its manufacture involves the same classical principles which have been followed since its creation, but technological advances have transformed it into a highly fashionable material.

The name 'denim' is thought to have its origins in the French word *serge de Nimes*, a fabric existed prior to the seventeenth century in the town of Nimes in France, while jeans seem to have their origin in a fabric made in the Italian city, Genoa. Later in the nineteenth century, the manufacture of copper riveted waist overalls out of denim by Levi Strauss in the US has laid the foundations of modern denim jeans. Ever since, denim has been in use in the clothing industry, initially in the manufacture of durable overalls and trousers for hard labour, which eventually identified itself as the hallmark of fashion wear. From the US, where it became the favourite of American cowboys, denim culture has now reached every corner of the world.

The future of denim is secure as it has an ever growing fashion appeal internationally among all age groups. Somehow it remains eternally young in the hearts of generations and is now the fabric of choice for manufacturing anything that can be worn by anyone, anywhere, at anytime. It has also remarkable social and cultural influence and is considered as a symbol of teen rebellion, an expression of youth independence, an icon of heroism, and it reveals a different style and attitude towards life. This blue magic material has survived over a century and is an ever inspiring fabric for today and tomorrow. It still remains as the evergreen favourite of all and hence a future world without denim is unimaginable.

Denim: Manufacture, Finishing and Applications provides an exhaustive coverage of the manufacturing and washing processes for denim and jeans, as well as information on the history, evolution, novel applications and environmental impacts of denim. The chapters are arranged systematically in order to provide an uninterrupted technological flow of the involved processes. Following a general overview of denim and jeans, Part One covers the manufacture of denim fabric, with chapters devoted to cotton fibre and yarn production, indigo dye and reduction techniques, indigo dyeing of denim warp yarns, role of non-indigo dyes and the weaving technologies for manufacturing denim. Part Two then elaborates the manufacture and finishing of jeans, which includes the role of denim and jeans in the fashion industry, joining techniques for jeans, denim garment dyeing, digital printing techniques, different washing techniques, biotechnological washing, reduced water washing, finishing of jeans and quality control, as well as the comfort aspects of denim garments. Finally, Part Three considers the novel applications and environmental aspects, which covers the novel varieties of denim, non-apparel applications, recovery and recycling of denim waste, reduction and treatment of effluents from the manufacturing plants, and finally the environmental impacts of denim manufacture.

All possible measures have been taken to ensure that no important technical information on denim is left out of this book and it is offered as a complete resource for the technical managers in the denim, garment, fashion, dyestuffs, textile chemicals, biotechnology, industrial laundry and machinery industries, as well as academic researchers and designers working on different aspects of textile and fashion technology. The topics covered are comprehensive and not easily available from a single source elsewhere. Denim experts from world over are brought together on a common platform in this book, so that it should live up to the expectations of present and future readers, and to continuously inspire them. It is intended to blend fashion with technology and the book is projected to stand apart as an authentic reference book for any relevant information on denim. Considering the ageless and timeless nature of denim, this book is expected to sail through years without losing its significance.

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# Denim and jeans: an overview

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# 1.1 Introduction

Among all the textile products, no other fabric has received such a wide acceptance as denim. It has been used extensively by people of all ages, classes and genders. Denim is a hard and durable warp faced 3/1 twill cotton fabric, woven with indigo dyed warp and white filling yarns, having weights of 14½ ounces per square yard. It has been in use for over a century in the clothing industry, especially in the manufacture of overalls and trousers for hard labour, which has demonstrated its durability, which along with its comfort made denim jeans extremely popular for leisure wear, too. From the seventeenth century to the present day, denim has been used for making trousers, upholstery and awnings, and has been found in museums, attics, antique stores and archaeological digs. It is also considered as the fabric of hard work, expression of youth rebellion and the favourite of American cowboys.

The name 'denim' is thought to have originated from the French *serge de Nimes*, a fabric from the town of Nimes in France. It was made of silk and wool, but denim has always been made of cotton. There was another fabric, a fustian made of cotton, linen and/or wool blend, and the fustian from Genoa, Italy was called jean. By the eighteenth century, jean fabric was made completely of cotton, and used to make men's clothing, valued especially for its property of durability even after many washings. The popularity of denim was also on the rise and it was stronger and more expensive than jean. Even though the two fabrics were very similar in other ways, they did have one major difference: denim was made of one coloured yarn and one white yarn while jean fabric was woven with two yarns of the same colour.

Over the years, Levi Strauss & Co. in the United States, has played a pivotal role in developing the denim jeans. The company was founded by Loeb Strauss, who was born in Bavaria, Germany in 1829. Along with his family members, he left Germany in 1847 and sailed to New York, where Loeb's half brothers were in business selling wholesale dry goods. For a few years, Loeb worked for his brothers and he changed his name to Levi Strauss sometime around 1850. In 1853, he decided to reinvent his life and took an adventurous journey to San Francisco, a city enjoying the benefits of the recent gold rush, and started his own dry goods business.

Levi Strauss & Co., founded in 1853, was selling only clothes, boots and other dry goods to small retail stores. In 1873, together with a tailor named Jacob Davis, Levi was granted a patent to manufacture riveted for strength workwear made of blue denim. Soon they began manufacturing copper riveted waist overalls out of a brown cotton duck and blue denim, marking the birth of denim jeans. Even though it originated in Europe, the durability and adaptable form of denim found a perfect home in the United States, where soon it became an American icon. Denim has had an incredible social and cultural influence on consumers and is considered an expression of youth independence, a symbol of opposition or an attitude towards life, and there is an international appeal of jeans among all age groups. Classical Hollywood movies with rebellious themes starring Marlon Brando and James Dean became symbolic of rebellious youth. Dean and Brando wore blue jeans and leather jackets in the movies, and this clothing style became a symbol of a defiant teen desiring freedom. From the United States, denim fever has spread the world over, and the wide acceptance of denim garments everywhere makes it clear that denim is here to stay. This book on denim covers all of the important aspects of denim fabric manufacture, the manufacture and finishing of jeans, as well as novel applications and environmental aspects.

# 1.2 Denim fabric manufacture

Part One of the book focuses on the manufacture of denim fabric, and it starts with the utilisation of cotton fibre in denim manufacture. Then it talks about indigo dye, reduction techniques and indigo dyeing technologies for denim yarns. Further, the dyeing of denim with non-indigo dyes as well as the weaving technologies for manufacturing denim are discussed.

## 1.2.1 Cotton fibre

Cotton is extensively used for denim manufacture, where the fibre quality and staple length are of crucial importance. Denim would not be denim without cotton, but the cultivation of cotton raises sustainability issues concerning the quantity of water and pesticides used. The use of organic or naturally coloured cotton in denim manufacture can address the sustainability issues to some extent. Another possibility to reduce pesticide application is the use of genetically modified cotton. Cotton can also be blended with lycra, polyester, lyocell, wool, flax, hemp, etc. for developing special types of denim. Even though many such fibres are now entering the denim sector, it is highly improbable that they will ever replace cotton completely.

The cotton fibre needs to undergo a series of operations in order to be spun into yarns. Most of the cotton processing techniques for denim manufacture have not changed over the years. Unlike the weft, the production of warp yarn needs special attention, as it can influence the final quality of denim. Productivity and yarn quality are getting more importance in spinning, and in this respect, rotor spinning is becoming more prominent than the conventional ring spinning. Weaving a combination of ring spun and rotor spun yarns can help to reduce fabric costs while still maintaining some favourable ring spun fabric characteristics.

## 1.2.2 Indigo dye

Indigo, which is otherwise a low quality dye, is widely used in denim dyeing, as it gives the characteristic blue colour to denim. While the low fastness of the dye is a boon for achieving a distressed look, it leads to major effluent problems during the dyeing process and later in the washing of denim garments. Natural indigo has now been completely replaced by synthetic indigo, which seems to be more sustainable, but bio-synthesis of indigo would be really sustainable. A comparison of optimised natural indigo powder extracted from plants and optimised synthetic production shows that natural production of indigo may not be necessarily more environmentally friendly than the synthetic product.

At present, what raises concern is the reduction technique in indigo dyeing. The use of sodium hydrosulphite as a reducing agent is associated with several environmental issues. Commercially available pre-reduced indigo shows better fixation, requires fewer chemicals and results in low effluent load. Alternate reducing systems have been explored, such as organic reducing agents, biological reduction, electrochemical reduction and catalytic hydrogenation of indigo.

## 1.2.3 Indigo dyeing

A unique feature of indigo dyed denim is the possibility of achieving wash down effects on repeated washing without losing the freshness of the colour. Indigo dyeing is a vital step in the manufacturing of denim, and the warp yarns are dyed by either rope or slasher dyeing methods. The major issues in dyeing are the reducing agents and the huge volume of effluents, and quality control involves the monitoring of dye bath parameters like pH, sodium hydrosulphite and leuco indigo concentration, and the temperature of the dye bath. The pH is of crucial importance, as it controls the level of ring dyeing, and other important factors are the immersion time and number of dips.

Denim manufacturing is now faced with an eco-efficiency challenge with respect to sustainability. Several attempts have been undertaken in order to develop novel 'green' processes of denim dyeing, which should be more efficient, rapid, cheaper and easy to apply. One of the outcomes is the loop dyeing process, where the yarns are dyed in a single bath with one squeezing unit, after passing through the pretreatment boxes.

# 1.2.4 Non-indigo dyes

Non-indigo dyes, such as sulphur dyes, are now widely used in denim warp dyeing, and they offer vivid colours and a better ecological alternative to conventional indigo dyeing. Due to their better affinity for cotton, this dyeing is more efficient, and modern techniques can further reduce water usage considerably. Dyeing equipment, originally meant only for indigo, is undergoing transformation to provide the conditions required for the application of other dyes. Nowadays, the proportion of 100% indigo dyed denim warp is very small, as it is commonly combined with other types of dyes in the same application process, or overdyed with them. Sulphur dyes are widely used for bottoming and topping of indigo for reducing the overall cost.

Indigo will remain as the king of dyes and will stay associated with denim as its standard dye. But the demand from the fashion market could eventually activate much interest in non-indigo dyes, as they offer a full spectrum of colours. The permanent search for new effects and the flexibility that denim has for continuously reinventing

itself will require exploring new application methods and developing new chemicals and dyes. A breakthrough dyeing process is Advanced Denim, which operates completely without indigo. It offers a great variety of colours, needs much less water and energy, and produces no effluents.

#### 1.2.5 Denim weaving

Weaving is the final process in the manufacturing of denim and is very important in determining the quality of the final garment. Denim fabric is woven as 3/1 twill by the interlacement of indigo dyed warp and grey weft, and the yarn counts influence the fabric properties such as weight, fabric tightness, cover, drape, tensile strength and other properties. The weaving looms often used for denim are projectile, rapier and air jet looms.

In general, the denim market is highly competitive and is driven by volume and not necessarily by the niches. So the success of denim weaving companies depends on aspects like process optimisation and marketing profile. The possibilities include the use of engineered yarns, weaving denim efficiently in intelligent machines and using online quality control systems. All these could reduce energy consumption in weaving and also optimise material and resource efficiency. The industrial implementation of these technologies represents the future of denim weaving, which should be economically viable and will produce high quality denim.

# 1.3 Manufacture and finishing of jeans

Part Two of this book deals with the manufacture and finishing of jeans. The different topics include joining techniques for denim jeans; dyeing technologies for denim garments; digital printing techniques for denim jeans; washing techniques for denim jeans; biotechnological washing of denim jeans; reduced water washing of denim garments; finishing of jeans and quality control; as well as the comfort aspects of denim garments.

### 1.3.1 Jeans and fashion

Denim jeans can be considered as the most widely used garment in the fashion business. It is well known that denim and jeans have had a major influence on the lives of consumers since their inception. Jeans have become symbols for cowboys, women, youth and economic status. Through the ages, jeans have evolved from workwear to casual wear and then to premium wear and functional wear.

Consumers evaluate jeans based on style, brand, country of origin and company ethics. As with any other apparel, denim garment companies target specific market segments, however, no other garment can claim the social culture that denim has already set. Designer jeans as well as premium jeans first influenced a small group of luxury consumers, but now consumers from all social and economic classes embrace them. Challenges faced by denim apparel manufacturers and fashion designers include the need for reinventing products for niche markets, and meeting consumer demands for better apparel sizing.

## 1.3.2 Joining techniques

The stitching process gives birth to denim jeans, and the joining techniques are crucial in determining shape, fitting and style. The conversion of denim fabric into garments requires machines that are able to cope with the density of the fabric and the thickness of the seams. Therefore, heavy duty machines need to be used and specialised components have been developed to feed the material effectively through the machine. Other components such as heavy duty needles, sewing threads that have high strength for securing the seams, and buttons and studs for securing the pockets have been specially developed for this garment.

The challenges in joining include stress on the operators when stitching the material, due to its heavy weight and dense construction. This can create greater operator fatigue, and therefore sophisticated equipments to automate certain processes have been developed to reduce some of this fatigue and at the same time increase productivity. Future trends in the joining of denim will be dictated by the developments in the material itself, environmental drivers and, of course, economic factors. The possible use of laser welding or soluble sewing threads that can be easily removed from a garment will allow for easier reconstruction of jeans into a new product.

## 1.3.3 Garment dyeing

Denim garments, especially jeans, are manufactured from either indigo dyed denim or ecru denim. Ecru refers to undyed denim, and has the natural hue of cotton. Once the garment is manufactured, it can be dyed in different colours and shades as per the market need. It has some advantages over fabric dyeing, such as rapid manufacturing, quick delivery and reduced environmental impacts. There are basically two types of garment dyeing machines: paddle machines and rotary machines.

Garment dyeing has continuously evolved and adapted to changes in fashion, market needs and technological advances, and it seems to be moving towards implementing sustainable industrial practices. It can be considered sustainable since only the fabric used in manufacturing the garment is dyed and therefore there is no wastage of fabric or dyes. Further, the effluent load could be reduced by reusing indigo dye baths for shade development instead of using fresh dye baths. Natural dyes and environmentally friendlier reduction and oxidation systems for vat and sulphur dyes are also becoming important in denim garment dyeing.

## 1.3.4 Digital printing

Digital printing can be considered as an environmentally friendly technique for denim colouration, mainly because of the low quantity of colourant applied on the fabric, with less use of water and energy. It can also be applied in small lots, and a variety of designs can be created digitally on jeans. Similarly, laser engraving methods have several environmental advantages over chemical or mechanical washing techniques. So it is clear that digital printing and engraving present ecological and cost effective alternatives to conventional colouration and washing techniques.

More interestingly, digital printing provides the designers with more artistic freedom to creatively broaden their ideas. An unlimited variety of motifs and patterns can be developed and printed onto denim fabrics. This technology also enables creative designers and producers to work closely with retail distribution networks in real time, as a quick response model. The addition of electronic data interchange capabilities can materialise a concept known as fast fashion, and it can simultaneously boost the competitiveness of the company.

## 1.3.5 Washing techniques

Denim is actually a stiff and dull blue fabric without any fashion appeal, and washing is the revolutionary process that has changed this mundane image of denim. Denim garment washing is now an indispensable process for producing fashion items for leisure wear. Stone washing is the most important process, and it has innumerable variants now. Industrial washing machines play an important role, and depending on the market requirements, these machines can develop uniform colour fading or appearance effects.

It is well known that denim garment washing depends greatly on the use of chemicals and stones for achieving the softening and colour fading effects. As all these processes provide new looks by deliberately removing the dyes, they create an effluent problem, which brings into question the sustainability of the whole process. In this context, the denim washing industry is striving to develop environmentally friendly washing techniques that can result in zero effluent discharge. Dry treatments or nearly water free treatments are slowly becoming a sustainable trend for replacing traditional wet treatments in denim garment washing.

## 1.3.5.1 Enzyme washing

Enzyme washing can be used industrially for replacing or complementing the stone washing process. Ecological aspects are now becoming increasingly important in denim garment washing, and enzymes have contributed to improve the environmental profile of this process. The application of cellulase enzymes is well known to the majority of industrial laundries and the big brands and retailers are also very much aware of their sustainability aspects.

The continuous research on new enzymes and formulations is going hand in hand with the innovation and sustainability strategies of leading fashion brands and laundries. Laccase enzymes can be used as an alternative to chemical bleaching where the enzyme oxidises indigo to soluble degradation products. Thus there will be more and more applications for enzymes in denim garment processing, and the further optimisation of existing enzymatic formulations or combining different processes will hold the key for efficient and sustainable washing.

#### 1.3.5.2 Reduced water washing

It is high time for the denim garment washing industry to show that it cares for the environment and its operators. Thus there is a radical transformation taking place in this industry from an artisanal, labour intensive industry towards a knowledge based industry, caring for both the operators and the environment. New techniques like laser, ozone, etc., which use a much smaller quantity of water, are now changing the environmental profile of the whole washing process.

These reduced water techniques are those that can obtain a washed look and excellent handle using a minimum quantity of water. The integration of such technologies into the conventional washing lines will ensure that vintage looks and other fashion effects can be created on jeans with much less water. In such cases, the effluent output is reduced to a negligible quantity, thus transforming denim washing to an environmentally friendly process.

#### 1.3.6 Jeans finishing

Finishing of denim fabrics and jeans can provide aesthetic as well as functional properties. There are countless dry and wet processes in denim garment processing to achieve fading, excellent handle and unique looks. Apart from such processes for achieving special fashion effects, several functional finishes can also be applied on denim garments for providing technical and functional properties. Microencapsulation, plasma techniques and nanotechnology are offering different possibilities that were not possible to achieve with normal finishing chemicals.

The functional finishes can create anti cellulite, odour resistant, wrinkle free, water/ oil repellent, mosquito repellent, antimicrobial, UV protection and flame retardant properties on denim garments. Thus denim, which is well recognised in the casual wear sector, is now finding new markets in technical textiles and non-apparel applications. More interestingly, many fashionable and multifunctional effects can be simultaneously created on denim garments.

#### 1.3.7 Comfort aspects

Cotton denim shows some sponginess, and in a highly humid atmosphere, it can assimilate a lot of moisture, causing discomfort to the wearers. This is because of the inherent character of cotton fabrics to wick well and to absorb moisture very easily. Apart from the fashion appeal, thermo-physiological and skin sensorial comfort properties are now becoming more important for denim garment users. The fabric structure and the types of fibres are the main contributors to thermo-physiological comfort.

The most established way to develop denim garments with better thermophysiological comfort is to manufacture denim with different fibre contents. As these blended fabrics are lighter in weight, they can dry rapidly, providing a warm feeling to wearers under highly humid conditions. The comfort can be further improved by applying moisture management finishes, which can transfer moisture away from the body by reducing the absorbent capacity and allowing faster drying. Cotton itself can be thus engineered to transfer moisture away from the skin to the outside of the denim, providing the wearer with a dry and comfortable feel.

# 1.4 Novel applications and environmental aspects

Part Three of this book deals with the novel applications and environmental aspects of denim. The different topics include novel varieties of denim fabrics; non-apparel applications of denim; recovery and recycling of denim waste; effluent treatment in denim and jeans manufacture; and the environmental impacts of denim manufacture.

## 1.4.1 Novel denim varieties

Apart from the well known standard denim, several novel varieties of denim fabrics exist, and they are finding extensive application in the fashion industry. Stretch denim, pseudo denim, generic denim and reverse denim are some interesting variants, and from the viewpoint of manufacturers and consumers, stretch denim has a huge potential. Cotton blends of lyocell, wool, silk, polyester, linen, hemp, etc. are also available on a commercial scale. The use of different fibres in combination with cotton has also improved the functionality of the denim material.

The colouration and washing techniques possible now on denim are innumerable, and the functional finishes are adding a different dimension to denim. As sustainability is becoming a major focus globally, use of biodegradable fibres in denim is ever increasing. Some sustainable varieties include denim made of polylactic acid, soybean and bamboo fibres. Other such variants include organic cotton denim and denim dyed with natural dyes without using metallic mordants.

# 1.4.2 Non-apparel applications

Known well for apparel use, denim is now finding novel applications in other sectors, including furniture, home interiors and automobiles. These alternative applications can increase the market share of denim considerably in industrial sectors where it was never thought to enter. Denim has become an interesting substrate to designers and technologists to create new products satisfying the changing consumer trends as well as the demands on creativity and unique products. It is clear that denim has a significant market potential for being used in several fields.

Denim and home textiles are two important and popular sectors of the textile industry, and it is possible to generate a synergistic effect and a different market by combining their aspects. If new denim fabrics are used for non-apparel applications, especially in home interior textiles, furnishings, curtains, etc., it can create value addition to denim. But the utilisation of used denim garments to produce non-apparel denim articles is an environmentally friendly approach and will be more economical in achieving new market shares.

# 1.4.3 Recovery and recycling

Denim and jeans waste is creating a municipal dumping problem, and a proper recycling of this waste can result in novel products for other industrial sectors. In general practice, the denim waste is either dumped in municipal landfills or incinerated in solid waste incinerators. Waste denim can be recovered from the denim mill as well as from the jeans manufacturing units. Apart from this virgin material, the used jeans and garments can also be recovered systematically. Denim recycling possibilities are unlimited, and the adoption of an effective strategy will reduce the environmental impact and simultaneously contribute to the competitiveness of the industry, by addressing increasing issues of raw material access.

Denim is usually triturated and converted into nonwoven felts for the insulation in construction and automotive industries, but it is possible to shred the fabrics to get them back into a similar kind of fibre to virgin cotton. There is an increasing attention for this high end recycling of denim, and a number of fashionable products are already available in the market with a high content of recycled denim fibres. Nowadays the possibility of manufacturing denim from other waste materials is also becoming important.

#### 1.4.4 Effluent treatments

Denim warp dyeing as well as the garment dyeing, washing and finishing processes result in huge effluent volumes, and their treatment is absolutely essential. The wastewater can be treated by several treatment methods based on biological or physicochemical processes, but it is not easy to decompose this type of wastewater to meet the discharge levels set by standards. However, a comprehensive treatment process that enables the reuse of this wastewater and process chemicals will be the preferable alternative in terms of environmental and economical considerations.

Rather than effluent treatment, effluent reduction at the source by implementing different ecological processes is receiving more attention nowadays. For pollution prevention, minimisation of the use of chemicals, dyes and water, as well as good housekeeping practices, should be considered. Combining different processing stages can also reduce the water and energy consumption, thereby increasing the productivity and decreasing production costs.

#### 1.4.5 Environmental impacts

The overall environmental impact of denim manufacture is significant, especially in areas such as cotton growing, dyeing and washing, and many consumers are not aware of this aspect. In the case of denim, there are some inherent limitations, such as the ever preferred use of indigo, its low affinity for cotton and poor fastness properties. As with other sectors, Life Cycle Assessment techniques are utilised to assess the impact of denim and to identify the possibilities for improving its environmental profile.

Improvements in each step of denim manufacture will offer significant reductions in the overall environmental impact as well as cost savings for the industry. Among all the processing steps, industrial as well as household laundries seem to offer the highest potential for improvement. Indeed, modern technologies have helped reducing the overall impact to some extent, but there is still a long way to go. Some of these possibilities include the use of organic cotton, reduction of dyes and chemicals, and producing less complex wastewater. Other environmentally friendly alternatives include electrochemical reduction, minimal application technologies and reduced water washing. It is very clear that the consumers will soon look for denim that has been manufactured with the highest environmental standards, maintaining sustainability throughout its life cycle.

## 1.5 Future trends

The manufacture of denim follows the same classical principles, what has changed is the technology. As ever, cotton is still the fibre for denim, but there is a clear trend towards organic cotton and blends with other fibres. Jeans made of viscose, lyocell, polyester or lycra blends will be more popular in the future due to their soft and comfortable feel. In a similar pattern, even though indigo will continue to dominate the denim sector, other dyes offering a full spectrum of colours will increasingly be used. In the future, indigo may be produced biotechnologically, and the current reduction techniques may be replaced by environmentally friendly techniques. The indigo dyeing technology has not much changed, but the slasher and loop dyeing processes may grow further. Modern sulphur dyeing techniques for denim will offer great savings and will improve the environmental profile of denim considerably. Similarly, the engineering of yarns and the use of automated intelligent machines will make denim weaving a very profitable business in the future.

Lots of developments are also taking place in the manufacture and finishing of jeans. It is well known that denim jeans have an undisputed role in the fashion industry. The joining techniques for the jeans are also improving with the use of automated machines, with an aim to reduce the workload and fatigue of the operators. The dyeing technologies for denim garments are also constantly adapting to rapid small scale production catering to niche markets. In the near future, digital printing techniques will also become established in the jeans industry. Manufacturers are ever competing to develop new washing effects on jeans, most of which are having great impacts on the environment. In this sense, there is a great future for biotechnological washing of denim jeans. To further enhance the environmental profile of washing, the reduced water washing of denim garments will grow at a very high rate in the future. Quality consciousness is also increasing in the denim garment sector, and quality control will play a greater role in future jeans production. Different finishing techniques are adding fashion value and functional properties to jeans. In the future, the functional finishes applied to denim will convert it to a technical or protective garment. Another area of future growth is the improved comfort aspects of denim garments. Even though fashionable looks are undoubtedly important, it is clear that in the future, consumers will pay for a more comfortable product.

Apart from normal denim, there are several novel varieties of denim finding applications in different industrial sectors, apart from fashion and clothing. In the future, the market for such novel products will grow and one such application is the use of denim for non-apparel products such as furniture, upholstery, automotive and home interiors, technical products, etc. It is also expected that denim insulation will be used and encouraged in future green buildings. Denim fabrics and garments create huge environmental impacts, and as a countermeasure, the recovery and recycling of denim waste will grow in the future. Also, effluent reduction and treatment in denim and jeans manufacture will become more stringent and at the same time more efficient.

The future of denim is secure and its popularity is ever growing throughout the world, but ecology and fashion will continue to be the driving factors for jeans production and marketing. In order to retain the rich tradition of denim and jeans, all possible measures should be taken to reduce the environmental impact. The future areas of growth in this direction include the use of organic cotton, eco-efficient non-indigo dyes, intelligent weaving machines, customised garment dyeing, digital printing, biotechnological as well as reduced water washings, functional finishing, non-apparel denim products, recycling of denim waste and reduction and treatment of effluents.

# 1.6 Conclusion

At present, denim is one of the most widely manufactured fabrics, and its manufacture involves different processes and complex machinery. The ability of denim to arouse creativity and to adapt to fashion trends is phenomenal, and it is very clear that full cotton indigo denim is here to stay. Sustainability is becoming the key for future growth in all industrial sectors, including denim manufacture. Several measures are being taken by the denim and jeans industry to improve its environmental profile. Denim mills are attempting to develop easy to wash fabrics while industrial laundries are using enzyme or reduced water techniques. Denim, a blend of fashion and technology, is definitely a fabric for today and tomorrow. Its ability to survive over a century is incredible, and this ageless and timeless blue magic material remains eternally young and stands apart as an evergreen favourite.

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Part One

# **Denim fabric manufacture**

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# Cotton fibre for denim manufacture

2

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# 2.1 Introduction

Cotton is the most important textile fibre and also one of the most abundant agriculturally produced raw materials. Cotton fibre has a high content of up to 95% cellulose, and it is classified as a natural, cellulosic, monocellular, staple fibre. The word 'cotton' is derived from Arabic and is pronounced 'kutan', as well as in other dialects 'qutn', 'qutun', etc. (Gohl and Vilenksy, 1983). It is thought that cotton dates back approximately 7000 years, though no one is quite sure when cotton was first discovered. Cotton as a fibre has achieved a legacy as one of the most versatile and widely used fibres since its creation thousands of years ago. It is grown in warm climates, and about 20 million tonnes of cotton are produced annually. Although grown in around 90 countries, China, the United States, India, Pakistan, Uzbekistan and West Africa account for over 75% of global production. Other major cotton producing countries are Brazil and Turkey.

Most of the production of this fibre goes into some kind of apparel, and one of the most important areas is the manufacture of denim jeans. The techniques in processing cotton have hardly changed to this day, what has changed is the technology and scientific knowledge that has enabled this fibre to be one of the most used and valued textile materials. Cotton is processed into short staple yarns, and to improve the final properties, the produced yarns or the fabrics are subjected to finishing processes. It is also blended extensively with polyester and with other synthetic fibres, particularly spandex (lycra), and is used in many applications including the manufacture of denim (Anon., 1997).

Denim is reputed to have been around since the sixteenth century, initially developed in France in the city of Nimes, a city renowned for weaving an off-white cotton fabric known for its strength. Gradually, the makers began to dye the fabric blue using indigo before exporting it to Italy where jeans (sailor trousers made from denim) were first made. It is claimed that the word 'jeans' is derived from the name of the Italian port city of Genoa. Cotton fibres – which are strong, comfortable and breathable – were the main fibres used for manufacturing this material, and the manufacture of denim fabrics using cotton fibres has continued to this day (Paul and Malanker, 1997).

# 2.2 Cotton cultivation

# 2.2.1 Cotton varieties

There are many different varieties and types of cotton. Their characteristics determine the use for the cotton and hence its value. Cotton is a member of the order Malvales, family Malvaceae and genus *Gossypium*. The genus *Gossypium* consists of 50 wild and cultivated species, out of which only 4 are grown on a commercial scale in the world. *Gossypium hirsutum*, or upland cotton, is native to Central America, Mexico, the Caribbean and southern Florida, and contributes to 90% of world production. The upland strains can range in staple lengths but are often processed to uniformity, making a harder, less supple fabric. Upland cotton is considered best suited for maufacturing denim fabric. *Gossypium barbadense*, known as pima cotton, with extra long staple, is native to South America and contributes to 8% of world production. Both these varieties are called New World species and account for about 98% of world production. *Gossypium arboreum* and *Gossypium herbaceum* are called Old World or Asiatic cottons, and are grown commercially in India, Pakistan and parts of Southeast Asia, accounting for about 2% of world production.

#### 2.2.2 Growing and harvesting

Cotton is an expensive fibre to produce, and in order to flourish it needs an abundance of sunlight, low humidity and also good quality soil with a good irrigation system. Cotton is predominantly grown on cracking self mulching clay soils found on flood plains adjacent to rivers. Cotton growers test the soil a few months prior to planting to check nutrient levels and how much fertiliser may be required.

Cotton can be planted in several ways and often it is planted straight into the stubble of a previous crop. The cotton growers who employ conventional tillage practices plow or list the land into rows, forming firm seed beds for planting. Those who plant using no-till or conservation tillage methods use special equipment designed to plant the seed through the litter that covers the soil surface. The seeding is done with mechanical planters, which cover as many as 10–24 rows at a time. The planter opens a small trench or furrow in each row, drops in the right amount of seed, covers them and packs the earth on top of them. Machines called cultivators are used to uproot weeds and grass, which compete with the cotton plant for soil nutrients, sunlight and water.

In about two months after planting, flower buds called squares appear on cotton plants. In another three weeks time, the blossoms open. The petals change colour from creamy white to yellow, pink and finally dark red. After three days, they wither and fall, leaving green pods called cotton bolls. Inside the boll, which is shaped like a tiny football, moist fibres grow and push out from the newly formed seeds. As the boll ripens, it turns brown. The fibres continue to expand under the warm sun and finally they split the boll apart and the fluffy cotton bursts forth. Thus the cotton fibre starts its journey into denim production from the cotton boll, as shown in Figure 2.1 (The Textile Institute).

While the cotton plant is growing, it needs to be watered a number of times depending on how hot it is and how well the plant is growing. It can take more than 20,000L of water to produce 1 kg of cotton, which is equivalent to a single T-shirt and a pair of jeans. About 73% of global cotton harvest comes from irrigated land. There are other factors that affect its growth, such as pests like insects, and the pesticides that kill these insects are environmentally unfriendly and can reduce the quality of the cotton fibre.



Figure 2.1 Cotton boll on a cotton plant.

It is claimed that cotton constitutes only 3% of the world's crops but accounts for 15% of the world's insecticide spraying. Unsafe use of agricultural chemicals has severe health impacts on workers in the field and on ecosystems that receive excess doses that run off from farms. Unsustainable cotton farming, with massive inputs of water and pesticides, has already been responsible for the destruction of large scale ecosystems and the deteriorating health and livelihoods of people living there.

Cotton harvesting is carried out either manually or by using machines. About 70% of the over 100 million bales of cotton produced globally are harvested by hand. In some countries like the United States, Australia and Israel, cotton harvest is completely mechanised. The modern harvesting machines are designed to reap cotton with a minimum damage to its structure, and they include a picker or a stripper. The plant height should not exceed about 1.2 m for picked cotton and about 0.9 m for stripped cotton, otherwise too much foreign matter will be collected. Cotton picking machines have spindles that pick the seed cotton from the burrs that are attached to the stems of the plants. Doffers then remove the cotton stripping machines use rollers equipped with alternating bats and brushes to knock the open bolls from the plants into a conveyor. A second kind of stripper uses a broadcast attachment that looks similar to a grain header. All harvesting systems use air to convey and elevate the cotton into a storage bin referred to as a basket. Once the basket is full, the stored seed cotton is dumped into a boll buggy, trailer or module builder.

# 2.3 Fibre properties

The cotton fibre consists of a cuticle, primary wall, secondary wall and a lumen. The cuticle is a few molecules thick and covers the primary wall with a waxy film. The wax is a mixture of fats, waxes and resins. The primary wall consists of numerous fibrils spiralling around the fibre axis. Fibrils are simply packs of cellulose chains. The secondary wall has several layers of spiralling fibres, which make up most of the weight

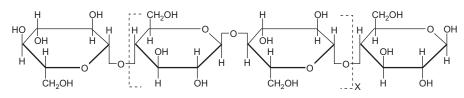


Figure 2.2 Structure of cellulose polymer.

of the cotton fibre. The lumen, located within the secondary wall, is a hollow canal that carries nutrients during the growth. It also contains the dried out remains of the protoplasm and nucleus when the cotton boll development is complete. Cotton fibre is about 95% cellulose and the rest of the materials are waxes, pertinacious substances and nitrogenous matter, which are primarily located in the primary wall and some in the lumen.

The fibre has natural twists along its entire length called convolutions. The convolutions help the fibres interlock when they are spun into yarn. Long fibres have about 300 convolutions per inch and short fibres have 200 or less. Layers of the secondary wall also contain fibrils that are arranged spirally and reverse in direction at regular intervals. These reverse spirals help the cotton fibre have better elasticity and twist. Also, beneath the primary wall is the winding layer, which has a single layer of fibrillar bundles that are at about a 70° angle around the fibre axis. This winding layer is also a layer of the secondary wall.

Cotton is basically a linear cellulose polymer and the repeating unit is cellobiose which consists of two glucose units. The cotton polymer system consists of about 5000 cellobiose units, which means its degree of polymerisation is about 5000. Cotton is a crystalline fibre, and its polymer system is about 65–70% crystalline and about 35–30% amorphous. Figure 2.2 (The Textile Institute) shows the structure of cellulose polymer.

Compared to other major fibres like wool, silk, viscose and polyester, cotton has many interesting properties. Table 2.1 gives a comparative analysis of the physical and mechanical properties of cotton with these fibres (Zupin and Dimitrovski, 2010). The fibre length is an important property of any fibre, and it is referred to as the staple length. Cotton with longer staple lengths tends to produce softer and hairier fabrics than those with shorter ones. Based on their staple length, cotton fibres can be classified into three groups. The first group of fibres have a staple length ranging from 25 to 65 mm. These are fine, lustrous fibres of the highest quality. Examples of these fibres include Egyptian, Sea Island and pima cottons. These fibres are the most difficult to grow, making them the most costly cotton to produce, and are used in products for the high quality end of the market. The term commonly used to describe these fibres is long staple cotton.

The next group is medium staple and is commonly produced in the United States (upland cotton). The staple length can be within a range of 13–35 mm. The third and final group, originating from Asia, has short staple fibres, with a staple length between 10 and 20 mm. These would be used in the production of lower quality carpets and

| Properties                    | Cotton   | Wool    | Silk                                  | Viscose   | Polyester |
|-------------------------------|----------|---------|---------------------------------------|-----------|-----------|
| Length (mm)                   | 10-65    | 50-200  | $3.5 \times 10^{6} - 9 \times 10^{6}$ | 30–180    | 32-150    |
| Fineness (dtex)               | 1.2-2.8  | 4-20    | 1–3.5                                 | 1.3–25    | 1.3-22    |
| Dry tenacity                  | 1.9–3.1  | 1.1–1.4 | 2.4–5.1                               | 1.5-3.0   | 3–7       |
| (cN/dtex)                     |          |         |                                       |           |           |
| Wet tenacity<br>(cN/dtex)     | 2.2–3.1  | 1.0     | 1.9–2.5                               | 0.7–1.11  | 2.4–7     |
| Dry breaking<br>extension (%) | 7–10     | 20–40   | 10–25                                 | 8–24      | 20–50     |
| Moisture regain (%)           | 8.5      | 14.5    | 11.0                                  | 12.5-13.5 | 0.4       |
| Density (g/cm <sup>3</sup> )  | 1.5–1.54 | 1.32    | 1.34–1.38                             | 1.46–1.54 | 1.36–1.41 |

Table 2.1 Properties of cotton and other fibres

blankets, and also for coarse and inexpensive fabrics and blends with other fibres. So in general, cotton fibre length can range from 10 to 65 mm, and the fineness values are in the range of 1-3 dtex. The average moisture regain of cotton is about 8.5%, and the density lies between 1.50 and 1.54 g/cm<sup>3</sup>.

Another property of the fibre that plays a major role during processing is the fibre maturity. The maturity degree depends on the provenance and the harvesting year. Values for the maturity degree are frequently between 75 and 85%. The maturity determines the dye uptake in further processes like indigo dyeing in the case of denim. Micronaire is another important characteristic of cotton fibre (Heap, 2000). It is an indicator of air permeability and is regarded as an indication of both fineness (linear density) and maturity (degree of cell wall development). For a given type of cotton, a relatively low micronaire has been used as a predictor of problems when processing, but a low micronaire may also indicate fine fibres with a low maturity (Montalvo, 2005). A high micronaire value indicates fibres that are coarse, which makes them less desirable for spinning and also gives greater yarn unevenness.

In order to produce a finer denim warp yarn, fine fibres of long staple length are needed. This will ultimately result in a denim fabric that is smoother and aesthetically more pleasing to the eye. It will be more comfortable to wear and is likely to last longer, and the manufacturing of garments from the fabric will be more efficient. In general, denim fabric manufacture requires cotton fibres with a minimum staple length of approximately 28 mm, short fibre content under 40% and micronaire of 4.0–4.5. Some other interesting properties of cotton are the following:

- It is one of the few fibres that gets stronger when it is wet, enabling a smoother manufacturing process when woven into denim fabric.
- It is a relatively strong fibre due to its polymer structure and its crystalline nature.
- It is relatively inelastic due to its crystalline nature.

- Cotton is a hydrophilic fibre due to its amorphous regions, and can absorb up to 50% moisture when wet.
- It has the ability to conduct heat energy, minimising any destructive heat accumulation, and so can withstand very hot ironing temperatures.
- · Cotton fibres are resistant to cold, weak acids, but disintegrate in strong acids.

# 2.4 Cotton fibre processing

Most of the seeds (cotton seed) are separated from the fibres by a process known as ginning. In the countries where cotton is hand picked as well as in the countries where mechanical harvesting is done, ginning is the first important mechanical processing that cotton undergoes. This process separates cotton seeds from fibre, making cotton useable for textile mills and other applications. By the time cotton enters the gin, its quality in terms of fibre properties such as length, strength, maturity and fineness has already been decided. It is only the ginning practices and conditions at the ginning factory that can maintain the quality of the fibre, with a very limited scope for betterment by cleaning process and baling parameters. Once the cotton has been ginned, it is then shipped in bales to the cotton textile mills for further processing.

Cotton is a rather dirty fibre due to its natural origin in the fields. Most of the trash like leaves, plant parts, immature bolls, small stones, dust, sand, etc. gets collected with cotton. The transportation from the fields or market yards to ginning factories, as well as further transportation of bales to textile mills, also add to the contamination. The storage of cotton in open areas full of dust and other contaminants may further contribute to fibre contamination (Bajaj and Sharma, 1999). In order to bring the cotton material to a level where it can be used commercially for manufacturing denim yarns, it needs to be cleaned thoroughly and processed through several stages. Figure 2.3 schematically shows all the main processes involved.

# 2.4.1 Opening, cleaning and blending

The opening process divides the compressed bales of raw cotton progressively into smaller clumps or tufts, which can then be fed to the carding machine for final subdivision into individual fibres. The production of tufts is a traditional process for storing and transporting material between the opening line and the card. It has now largely been replaced by direct feeding, where the opened material is transported directly to the card by a ducted air flow and then consolidated into a sheet of fibre in a chute. A unique feature of the opening line is the inclusion of such a chute mounted on top of the scutcher.

The opening action creates new fibre surfaces, which may expose impurities or trash adhering to the fibres or buried within the larger clumps. These impurities may then be removed by a simultaneous cleaning action, heavy impurities being ejected below the machines, lighter impurities being carried away in an air flow for subsequent filtering. To assess the effectiveness of opening and cleaning lines, it is possible to determine the tuft size (difficult) and the amount of trash removed (relatively easy). Four important factors associated with cleaning are the following:

- Amount of trash in the raw cotton.
- · Amount of fibre that is removed along with the trash, as this increases costs.
- Levels of fine trash (dust) in raw cotton, as this is both hazardous and causes a spinning fault called a moiré (an undesirable fault that occurs in fabric from yarns that have a rippled appearance) in rotor spun yarns.
- Cleaning efficiency of the opening line.

Further, the action of the opening machine breaks up and redistributes the fibres, which results in a blending action that may be enhanced by specific machine

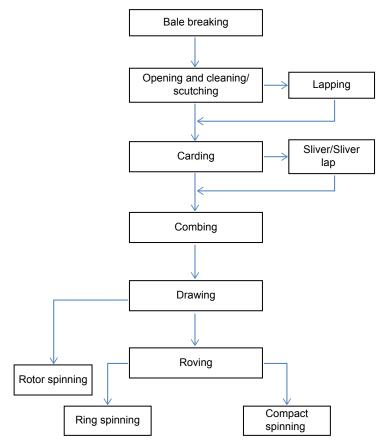


Figure 2.3 Cotton processing stages.



Figure 2.4 Opening and cleaning line.

configurations. The blending is the mixing of fibrous tufts from opened bales to produce a homogeneous mass for consistent yarn properties. A typical opening and cleaning line is shown in Figure 2.4.

# 2.4.2 Carding

Carding is one of the most important operations in cotton fibre processing, as it directly determines the final features of the yarn. In addition to the removal of trash and neps (small bundles of redundant fibres), important aspects of the carding process in relation to yarn quality and spinning performance are the degree of fibre individualisation and the fibre hook configurations in the sliver. The overall purpose of carding can be summarised as:

- Separation of fibres into an individual state.
- Parallelisation and orientation of fibres.
- Reduction of the mass/unit length.
- · Disentangling neps and the elimination of short fibres.
- Blending of fibres.
- Removal of remaining impurities from the cotton.

In the carding technique, fibre separation to the ultimate degree is achieved by means of opposing wire points or teeth. In order to obtain the required degree of fibre separation, the following factors are considered important. The wire points must be capable of taking hold of individual fibres and holding them back or taking them forward. These wire points must be in good condition, and also there must be a very high tooth population in relation to the number of fibres fed, and so there should be more points than fibres.

The carding process can be carried out using revolving flat carding action, stationary tops, and roller and clearer systems. The most common machine used in the processing of cotton fibres is the revolving flat card. Over the years numerous



Figure 2.5 Typical carding machine.

developments have taken place with the carding machine. With increased production rates, the main rotating components can run at significantly higher speeds. Triple intake rollers and modified feed systems are in use, additional carding segments are fitted for more effective fibre opening and improved wire clothing profiles have been developed for a better carding action. Advances in electronics have provided much improved monitoring and process control. Most of these developments have resulted in enhanced cleaning of cotton fibres, reduced neppiness of the card web and better sliver uniformity. Figure 2.5 shows a modern carding machine from Toyoda.

# 2.4.3 Combing

Combing is an extra operation for improving the quality of the sliver coming out of the card. It results in the elimination of short fibres, achieving better parallelisation of fibres, straightening curls and removing neps. Thus the combing process improves the evenness, cleanness, smoothness, appearance as well as the level of twist in yarn. In order to achieve the improvement in fibre quality, the comber must perform the following operations:

- Remove a precise quantity of short fibres.
- Remove all remaining impurities.
- Eliminate most of the neps.
- Form a very regular sliver.

The comber is considered an unusual element among the cotton processing machines as the mode of its operation is discontinuous and a series of synchronised actions is needed for achieving the desired effect. These actions and the order in which they occur are called the combing cycle. The method of combing depends on the fibre type, but the most frequently used technique for both long and short staple fibres is referred to as rectilinear combing. This requires the fibres to be presented to the comber in the form of a sheet or lap, which will be combed and



Figure 2.6 Typical combing machine.

converted into a web. In the case of short staple fibres a number of these webs will be condensed into slivers and then combined in a draw box to form the final combed sliver. Combing is normally used in the production of medium fine to fine yarns in the range of 5–16 tex. Depending on the quality of the final product, waste from combing varies from 12 to 25%. Figure 2.6 shows a typical combing machine.

# 2.4.4 Draw frame

The draw frame combines the two actions of drafting (reduction in mass per unit length) and doubling (combining two or more ends to produce a single end). Draft is an important machine variable that can affect sliver regularity. The total draft on a machine is the ratio of input to output mass per unit length, and it has no units. The total draft is divided between pairs of rollers that grip the fibres and rotate to give different surface speeds, where the speeds are always increasing from the back to the front of the machine. Major drafting is always occurring in a drafting zone where the roller design and configuration is able to grip and accelerate fibres to allow relatively high drafts to occur.

Doubling is the process by which a single sliver is produced from several slivers that are fed to the draw frame. The main purposes of doubling are elimination of mass variation of the delivery sliver and fibre blending. The draw frame combines both drafting and doubling in order to achieve the process objectives such as:

- Improvement in sliver regularity.
- Fibre alignment with the material axis.
- Improvement in fibre blending.

Sliver regularity is very difficult to observe but is of crucial importance to the efficient operation of subsequent processes and the final yarn quality. Regularity is a measure of variations in mass per unit length along the length of the sliver (thick and thin places). The mass of a textile material is directly related to its dielectric properties, and this can be used to measure variations in mass along the length of a moving sample.



Figure 2.7 Draw frame for cotton processing.

These measurements may be taken online on the machine or remotely in the offline mode. The improvement in fibre alignment can be observed by studying the appearance of the slivers before and after drawing. It can be seen that the sliver appears more lustrous as a consequence of the improved fibre orientation. Fibre blending can be observed if slivers of dissimilar fibres are processed and the resultant sliver will be a combination of those fibres fed to the machine. A typical draw frame used in cotton processing is shown in Figure 2.7.

# 2.4.5 Speed frame

The speed frame is a necessary evil in the manufacture of ring spun yarns. A drawn sliver has all the characteristics required for the creation of a yarn. It is a clean, orderly strand of fibres lying parallel to the material axis. However, between the drawing and spinning stages is the intermediate stage of roving production, a stage that uses complicated machinery, has low productivity, adds faults and produces a product that is sensitive to both winding and unwinding.

One of the main reasons for its use lies in the total reduction in linear density required between the sliver and the yarn, and this may be in the order of a draft between 100 and 500. The roller drafting systems in the draw frame cannot impose drafts of this magnitude in a single stage, and they are limited to a maximum draft of about 50. The second reason is that draw frame cans are not suitable for transport or presentation to the ring spinning machine.

Thus the main objective of the speed frame is to reduce the linear density of the sliver. Since the resulting strand is so fine it lacks coherence, and so a low level of protective twist is inserted to hold the strand together. Finally, the twisted strand must be wound to form a package suitable for transport, storage and processing on the ring frame. It is this final objective of winding and package formation that makes the speed frame such a complicated piece of machinery. Efforts have been made to overcome these difficulties but none have been successful, and it required



Figure 2.8 Speed frame for cotton processing.

the introduction of the newer spinning technologies like rotor spinning to eliminate the speed frame and convert sliver directly to yarn. A typical speed frame used in cotton processing is shown in Figure 2.8.

# 2.5 Spinning of denim yarns

Spinning is a process dating back to many hundreds of years when natural fibres such as cotton were processed into yarns to be woven into fabrics. This age old process has never changed to this day, and it consists of:

- Drawing, to thin the fibres and to reduce the density of the material.
- Inserting twist, to create the yarn and to give it strength.
- · Winding of yarn packages, ready for warping on a warping beam.

These techniques are still followed in the modern sophisticated machinery that produces denim warp yarns of different characteristics and qualities. The most common processes for spinning the cotton fibres are ring spinning, compact spinning and rotor spinning. All of these processes are currently used for spinning cotton warp yarns for denim production. The denim warp yarn should fulfil certain attributes concerning the volume, low curling tendency and hairiness in order to guarantee problem free warping, dyeing and weaving processes. These yarns typically range in count from Ne 4.0 to Ne 12.5. Finer yarns are used for producing lighter weight jeans, vests, dresses and skirts, and these yarns may range in count from Ne 12.5 to Ne 30.0.

# 2.5.1 Ring spinning

The ring frame is capable of high speeds and can spin very fine yarns that are regular along the yarn axis. The ability of these machines to produce high quality warp yarns

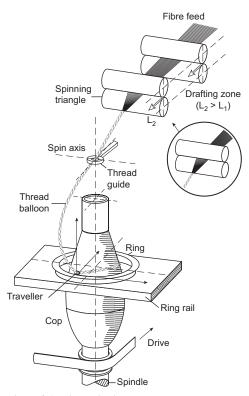


Figure 2.9 Schematic view of the ring spinning process.

results in the production of a smoother and high quality denim. A schematic view of the ring spinning process is shown in Figure 2.9 (Wulfhorst et al., 2006), and a typical ring spinning machine is shown in Figure 2.10.

In ring spinning, the roving is first attenuated to achieve a fibrous bundle that corresponds to the yarn fineness using a double apron drafting system (draw ratios of about 10–40). The untwisted fibrous bundle exits the drafting field and is twisted by the rotation of the traveller on the ring, which induces the twist. The yarn is twisted once with each revolution of the ring traveller. The twist formation moves up to the spinning triangle, whose geometry is determined by the equilibrium of the torsional moment of the yarn and the opposing movement of the loose fibrous bundle. Owing to the trailing of the traveller, the twist of the yarn is a little lower than the twist that would be produced only by the rotating cops. The ring and traveller system realise not only the twist in the yarn but also the winding of the yarn on the bobbin. The ring spinning technology twists the fibres from the outside of the spinning triangle to the inside so that the fibres in the middle of the spinning triangle lie relatively parallel and the outer fibres are twisted around them.

The maximum production of ring spinning is limited by the maximum velocity of the traveller, which is about 40 m/s, producing local temperatures on the traveller of up to 450 °C. The utilisation of the fibre material or the percentage of the fibres in the



Figure 2.10 Modern ring spinning machine.

compound yarn that supports the tensile loads of the yarn is about 30–65% with ring yarns. Because this value is substantially higher than with other spinning methods such as rotor spinning, ring spinning produces the finest and strongest yarns, best suited for denim.

# 2.5.2 Compact spinning

One of the major challenges observed by ring spinning technology over the years is the existence of hairy yarn structures, and this is avoided in compact spinning. Figure 2.11 provides a comparison of the ring and compact spinning technologies (Smekal, 2001). This is achieved through a condensing of the fibres after the main draft by using a perforated roller in combination with a suction unit. The hairiness of the yarn is thus reduced and the tenacity is higher when compared to ring spun yarns. The yarn evenness is also significantly improved.

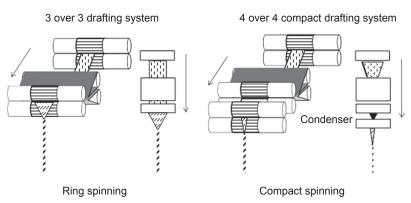


Figure 2.11 Comparison of ring and compact spinning.

Compact spinning can be realised by means of different techniques. The techniques conventionally used are the following:

- The delivery roller is replaced with a perforated bottom roller with suction. The roller helps gather all the fibres together, before they are spun into a yarn.
- Another method for the compaction of fibres is the use of a perforated apron that is wound around a roller and spacer bar with a suction zone.
- Yet another technology is the mechanical compacting of fibres using guides that act as condensers for controlling the spinning triangle, and no suction is used in this case.

# 2.5.3 Rotor spinning

Rotor spun yarns were previously used only as the weft but are now extensively used also as denim warp. Compared to ring spinning, rotor spinning offers higher productivity and so the production costs are much lower. As the speed is higher than ring spinning, the produced yarns are coarser than ring spun yarns. The rotor spinning machine is referred to as open end spinning, since there is a definite break in the fibre flow prior to the yarn formation. A schematic view of the rotor spinning process is shown in Figure 2.12 (Alagirusamy and Das, 2010) and a typical rotor spinning machine is shown in Figure 2.13.

Full automation is possible in the rotor spinning process, as it combines three manufacturing processes: speed frame, ring spinning and winding. The process sequence in rotor spinning includes feeding of the input sliver, opening of fibres to the individualised stage, transportation of fibres up to the rotor groove and insertion of twist and winding of yarn (Alagirusamy and Das, 2010). The machine is fed with a sliver that is delivered by either a combing machine or a draw frame. A feed roller/feed plate unit transports the sliver to the opening roller. The opening roller rotates at a circumferential speed (5000–8000 rpm) of 20–30 m/s, which provides a very intense combing and separation of the

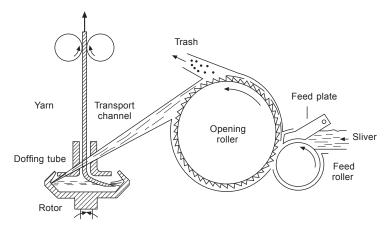


Figure 2.12 Schematic view of the rotor spinning process.



Figure 2.13 Modern rotor spinning machine.

| Table 2.2 Comparison of ring spun and rotor spun yar |
|--|
|--|

|                          | Spinning method |                |  |
|--------------------------|-----------------|----------------|--|
| Characteristics of yarns | Ring            | Rotor          |  |
|                          |                 |                |  |
| Production rate          | High            | Higher         |  |
| Tenacity                 | Very high       | Average        |  |
| Linear density           | 5–600 tex       | 20–60 tex      |  |
| Twist                    | Lower           | Higher         |  |
| Extensibility            | Average         | Higher         |  |
| Abrasion resistance      | Lower           | Higher         |  |
| Strength variation       | High            | Low            |  |
| Yarn faults              | High            | Reduced by 80% |  |
| End breaks               | High            | Reduced by 75% |  |
| Fly liberation           | High            | Less           |  |
| Neppiness                | Higher          | Lower          |  |
| Hairiness                | Very high       | Lower          |  |
| Regularity               | Lower           | Higher         |  |
| Handle                   | Softer          | Harsher        |  |
| Appearance               | Less uniform    | More uniform   |  |
| Fibre blending           | Lower           | Higher         |  |
| Wrapper fibres           | None            | Present        |  |

fibres. The fibres are detached from the roller clothing with an air stream and accelerated in a conical transport channel. This channel ends in a rotor rotating with up to 200,000 rpm. Because of their centrifugal force, the fibres slide along the outside of the rotor wall and form a ring like structure in the rotor

groove. As the fibres are continuously accelerated during this process, their position in the rotor groove is mostly straightened. A new yarn is spun when an open yarn end is led into the rotor via a pull off pipe and nozzle. The yarn rotates in the rotor groove, which causes fibres lying in the groove to attach to its yarn end. With the pull off of the yarn through the nozzle and the uptake pipe, a continuous spinning process is commenced.

For rotor spinning, a minimum of 70–100 fibres in the yarn cross section is necessary. Because of the inherent restriction of this process, rotor yarns cannot be spun as fine as ring yarns. The tenacity of rotor yarns is lower than that of comparable ring yarns. As the rotor spinning is fully automated, it delivers cross wound bobbins ready for further processing without any additional winding step. The rotor groove also plays a very significant role in the yarn properties. Rotors with diameters of 40 or 46 mm with T, U, S shaped rotor grooves are normally used for manufacturing both warp and weft denim yarns (Biermann and Schmidt, 2002).

Rotor spun yarns have a two part structure consisting of a central core, which is similar to ring spun yarns, and an outer sheath (wrapper) that contains fibres in random disarray. The outer sheath is produced as the fibres are still fed to the yarn after it has been formed. Denim warp yarns usually have a metric twist factor of 140 and weft yarns a factor of 130. Table 2.2 gives a detailed comparison of the yarns from the ring and rotor spinning methods used for denim manufacture (Iqbal and Kolhatkar, 2009; Wulfhorst et al., 2006).

# 2.5.4 Warping of yarns

The cotton warp yarn used in denim manufacture is uniquely prepared unlike in the conventional woven fabrics. The yarn goes through numerous processing stages before it is placed on the weaving machine. Unlike warp yarn, weft yarn is put onto yarn packages and delivered directly to the weaving machine, where it is inserted into the fabric without any further preparation. Warping is the process of transferring multiple yarns from individual yarn packages onto a single package assembly. For ball warp denim, the yarns are brought together and condensed into a rope before being wound onto a relatively short cylindrical barrel or shell that has no end flanges. In beam warping, the yarns are collected in a sheet form, where the yarns lie parallel to each other and in the same plane, onto a beam, which is a cylindrical barrel with side flanges. In both cases, the supply yarn packages are placed on spindles, which are located in a framework called a creel.

# 2.5.4.1 Ball warping

In ball warping, 250–400 yarn ends are pulled from the creel. The yarns then pass through a comb like device (also known as hack or reed), which keeps each warp yarn separate and parallel to its neighbouring ends. At intervals of every 1000 or 2000 m, a lease string is placed across the sheet of warp yarns to aid yarn separation for the re-beaming operation, which will occur later. The yarns then go through a funnel shaped device called a trumpet or condenser, which collapses and condenses the sheet

of yarn into rope form. This device is located at the base of the warper head and traverses back and forth, guiding the newly formed rope of yarn onto a log. The rope must be wound at a constant tension to keep the yarns from tangling. The ropes are then used for dyeing with indigo in the rope dyeing range.

#### 2.5.4.2 Beam warping

Beam warping maintains the yarns in an open sheet form and winds the yarns parallel to each other onto a slightly wider flanged beam. These yarns will not go through the indigo rope dyeing range, but will end up either as slasher dyed or undyed fabric, which can later be piece dyed, garment dyed or left natural. Another option would be to beam dye the yarns using a dye other than indigo (Anon., 2004).

# 2.6 Developments in cotton for denim

Cotton growers are continuously struggling for a reasonable price for their cotton. There is now a move towards a fair trade practice with cotton, which should enable cotton growers to be paid a fair price for their product. In this respect, there is an increasing trend towards the cultivation and production of organic cotton for denim manufacture. This is generally understood to be cotton that is not genetically modified and grows without the use of synthetic agricultural chemicals, which includes both fertilisers and pesticides.

Organic cotton production and trade is also promoted as a more viable and sustainable alternative to conventional cotton production. However, cotton growers generally do not adopt new production techniques unless they are profitable. Organic cotton yields are generally lower than conventional ones, and even lower than what might be acceptable in view of lower production costs. Nevertheless, some consumers are willing to pay a premium for denim garments made out of certified organic cotton fibre, and labelled as such. Although production of organic cotton is expanding rapidly, conventional cotton still accounts for about 99.9% of total world output.

In recent years, naturally coloured cotton has also become important for denim in view of its eco friendly character. Cotton occurs naturally in different colours like creamy white, brown, green, blue and pink. The colour is a genetically controlled characteristic, and the accumulation of pigments in the fibre lumen starts before boll bursting. However, the complete expression of colour takes place only when the boll bursts open and the fibre is exposed to sunlight. It takes about a week for the fibre to develop a complete natural colour. It is interesting to note that while sunlight is essential for the development of colour, continuous exposure leads to colour fading. Some genotypes may show colour fading with time and washing, while others may not. Brown colour in some genotypes may intensify after several washings.

Naturally coloured cotton has some inherent drawbacks, which include low yield potential, short fibre length, limited colours and instability of colours. It also requires specialised harvesting techniques and facilities, making it more expensive to harvest than white cotton. As the fibre length is short, the spinning is more complicated as compared to white cotton. Even though companies like Levi Strauss has shown interest in naturally coloured cotton, in general the market for coloured cotton can be considered a niche market.

Another area of development is genetically modified cotton, which has been engineered to be insect resistant or tolerant to herbicides. One of the commercial varieties is *Bacillus thuringiensis* (Bt) cotton, which is resistant to bollworms. *Bacillus thuringiensis* is a very common bacterium occurring in the soil and capable of producing crystal proteins that have insecticidal action. These proteins are toxic to certain types of insects (moths such as bollworms) that attack cotton, and the action is specific to those insects. The target insect must ingest the crystal protein for the protein to be effective. Bt cotton was first planted on a commercial scale in 1996 in Australia and the United States. Genetically modified cotton has been officially approved for commercial release in some countries and experimentation is under way in several other countries. Monsanto, USA, has a dominant position and controls about 80% of commercially grown genetically modified cotton (Joseph and Paul, 2007; Paul and Joseph, 2003).

Many scientific studies have also been undertaken for converting cotton fibre into new and innovative denim textile material. In this respect, an experimental study has been undertaken for improving the physical appearance by using low torque ring spun yarns (Hua et al., 2013). In this work, the residual weft torque in the cotton yarn was reduced. Low torque cotton yarns of 84 and 58 tex linear density with different twist levels were produced on a modified ring spinning machine. The results from the study showed that the low torque yarns possessed fewer yarn snarling turns. This enabled denim to improve fabric smoothness and appearance. There are many other research studies undertaken on cotton fibre used in the production of denim. These include modified rotor spinning of denim warp yarns, testing of physical properties of different types of denim fabrics and enzyme treatments on denim products (Biermann and Schmidt, 2002; Miettinen-Oinonen et al., 1996; Rathod and Kolhatkar, 2013).

Cotton is often blended with other fibres like lycra to produce desired effects on denim. This imparts a high degree of extensibility to the yarn that is used in denim, to produce tightly fitting garments. These are particularly used for the manufacture of ladies denim jeans. Blending the cotton fibre with the DuPont fibre T400 polyester enables the fabric to be more bleach resistant and withstand chlorine more effectively. DuPont has also created a knitted stretch denim called Veloflex, which contains 96% cotton and 4% lycra. The fabric is reputed to have soft hand, is supple and it enables designers to create slim cut jeans that provide comfort and freedom of movement.

The developments in blending cotton fibres with lycra have also led to some leading companies collaborating to bring improved performance on denim stretch fabrics (Anon., 2013). Invista, the holder of the lycra brand, and Lenzing AG, a leading producer of man-made cellulosics, have worked together to improve the aesthetic performance of stretch fabrics. The outcomes included the delivery of unique solutions to the denim industry with the combination of Invista's patented lycra dualFX fabric technology with Lenzing's lyocell fibre, for the improvement of stretch cellulosic fabrics and reinvention of lyocell fibre.

One of the innovative cotton finishing technologies from Cotton Inc. USA is Stay True Cotton, which helps indigo dyed denim retain its original colour longer. A very small quantity of dye is released during home laundering of these garments, giving it an environmentally friendly appeal. Wicking Windows is a moisture management technology for cotton that transfers moisture away from the body and reduces absorbent capacity for faster drying. Fabrics treated with this technology show 1400% improvement in one way transfer of moisture to the outside of the fabric over their untreated cotton equivalent. Cotton fabrics made with TransDRY technology offer comfort and softness of cotton while staying dry, keeping the wearer cooler and more comfortable. Another technology, termed Storm Denim, is a super repellent finish that protects the wearer from moderate rain, snow and wet conditions, while maintaining the natural comfort and breathability of cotton (Crumbley, 2008).

There are also studies to replace cotton in denim with more sustainable fibres. In this respect, the researchers at Herriot-Watt School of Textiles and Design, in the United Kingdom, have developed jeans using a fibre made from sustainable wood instead of cotton, and it is claimed that this could be the key to cutting carbon emissions in the denim jeans industry around the world. The developed jeans have cotton like qualities but use only one fifth of the water and energy needed to manufacture conventional jeans.

# 2.7 Future trends

Sustainability will hold the key in the future, and it is high time for cotton to become a sustainable fibre: in the cultivation, denim manufacturing as well as in the subsequent processing of garments. In this respect, organic cotton, which offers sustainability in cotton cultivation, is slowly gaining importance in denim manufacture. Many retailers are now pledging their support towards selling organic cotton, which includes some of the top brands. However, in future, it is probable that this trend is likely to be led by demand from the consumers for an organic product. Other areas of future developments include naturally coloured and genetically modified cotton.

Cotton is now extensively blended with lycra, polyester, lyocell, flax, etc. to develop special types of denim. Although most of the world production of denim jeans is still 100% cotton, the market for stretch denim is one of the fastest growing segments of jeans manufacture. Cotton blends that use both lycra and polyester, combining both strength and stretch properties, are becoming more popular, especially in Europe. This trend is also significantly growing in other parts of the world. The European linen and hemp weavers are developing denim fabrics in a variety of looks and weights, and yet another fibre that will be widely used for denim is lyocell. These fabrics have a clean and neat look and natural lustre. High levels of stretch can be obtained without the use of elastomeric fibres because of the swelling properties of lyocell fibres. Even though many such fibres are now entering the denim sector, it is highly improbable that they will ever replace cotton completely.

Awareness of the final quality of denim warp yarns and the productivity of spinning processes is also increasing. Even though ring spinning is still preferred for manufacturing denim warps, there is a clear trend towards using rotor spinning. It is slowly gaining importance, as it has several advantages such as increased production rate,

separation of twisting and winding, elimination of speed frame and winding, and possibilities of full automation.

# 2.8 Conclusion

Denim would not be denim without the cotton fibre, and the whole process begins from a plant grown in a field in some country in the world. Most of the cotton processing techniques have not changed during the years, and the general principles outlined in this chapter are followed for denim manufacture. Apart from ring spinning, rotor spinning is becoming more important in denim production. Weaving a combination of ring spun and rotor spun yarns can help to reduce fabric costs while still maintaining some favourable ring spun fabric characteristics.

As the cotton fibre is spun into a yarn and that yarn is woven into denim material, the cycle of manufacturing a wearable product has begun. From work wear to business attire, denim has become a universal material in apparel. It is used in almost every type of garment from jeans and jackets to skirts, dresses and even evening wear. This phenomenon shows no signs of abating, meeting the market demands and fashion needs. Manufacturers are constantly developing denim materials using new fibre blends, weights and finishes. Even with all of the new developments in fibre blending, full cotton denim still remains as the eternal favourite of the masses.

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# Indigo dye and reduction techniques

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# 3.1 Introduction

Indigo has been used for colouration of textiles since antiquity. Natural indigo extracted from the *Indigofera tinctoria* plant species maintained its dominant position in the international market until the synthesis of indigo in 1897. The classical denim is a blue coloured durable twill fabric made from 100% cotton and woven from coarse indigo dyed warp and grey undyed weft yarn. The most important feature of denim fabric is the vintage look created by abrasion or different kinds of finishing applications. The simple reason for this special look is the magical indigo dye used for the dyeing of warp yarns.

Denim production remained at relatively stable and low levels until the 1970s, when the demand reached explosive levels as a result of the potential for colour fading of indigo. Until the 1960s this colour loss after washing was not a characteristic of indigo dyed denim, and it was completely unacceptable to consumers to pay for garments that lost colour after washing. Indigo dyeing machinery and procedures were quite different from those in use today (Mercer, 2010a).

Despite its long history and current importance, it is surprising that indigo must be classified as a vat dye, because the present application methods for indigo and the fastness properties of indigo dyeing are not typical of vat dyes as a whole. Vat dyes show outstanding colour fastness properties, particularly to light, washing and chlorine bleaching; while indigo dyeings have poor washing and chlorine fastness and poor abrasive resistance (Aspland, 1992). In spite of these drawbacks, the credit for the present importance of indigo should be given to aggressive marketing. Satisfying the needs of the customer is generally more important than achieving the highest levels of technical performance in dyed and finished goods, although the two sometimes coincide. Since the early 1970s, customers wanted indigo blue denim primarily for the appearance that can result from the inferior fastness properties of the dyeings. This is exploited by garment dyers and finishers in stone washing and other wet processes (Baumgarte, 1987; Seefelder, 1994).

# 3.2 Indigo popularity for denim

The indigo colour is the principal source of the almost magical appeal of denim. The dye imparts a brilliant blue hue to fabric. In fact there is no other dye that creates such an intense blue colour with so few carbon atoms in its molecule (Agarwal, 2011).

Indigo is unique in its ability to impart surface colour due to partial penetration in cotton fibres. When cotton yarn dyed with indigo is untwisted, it can be seen that the inner layers remain uncoloured. The dye also fades and abrades continually. This characteristic of indigo lets denim fabric have its final worn look with different types of washing and finishing applications. It enables denim fabric to respond to finishing applications that give a real life to the fabric (Adnan, 2010).

Despite many other blue dyestuffs, indigo has kept its popularity for denim dyeing. This no doubt is achieved by the fact that indigo has a number of properties that have not yet been achieved by another single dyestuff. The unique feature of indigo dyed denim is the possibility of achieving wash down effects on repeated washing without losing the freshness of the colour. Another important feature of indigo is that unlike many other dyes, indigo dyed denim does not pose health hazards. In fact, indigo is so safe for living things that it has long been used to colour polyester medical sutures. Indigo is also used as food colour and as a medical indicator applied intravenously (Mercer, 2010b).

Technical features of indigo include possibility of dyeing at room temperature, favoured shades from black to navy to sky blue that are not too brilliant or not too dull, reduced indigo solution is not sensitive to water hardness and this allows the dyeing of greige or minimum pretreated cotton, does not strongly bond to the fibre, repeated washings slowly remove the dye without losing freshness and most importantly the competitive price. In fact, many synthetic blue dyes have superior qualities compared to indigo, and this would have ruined synthetic indigo as well if denim had not begun its invasion to Western culture after the Second World War (Balfour-Paul, 2000).

# 3.3 Dyes other than indigo

Since denim is made of 100% cotton, therefore in addition to indigo it can be dyed with dye classes such as direct, vat (other than indigo), reactive, sulphur dyes and pigment colours. In the last decade, denim was mainly dyed with indigo (67%), sulphur black (26%) and other sulphur colours (6%). The changing fashion trends have also led to vat, reactive and direct dyestuffs, as well as pigments being used to colour denim (Holme, 2010).

Direct dyes are currently being applied in garment dyeing of jeans in light colours for the higher fashion market. Direct dyes can also be used for tinting denim fabrics by adding to finishing formulation. Reactive dyes are often used in garment dyeing. There have been attempts to apply reactive dyes on indigo machinery, but control of dyeing is nearly impossible because of the large dye boxes on most indigo equipment, much of the dye being hydrolysed before it can react with cotton. Therefore, reactive dyes should be applied in a small box, then dried, chemical padded and steamed. The only practical alternative for most denim companies is to apply reactive dyes during sizing with special procedures. There are few vat dyes that can be mixed with indigo for casting; however, pure vat colours are best applied on denim with specially designed rope ranges with an additional set of drying cylinders, steamer and small pad boxes for dye pad, dry, chemical pad, steam methods. However, vat dyes produce shades with high fastness properties and therefore it is difficult to get the classic denim look. Sulphur dyes are of low cost and can be applied on indigo machinery, fabric dyeing machinery, jiggers, pad-batch and garment dyeing machinery with properly designed methods. Sulphur dyes have an appearance that is more natural than reactives or directs, having a softer appearance and allowing versatile wash down effects in laundering. Therefore among the different dye classes other than indigo, sulphur dyes are more popular and are used for bottoming or topping or over dyeing of finished indigo dyed garments to produce a variety of shades with fancy looks. Pigments are relatively easy to apply, and since they are a surface colouration, can produce a distressed look, but they present colour fastness problems in darker shades and have a harsher feel than dyed garments (Mercer, 2012).

# 3.4 History of indigo

Excavations in the Indus valley indicate that indigo dye was used in India since ancient times. The association of indigo with India is reflected in the Greek word for the dye, *indikón* (wðuxóv, coming from India). The Romans Latinised the term to indicum, which passed into Italian dialect and eventually into English as the word 'indigo'. The dye was also known to ancient civilisations in Mesopotamia, Egypt, Greece, Rome, Britain, Peru, Iran and Africa (The Story of Indigo; Indigo Dye). Indigo was also the foundation of centuries old textile traditions throughout West Africa (Kriger and Connah, 2006). Thus indigo is one of the oldest dyes used by mankind. Historians claim indigo was used as far back as 5000 BC. Mummies from Egyptian tombs from about 2500 BC have been found covered by indigo dyed hemp fabrics (Balfour-Paul, 2000; Gilbert and Cooke, 2001).

In fact, before the synthetic substitute for the dye was invented, all blue textiles used to be dyed with the dye derived from different species of indigo plant sources. *Indigofera* species (*I. tinctoria*) were used in the tropics like India. In Europe, dyer's woad (*Isatis tinctoria*) was cultivated for indigo production, and dyer's knotweed (*Polygonum tinctorium*) was cultivated for indigo in China and Japan (Akram Rashid, 2010). In colonial North America there were three commercially important species: the native *Indigofera caroliniana* and the introduced *I. tinctoria* and *Indigofera suffruicosa* species (Rembert, 1979).

India is believed to be the oldest centre of indigo dyeing in the Old World. Phoenician traders and migrating peoples gradually introduced this dye to the Mediterranean area, and then spread to Europe. In Northern Europe from the Bronze Age (2500–850 BC) people used blue dye woad from the plant *Is. tinctoria*. It has since been discovered that this plant contains the chemical indigo, but due to other compounds in the plant it is not a 'pure' blue like the *Indigofera* (Sequin-Frey, 1981). Woad is native to Southeast Russia and it has spread from there to cultivation in the rest of Europe (Hurry, 1930).

In the Middle Ages, woad was an important crop in Europe and it brought immense wealth to the woad traders. The renowned centres of the trade were Toulouse in France and Erfurt in Germany, which still have some lingering effects of woad commerce (Balfour-Paul, 2000). In the late fifteenth century, the Portuguese explorer Vasco da Gama discovered a sea route to India, and as a result tropical indigo overtook European markets in the seventeenth century even if the woad traders did all in their power to stop that (Clark et al., 1993). The demand for indigo towards the end of the nineteenth century is indicated by the fact that about 7000 square kilometres were dedicated to the cultivation of indigo producing plants, mainly in India (Steingruber, 2004).

India exported so much raw indigo dyestuff that one million people were employed in either production or transport to Europe. At one point it was the largest export business in the world. Because of its high value as a trading commodity, indigo was often referred to as 'blue gold' (The Story of Indigo). The indigo produced in India and Java replaced woad in such a way that woad cultivation was diminished until it disappeared entirely in the beginning of the twentieth century with the appearance of synthetic indigo for the markets. Synthetic indigo destroyed almost completely the production of tropical indigo as well (Balfour-Paul, 2000; Gilbert and Cooke, 2001).

## 3.4.1 Indigo colour

Indigo is a colour named after the blue dye derived from the plant *I. tinctoria* and related species. The colour is placed on the electromagnetic spectrum between about 420 and 450 nm wavelength, placing it between blue and violet. Although traditionally considered one of seven colours of the rainbow or the optical spectrum, modern colour scientists do not usually recognise indigo as a separate division and generally classify wavelengths shorter than about 450 nm as violet (Hunt, 1980). The first recorded use of indigo as a colour name in English was in 1289 (Maerz and Paul, 1930). Though the word 'indigo' has existed in English since the thirteenth century, it may never have been a common part of the basic colour naming system (Ottenheimer, 2009).

# 3.5 Indigo production

There are three routes through which indigo can be produced: natural indigo, synthetic indigo and bacterial or microbial indigo.

### 3.5.1 Natural indigo

#### 3.5.1.1 Plant species

Natural indigo was the only source of the blue colour until about 1900. The raw materials used in the natural production of indigo are leaves from a specific plant species containing only a small amount of the dye (about 2–4%). Therefore, a large amount of plant material is required to produce a significant quantity of dye. To ensure a controlled supply, indigo was planted in many parts of the world (Indigo Dye).

There are three types of plants with about 300 species that make indigo.

Leguminosae (pea family)

The most famous indigo bearing plant is *I. tinctoria*, commonly known as indigo. It is a shrub originally grown in the tropics, particularly in India, Southeast Asia and the Middle East.

Crusiferae (cabbage family)

This plant is *Is. tinctoria*, commonly known as woad. The plant was grown in the Mediterranean and Western Asia. Woad is also grown in North America and in Europe.

Polygonaccae (dock family)

Dock is the name applied to a group of broad-leaved wayside woads. Rhubarb comes from the same family. This species is commonly called Japanese or Chinese indigo (The Story of Indigo).

The most important indigo species is *I. tinctoria*. The species is also known as *Indigofera sumatrana*. A common alternative used in the relatively colder subtropical locations such as Japan's Ryukyu Islands and Taiwan is *Strobilanthes cusia*. In Central and South America the two species *I. suffruticosa* (Añil) and *Indigofera arrecta* (natal indigo) were the most important. In temperate climates, indigo can also be obtained from woad (*Is. tinctoria*) and dyer's knotweed (*Polygonum tinctorum*) (Indigo Dye).

## 3.5.1.2 Indigo extraction

The traditional methods of extraction of indigo from the plants *I. tinctoria* and woad (*Is. tinctoria*) differ from each other.

#### Extraction from I. tinctoria

Indian method: Cultivation of indigo for extraction of dye is an age old practice in India. Although there are several variations, traditionally the cut plant is tied into bundles, packed into the fermenting vat and covered with clear water. The vats, which are usually made of brick lined with cement, have an area of about 400 square feet and are 3 feet deep, arranged in two rows over each other. The top vat is known as the fermenting vat and the bottom as the beating vat. The indigo plant is allowed to steep up to 10–15 h, during which natural fermentation sets in. The liquor, which varies from a pale straw colour to a golden yellow, is then run into the beating vat, where it is agitated either manually or mechanically. The colour of the liquid becomes green, then blue, and finally indigo separates out as flakes and is precipitated to the bottom of the beating vat. The indigo is allowed to thoroughly settle, when the supernatant liquid is drawn off. The pulpy mass of indigo is then boiled with water for a few hours to remove impurities, filtered through thick woolen or coarse canvas bags, then pressed to remove as much of the moisture as possible, after which it is cut into cubes and finally air dried (Adnan, 2010).

Japanese method: Historically, the Japanese have used another method, which involves extracting indigo from the *Polygonum* plant. In this process the plant is mixed with wheat husk powder, limestone powder and lye ash. The mixture is allowed to

ferment for about one week to form the dye pigment, which is called Sukumo (Akram Rashid, 2010).

#### Extraction from Is. tinctoria

In the traditional method of producing indigo dye (also called woad) from woad, the leaves were crushed to a pulp, which was kneaded into balls, which were then allowed to dry for several weeks. These dried balls could then be stored. The balls needed to be couched. The couching meant crushing the balls into powder and wetting it and allowing the material to ferment for several weeks. After couching, the woad was dark clay like material that was dried and packed tightly before use (Hurry, 1930; Kokubun et al., 1998).

The dye from woad was very impure and it gave only light colours, whereas the indigo from the tropics was of better quality and could be used to produce darker blues. This was the reason why the exotic indigo from the *Indigofera* species could overtake woad so completely.

The modern extraction method of indigo from woad uses the water solubility of the indigo precursors in steeping the leaves in hot water. The precursors are broken down to indoxyl and sugar moieties by enzymes in the plant. Subsequent aeration produces indigo by oxidation of indoxyl (Stoker et al., 1998a,b; Minami et al., 1996).

#### 3.5.1.3 Colouring component in plant species

Indigo as such does not exist in the leaves of indigo producing plants. Instead, there are its precursors, indican in *Indigofera* and *P. tinctorium* species (Perkin and Bloxam, 1907a), and *isatan B* in addition to indican in *Is. tinctoria* (Balfour-Paul, 2000). Indican in fresh green leaves is stable, as it is attached to glucose, forming a stable indican glucoside. However, when the leaves are fermented, indican is hydrolysed (cleavage of sugar residue) by an enzyme glucosidase present in the leaves to yield indoxyl, which transforms rapidly into indigo by oxidative dimerisation (Clark et al., 1993; Russell and Kaupp, 1969). The reaction is shown in Figure 3.1 (Clark et al., 1993).

Surprisingly, indican is also biosynthesised in the human body from the amino acid tryptophan. Part of the indican is degraded by intestinal bacteria to the smelly indole. Some of the colourless and water soluble indican is also eliminated via the kidneys. In rare cases certain people are unable to metabolise the indican properly, and they

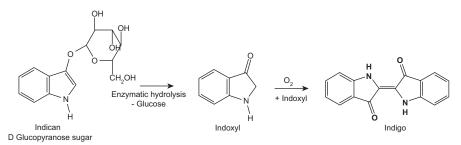


Figure 3.1 Conversion of indigo precursor into indigo. Clark et al. (1993).

excrete traces of the intensely blue indigo in their urine. This medical condition is also known as PUB, 'purple urine bag syndrome' (Indigo Chemistry).

# 3.5.1.4 Natural indigo purity

The purity of plant-derived indigo even with the modern extraction method is somewhat low when compared to synthetic indigo. Natural indigo contains impurities such as indirubin, indigo-brown, indigo gluten and mineral matter (Orchardson et al., 1907; Perkin and Bloxam, 1907b). The indigo purity for woad has been reported to be 20–40% (Bechtold et al., 2002a), and for *Indigofera* indigo from 50% up to 77% (Stoker et al., 1998a). There is also the question of the efficiency of the extraction; the theoretical yield of indigo formation from indoxyl molecules has been discovered to be approximately 60% (Garcia-Macias and John, 2004). So 40% of the indoxyl is lost during the process to impurities such as isatin and indirubin and other by-products of the reaction (Orchardson et al., 1907).

# 3.5.1.5 Revival of natural indigo

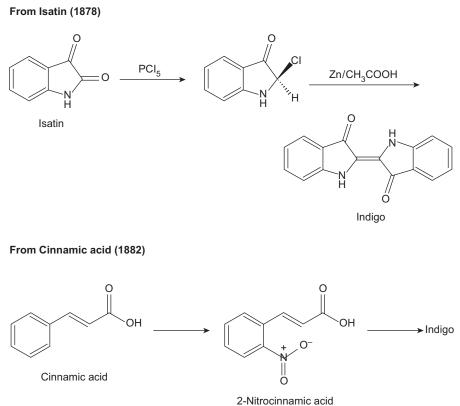
Since the commercialisation of synthetic indigo, the use of natural indigo has almost become extinct. In recent years, the demand for natural dyes has been increasing in many countries, because of health and pollution effects and a revival of interest in the relationship between dyes and culture. In the present time, indigo is still cultivated for dyeing on a small scale in India and in some parts of Africa and Central America. It is frequently grown as a secondary crop (Chavan, 2004).

# 3.5.2 Synthetic indigo

Demand for natural indigo dramatically increased during the industrial revolution, in part due to the popularity of Levi Strauss's blue denim jeans. The natural extraction process was expensive and could not produce the mass quantities required for the growing garment industry. So chemists began searching for synthetic methods of producing the dye. Indigo has been prepared by many methods (Steingruber, 2004).

In 1865, the German chemist Adolf von Baeyer began working on the synthesis of indigo. He described his first synthesis of indigo in 1878 from isatin, second synthesis from cinnamic acid and third synthesis from 2-nitrobenzaldehyde. But these synthesis routes were not economically feasible for large scale production (Indigo Dye). Therefore, the search for alternative starting materials continued. The synthesis of N-(2-carboxyphenyl) glycine from aniline provided a new and economically attractive route. This led the development of a commercially feasible manufacturing process by BASF in 1897. The development of different methods of indigo synthesis and the chemical reactions involved are shown in Figure 3.2 (Indigo Chemistry).

The third indigo synthesis, from 2-nitrobenzaldehyde (1882), was simple and gave a good yield of indigo, but again was economically impractical due to the high cost of the starting material, 2-nitrobenzaldehyde. This route to indigo is shown in Figure 3.3 (Indigo Chemistry), now commonly called the Baeyer–Drewson process.



**Figure 3.2** Early synthesis of indigo by Adolf von Baeyer. Indigo Chemistry.

Adolf von Baeyer was awarded the Nobel Prize for chemistry in 1905 in recognition of his works on indigo, among his many other chemical accomplishments. However, economically practical syntheses of indigo were later developed by a Swiss-German chemistry professor, Karl Heumann (1850–1894), and by a German industrial chemist, Johannes Pfleger (1867–1957).

Heumann's first synthesis, in 1890, used the industrial chemical aniline as a starting material. It was converted into *N*-phenylglycine, which was internally condensed into indoxyl in molten alkali at  $\sim$ 300 °C. The indoxyl was quickly oxidised by atmospheric oxygen, dimerising into indigo. Unfortunately, the yield of product was too low by this route to make it commercially attractive.

His second synthesis at the same time used the more expensive fine organic chemical anthranilic acid as the starting material. In the same sort of reactions utilised by his first route, Heumann obtained a high yield of indigo in this alternate procedure. The process was scaled up to an industrial level (several thousands of tons per annum) by BASF and Hoechst in 1897. Thus commercial production of indigo began in 1897. By 1900, it equaled the yield of farming 250,000 acres of indigo containing plants (Mutnuri et al., 2009).

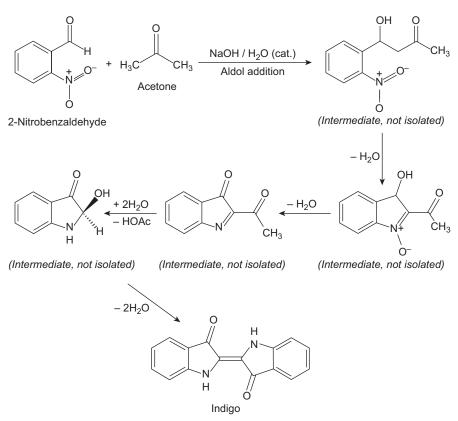
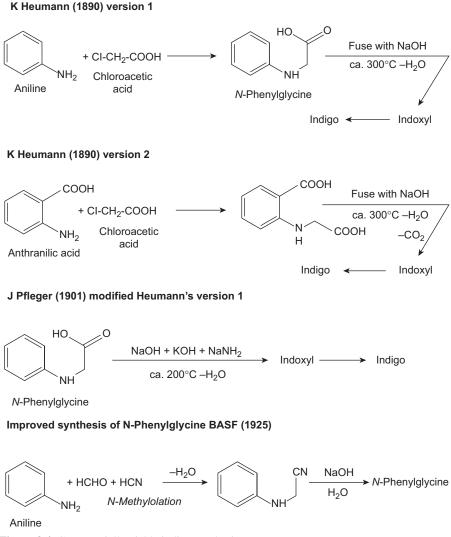


Figure 3.3 Indigo synthesis by Baeyer and Drewson. Indigo Chemistry.

By 1914 BASF was producing 80% of the world's synthetic indigo, as a result of which Indian exports of natural indigo fell from 187,000 tons in 1895 to 11,000 tons in 1913 (Freeman, 1997). Thus by 1913 natural indigo had been almost entirely replaced by synthetic indigo. In 1901, Pfleger, working for Hoechst, modified Heumann's first method by adding sodamide (NaNH<sub>2</sub>) to the alkaline flux. Sodamide is a very powerful dehydrating agent, and it drove the ring closure reaction, to form indoxyl, to completion. Sodamide reacts with excess water, thus lowering the overall reaction temperature from almost 300 to 200 °C. This results in a much more efficient reaction process. Use of the relatively cheap aniline as the starting material and of sodamide as the condensation agent were the two key factors in the economic success of the BASF–Hoechst industrial indigo synthesis. These synthesis routes are shown in Figure 3.4 (Indigo Chemistry).

# 3.5.2.1 Improved synthesis of N-phenylglycine

In 1925 BASF researchers devised an improved synthesis of *N*-phenylglycine from the N-methylolation of aniline with formaldehyde and hydrogen cyanide, followed by saponification of the resulting nitrile intermediate. This modification provided an additional



**Figure 3.4** Commercially viable indigo synthesis. Indigo Chemistry.

economy in the overall indigo production method. BASF's indigo capacity could not meet the huge global indigo demand during the 1960s and 1970s. The increasing prices encouraged quite a few competitors to invest in indigo production, particularly in China.

# 3.5.3 Microbial production of indigo

While synthetic indigo has enjoyed a virtual monopoly for nearly a century, an environmentally friendly microbial production of indigo is under development. The microbial production of indigo has been known since the 1920s (Gray, 1928). Indigo production with hydrocarbon degrading bacteria expressing mono-oxygenases or dioxygenases has also been investigated in search of a possible alternative for the chemical synthesis of indigo (O'Connor and Hartmans, 1998; Bhushan et al., 2000). Berry et al. (2002) developed a fermentation process where indigo was produced from glucose with recombinant *Escherichia coli* that had been modified with *Pseudomonas putida* genes. However, the method produced also indirubin, which gave an undesirable red hue to the dyeing (Biotech, 2002).

A number of bacteria, most notably *Pseudomonas* species, have the ability to use a variety of organic compounds such as naphthalene, toluene, xylene and phenol as their sole carbon source. In many instances, the genes encoding the enzymes for the degradation of these organic compounds are located on large, naturally occurring plasmids. For example, pseudomonads that contain NAH7 plasmid were allowed to grow on naphthalene as a sole carbon source. The clone bank was then introduced into *E. coli* cells. During the characterisation of one of the transformants that could convert naphthalene to salicylic acid, it was observed that when the growth medium contained tryptophan, it turned blue. A thorough analysis of the blue colour revealed that the transformed *E. coli* cells were synthesising the dye indigo. This synthesis is achieved in four steps (Synthesis of Commercial Product):

- Conversion of tryptophan in the growth medium to indole by the enzyme tryptophanase, which is produced by the *E. coli* host cell.
- Oxidation of indole to *cis*-indole-2,3-dihydrodiol by naphthalene dioxygenase, which is encoded by the DNA that was cloned from NAH7 plasmid.
- · Spontaneous elimination of water.
- · Air oxidation to form indigo.

In addition, introduction of the gene for enzyme xylene oxidase, which is encoded in the TOL plasmid, can convert tryptophan to indoxyl, which then spontaneously oxidises to indigo.

In pathway A, the naphthalene dioxygenase is derived from the NAH plasmid. In pathway B, the xylene oxidase is from the TOL plasmid. *E. coli* transformants that synthesise indigo contain either pathway A or B (Synthesis of Commercial Product). The conditions for large scale growth of an *E. coli* strain capable of synthesising indigo, including temperature, pH and the amount of tryptophan that must be added to the medium to give maximum yields, are being tested.

Although this system has not yet been commercialised, a microbial process for the synthesis of indigo might include a bioreactor in which the recombinant *E. coli* is chemically immobilised to a solid matrix (e.g. cellulose or silica gel). The unit could be run continuously by adding tryptophan to one end and removing indigo at the other. Genencor International, of Rochester, New York, is experimenting on a process to produce indigo using biotechnology. However, at this stage the technology is expensive and production costs might be prohibitive (Microbial production of indigo, 2001).

Ma et al. (2012) critically reviewed the research and development efforts made in the field of microbial synthesis of indigo from 1927 onwards. The highlights of this critical review indicated that biosynthesis of indigo could be divided into three periods: biosynthesis by wild microbes, whole cell catalysis by engineering bacteria and biotransformation regulated by metabolic engineering. Most aromatic degrading microbes and their relevant enzymes possess the ability to convert indole to indigo.

New technologies such as directed evolution, metagenome and two phase reaction systems could facilitate in-depth investigations of the enzyme resources, and they will play a crucial role in indigo biosynthesis research. Meanwhile, hydroxyl-indoles and indigo derivatives produced in the process are promising pharmaceutical and chemical precursors with great research interest. However, the transformation interactions between intermediates and by-products are still unclear. Besides, low indigo yield and efficiency with high cost have hampered practical production. Therefore, it is essential to combine the molecular biology and metabolic engineering technologies to investigate the mechanisms and industrial application of indigo biosynthesis in the future (Ma et al., 2012). In addition, several other processes not commented on in this chapter have been described in the literature (Ensley et al., 1983; Floras et al., 1996; Mermod et al., 1986; Pathak and Madamwar, 2010).

## 3.6 Indigo properties

Indigo, also known as indigo blue and indigotin (C.I. Vat Blue 1, C I 7300, CAS number: 482/582-89-3, IUPAC name 3H-indol-3-1, 2-(1,3-dihydro-3-oxo-2H-indol-2-ylidene)-1,2-dihydro-, chemical formula  $C_{16}H_{10}N_2O_2$ ), is present at ambient temperature and normal pressure as dark blue-violet needles or prisms with a distinct coppery lustre, melting point 300 °C (Indigo Blue, 1994). Indigo absorbs light in the orange part of the spectrum ( $\lambda_{max}$ =613 nm). The compound owes its deep colour to the conjugation of the double bonds (Indigo Dye). Indigo is insoluble in water and poorly soluble in most of the common solvents (Clark et al., 1993). It is more soluble in polar organic solvents than non-polar ones (Steingruber, 2004; Green, 1989). The poor solubility is most likely due to the strong inter- and intramolecular hydrogen bonds that are formed in indigo crystals (Holt and Sadler, 1958). The hydrogen bonding also explains indigo's relatively high melting point (~300 °C) (Christie, 2001).

The colour of indigo is dependent on its environment. In the gas phase, where indigo is in its monomeric form, it is red, and in non-polar solvents it is violet, but in solid form and in polar solvents as well as when it is applied to textiles as a vat dye, it is blue (Christie, 2007). Indigo is non-biodegradable, has a low mammalian toxicity and there is no indication of sensitisation in humans after repeated skin applications (Steingruber, 2004). Indigo is classified as a vat dye, although its properties are not typical of the vat dyes as a whole (Aspland, 1992).

Indigo has moderate to very high light fastness depending on the substrate it is on or whether it is a pigment or a dye (Christie, 2001). The light mostly affects the oxidative degradation of indigo to the degradation products such as isatin, isatoic anhydride and anthranilic acid (Novotna et al., 2003). There are synthetic dyes, especially vat dyes, with better fastness properties particularly to light, washing and chlorine bleaching, than indigo, but it is this fading of colour that is so characteristic of indigo that has kept it so popular with jeans-wearing people (Aspland, 1992).

# 3.7 Reduction of indigo

Indigo is insoluble in water, and since it belongs to the vat dye class, it has to be converted into a water soluble form by reducing under alkaline conditions. In ancient times the reduction process was carried out in wooden vats; therefore, this class of dyes is known as vat dyes. The process of dyeing of cotton with indigo essentially consists of alkaline reduction of indigo into a water soluble form known as leuco indigo, dyeing by multiple dips and air oxidation to convert leuco indigo to its water insoluble form. The reduction/oxidation process is shown in Figure 3.5.

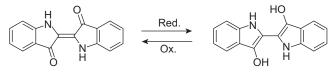
Several processes are used for the reduction of indigo:

- · Fermentation or bacterial reduction.
- · Chemical reduction.
- Electrochemical reduction.
- Catalytic hydrogenation.
- · Electrocatalytic hydrogenation.

## 3.7.1 Bacterial reduction

Before the modern reduction methods were invented, indigo was reduced by a process known as fermentation vat, which relies on bacterial action. This method was used for centuries. Several fermentation techniques were in practice in different countries, consisting of the use of ripe fruits, stale urine, madder and bran along with wood ash or lime as alkali. Each method has its own benefits and drawbacks. A considerable amount of time was involved in the reduction process. As biological components were involved, the consistency of reduction could not be guaranteed (Blackburn et al., 2009; Bühler, 1951; Fox and Pierce, 1990).

Attempts have been made to identify and isolate the bacteria present in fermentation vat. Padden et al. (1999) isolated an anaerobic moderate thermophile from a woad vat and they named the bacterium *Clostridium isatidis*. The woad vat was prepared with the medieval method from couched woad. The isolated bacteria grew in nutrient-rich medium at an optimum temperature of 49–52 °C and at an optimum pH of 7.2. The pH was changed to 9 for indigo reduction to occur (Nicholson and John, 2005). Indigo-reducing bacteria *Alkalibacterium psychrotolerans* and *Alkalibacterium iburiense* have also been isolated from indigo fermentation liquor. The optimum pH range for growth of isolate was 9.5–11.5 (Yumoto et al., 2004; Nakajima et al., 2005). Nicholson and John (2005) observed that the madder powder and anthraquinone-2,6-disulphonate and



Indigo Figure 3.5 Indigo reduction/oxidation.

Leuco indigo

humic acid stimulate the bacterial reduction of indigo, and it was speculated that it was due to their ability to alter the surface properties of the bacteria or indigo.

Aino et al. (2010) suggested that in addition to the strains belonging to the genus *Alkalibacterium*, strains belonging to genera *Amphibacillus* and *Oceanobacillus* play important roles in sustaining the reduced state of indigo during fermentation. Osimani et al. (2012) evaluated two broth media containing yeast extract and corn steep liquor (CSL) for their capacity to sustain the growth and reducing activity of the strain *C. isatidis* DSM 15098(T). Subsequently, in order to test the suitability of CSL for dyeing, the CSL medium containing 140 g/L of woad powder, and 2.4 g/L of indigo dye was fermented in laboratory bioreactors under anaerobic or microaerophilic conditions. In all fermentations, a sufficiently negative oxidation/reduction potential for reduction of indigo was reached as early as 24 h and maintained up to the end of the dyeing period.

Enzymatic technologies using dehydrogenases and azoreductase have also been investigated for the reduction of vat dyes in general (Božič and Kokol, 2008; Pricelius et al., 2007). Mojca Božič et al. (2009) suggested using NADH dependent reductases from *Bacillus subtilis* in the presence of redox mediators for reduction of indigo. The efficiency of mediated enzymatic indigo reduction on the dyeing of polyamides 6 and 6,6 was studied at 60 °C, pH 7 and 11 and different indigo concentrations. The colour values and colour fastness properties (to wash, light and perspiration) were evaluated and compared to chemically indigo dyed polyamides. The results indicated that the dyeing properties were pH, time and polyamide type dependent. Successful reuse of the enzyme was confirmed.

Revival of the traditional method of indigo reduction would minimise the use of chemical reagents, which are burdens on the natural environment. However, at present there is no commercial enzymatic process that could be used as an alternative for the chemical reduction of indigo.

### 3.7.2 Chemical reduction

The earlier methods for reducing indigo based on the use of chemicals instead of bacteria were the 'copperas' method, which combined ferrous sulphate with slaked lime with the precipitation of ferrous hydroxide, which then combined with oxygen to form ferric hydroxide accompanied by the liberation of hydrogen. The copperas method was followed by the zinc–lime method, based upon the fact that zinc dissolves in lime water, forming sodium zincate and hydrogen.

Both of these methods were not satisfactory due to heavy precipitates of ferrous and zinc hydroxide. These methods are of historical importance now (Trotman, 1970; Paul and Naik, 1997a). Modern large scale dyeing of indigo was made possible by the appearance of sodium hydrosulphite as a commercial product.

#### 3.7.2.1 Sodium hydrosulphite

Sodium hydrosulphite, or 'hydro', is universally used as a reducing agent for the application of vat dyes including indigo. Interestingly, soon after the invention of

synthesised vat dyes in 1901, sodium hydrosulphite was identified as a reducing agent in 1904 (Baumgarte, 1974; Aspland, 1992).

The reducing property of sodium hydrosulphite is due to the evolution of hydrogen when dissolved in water or sodium hydroxide solution (Shore, 1995). The advantage of sodium hydrosulphite is that it causes a swift reduction of indigo as well as other vat dyes at temperatures ranging from 30 to  $60 \,^{\circ}$ C and above. It enables very short dye fixing times in various dyeing methods and produces levelness in continuous dyeing (Božič and Kokol, 2008).

In fact there is no reducing agent available today that can replace hydrosulphite in vat dye application. The dominant position of sodium hydrosulphite is due to the favourable relationship between its properties and its cost. However, sodium hydrosulphite reacts readily with atmospheric oxygen, diminishing the degree of reduction of indigo. This requires continual addition (topping up) of hydrosulphite to the dye bath. The constant control requires skill and experience to obtain a uniform shade (Etters, 1992).

The use of sodium hydrosulphite is being criticised for the formation of nonenvironment-friendly decomposition products such as sulphite, sulphate and thiosulphate, which are toxic and have a corrosive effect on wastewater lines. In addition, sodium hydrosulphite affects the aerobic processes in the water treatment, and toxic hydrogen sulphide ( $H_2S$ ) can form anaerobically from the sulphate deposits present in the wastewater (Cegarra et al., 1992; Anbu Kulandainathan et al., 2007a). In the 1960s and the early 1970s, many attempts were made to reduce the sodium hydrosulphite consumption by using additives in the dye liquor (Shah and Gokhale, 1975; Etters, 1999). Unfortunately, the results were not satisfactory.

Developments in the field of indigo dyeing indicate that the consumption of sodium hydrosulphite can be reduced to an almost stoichiometrical minimum of 1.1 (1.1 mol of hydro for 1 mol of indigo). Optimal concentrations and reaction conditions in the vatting reactor can be achieved on the one hand by controlling the concentrations of the dye, the reducing agents and the caustic soda by appropriate modern analytical methods (Merritt et al., 2001). On the other hand it could be demonstrated that 100% vatting can be accomplished in a few minutes in a completely oxygen free atmosphere in the vatting reactor with the use of ultrasonic resonators (Marte et al., 1990).

## 3.7.2.2 Sodium hydrosulphite regeneration

It is obvious that another alternative could be based on the application of electrochemical techniques to the non-regenerable reducing agents. The first attempt in this direction, although not directly involving electrochemical dyeing, was made by Daruwalla (1976). He attempted to reduce sodium hydrosulphite in quantities needed for the reduction of vat dyes by the application of a direct voltage. It was possible to generate a powerful reducing species from sodium hydrosulphite with a redox potential higher than sodium hydrosulphite itself, which should reduce hydrosulphite consumption by 30%. This behaviour of sodium hydrosulphite has been explained to be due to the decomposition of hydrosulphite to produce a free radical ion,  $SO_2$ . However, until now no commercial realisation of the proposed process is known. Indigo can be successfully reduced by the electrolysis of a suspension of indigo in a warm solution of sodium bisulfite (Oloman et al., 1990; Cawlfiled et al., 1988). Ding et al. (1998) carried out the electrosynthesis of sodium hydrosulphite.

## 3.7.2.3 Eco-friendly reducing agents

To overcome the effluent and ecology related problems associated with sodium hydrosulphite, attempts were made by several researchers to develop eco-friendly reducing systems. Some of these systems are briefly discussed.

#### Alpha-hydroxy ketones

It has been found that sodium hydrosulphite can be successfully replaced by organic compounds such as hydroxyacetone (Rongal 5242), acetoin, glutaroin or adipoin and  $\alpha$ -hydroxycarbonyls (Marte, 1989; Meksi et al., 2012). This class of  $\alpha$ -hydroxyketones meets the requirements in terms of reductive efficiency and biodegradability. However, some substances are expensive and the use of hydroxyacetone is restricted to closed systems because it forms strong-smelling condensation products in alkaline solution.

#### Glucose

Glucose has been used as a reducing agent for sulphur dyes for quite some time, but it was considered to give unsatisfactory results since it was dependent on high temperatures. This was improved by having strongly alkaline conditions in the dyeing vats (Chavan, 2001).

Cost effective glucose can be produced by hydrolysis of starch (Shankarling et al., 1997) or molasses (Vhanbatte, 1998). Glucose in combination with NaOH can also be used for indigo reduction preferably at boil, producing a highly stable dye bath for several hours. One problem related to this reducing system is that padded textile requires more time for oxidation in between two successive dips and indigo uptake is less (Nowack et al., 1982).

#### Thiourea dioxide

Another reducing agent receiving considerable attention is thiourea dioxide (THDO), formamidmesulphamic acid. It is stronger than sodium hydrosulphite in reducing action, and therefore many vat dyes are likely to over reduce. Its use has been proposed for exhaust dyeing and printing with vat dyes especially on silk and cellulose acetate (Krug, 1953). It is stable both as a solid and in aqueous solution till 40 °C. It reaches full reduction potential at 100 °C. The degradation products are less harmful as compared to those of hydrosulphite (Baumgarte and Schlüter, 1984).

Thiourea dioxide is apparently even more readily oxidised than hydrosulphite. At current prices for thiourea dioxide it appears less attractive. However, its relatively low sulphur content and the lower equivalent weight than that of hydrosulphite lead to less contamination of effluent by sulphite and sulphate (Weiss, 1978; Ratnapandian et al., 2012). Sodium borohydride is also suggested for the reduction of vat dyes; however, it reacts too slowly for vat dyeing (Medding, 1980; Nair and Shah, 1970).

## 3.7.2.4 Two component systems

#### Iron (II) salts

Ferrous hydroxide is a strong reducing agent in an alkaline medium. The reducing effect increases even more with an increase in pH value. However, ferrous hydroxide is poorly soluble in alkaline conditions and precipitates. It has been found that  $Fe(OH)_2$ , produced via the reaction of iron (II) salts with NaOH, can be complexed (e.g. by gluconic acid) and brought into solution to achieve the desired value for the reduction potential. Regarding eco-friendliness, gluconic acid can be eliminated in the sewage tank through neutralisation with alkali; free  $Fe(OH)_2$  can be aerated and converted to  $Fe(OH)_3$ , which acts as a flocculent and brings down wastewater load. Thus, the problems associated with the use of  $Na_2S_2O_4$  as a reducing agent have been eliminated in this new technique (Semet et al., 1995; Bechtold, 1990; Bechtold and Burtscher, 1991; Bechtold et al., 1997a).

This concept of the use of iron (II) complexes is further extended by Chavan and Chakraborty (Chakraborty, 2000; Chavan and Chakraborty, 2000, 2004). They established that successful dyeing of cotton with indigo can be carried out using Fe (II) salt complexed with suitable molar ratios of tartaric acid, citric acid or triethanolamine along with NaOH. Such a system is termed as a single ligand system. Although the single ligand system was suitable for dyeing cotton with indigo, it was not suitable for dyeing cotton with vat dyes other than indigo. For this reason, a two ligand system consisting of Fe (II) salt complexed with citric acid and triethanolamine, or Fe (II) salt complexed with tartaric acid and triethanolamine, has been suggested. The suitability of two ligand systems for the successful dyeing with a large number of vat dyes was established on the basis of higher reduction potential and an increase in Fe(OH)<sub>2</sub> solubility compared with the single ligand system. It may be summarised that, for quality dyeing, whatever may be the reducing agent, reduction potential and alkalinity of the bath should be accurately adjusted for development of a true shade of indigo (Paul et al., 1996; Paul and Naik, 1997b).

## 3.7.3 Catalytic hydrogenation

The catalytic hydrogenation of vat dyes was suggested a long time ago by Brochet (1917). Although there are many problems with several vat dyes (either over reduction or slow reduction rate), the preparation of leuco indigo solutions by catalytic hydrogenation of indigo can be effected by reducing an alkaline indigo paste (customarily from 10% to 35% by weight of indigo, from 2% to 10% by mass of NaOH) using Raney nickel as catalyst at a hydrogen pressure generally between 2 and 4 bar and at a temperature generally between 60 and 90 °C. However, it is not possible to use this technique on-site in a dye house due to the high explosion and fire risk. Thus, pre-reduced indigo is produced as a commercial product in an indigo plant and shipped as a 40% aqueous solution. It can be used directly in a dye bath, which has only to be stabilised by reducing agents.

Pre-reduced indigo is marketed by DyStar under the trade name of DyStar Indigo Vat 40% Solution. Being sensitive to air oxidation, it has to be handled carefully under nitrogen and fed into the dyeing range with special equipment developed for process

optimisation from DyStar (Holme, 2008). This product offers the advantage that in the dyeing process, a considerable proportion of the sodium hydrosulphite can be dispensed with. The concept of pre-reduced indigo has the potential to conquer the denim market. Some dye houses are already using the product even though they get completely dependent on the dye supplier, because at present only DyStar is offering this technology.

## 3.7.4 Electrochemical reduction

Chemical reducing agents used for the reduction of vat dyes including indigo oxidise into the dye bath and cannot be recycled because the reducing power of these chemicals cannot be regained. Disposal of the dye baths and the wastewater causes a variety of problems due to the non-eco-friendly nature of the decomposition products; e.g. sulphite and sulphate from the use of sodium hydrosulphite, sulphides from sulphur compounds and a high COD from the use of organic reducing agents. Therefore for ecological and economic reasons, electrochemical reduction is an attractive alternative to chemical reducing agents for vat dye reduction.

In electrochemical reduction of vat dyes, chemical reducing agents are replaced by electrons from the electric current and effluent contaminating substances are dispensed with altogether (Baumgarte, 1974). This technique could become the dyeing process of the future for vat, indigo and sulphur dyes (Schrott and Salinger, 2000).

The following techniques for electrochemical reduction of vat dyes can be used:

- · Direct electrochemical reduction.
- · Indirect electrochemical reduction using mediators.
- Electrochemical hydrogenation.

## 3.7.4.1 Direct reduction

It is possible to reduce solid indigo microcrystals immobilised on the surface of several electrode materials in aqueous solution, and the results are very similar to those obtained for indigo dissolved in various solvents (Bond et al., 1997; Komorsky-Lovrić, 2000). However, if indigo is not immobilised but instead is present as solid particles in aqueous suspension, it shows a distinctly different behaviour.

Nevyas (Nevyas and Lowy, 1926) attempted the electrochemical reduction of indigo from an aqueous suspension. Unfortunately, it was not industrially feasible to reduce indigo electrochemically under dye bath conditions on a planar electrode. Roessler and co-workers attempted direct electrochemical reduction of indigo (Roessler et al., 2001, 2002a,b). The most limiting factor seems to be the poor contact between indigo particles and the electrode. It is therefore desirable to develop a reduction of the contact between the dye particles and the electrode.

#### Reduction via the indigo radical

In this technique the vat dye is partially reduced by using a conventional reducing agent and then a complete dye reduction is achieved by the electrochemical process. This facilitates the improved stability to the reduced dye (Roessler et al., 2001). To

start the process, an initial amount of the leuco dye has to be generated by adding a small amount of sodium hydrosulphite. Once the reaction has begun, the further process is self sustaining. However, this method still needs the conventional reducing agent to produce the necessary leuco dye to start the reaction, after which it continues independently and it is not very efficient due to the low amount of radicals formed during the process. This system is found to be successful in case of sulphur dyes. However, concentration of the dye required to get a specific shade is higher than that for a conventional reduction process due to the limited cathode–dye particle interface.

#### Reduction on graphite electrodes

For successful dyeing it is essential to have a cathode with large surface area, which is itself a constraint. Roessler et al. (2003a) used graphite granules as an electrode material to increase the surface area in a fixed and fluidised bed reactor to address the question of industrial feasibility of a direct electrochemical reduction method for vat dyes. Under optimised conditions it was possible to reduce a 10 g/L solution of indigo. This observation was promising, because graphite is a very cheap and stable material.

A special pretreatment of the graphite (i.e. soaking with hydrogen peroxide or pre-anodisation) was investigated to enhance the reduction rate. Another interesting approach to enhance the electrocatalytic properties is based on the covalent bonding of quinoid molecules onto the graphite surface (Ramesh and Sampath, 2001). These results are obviously the basis for the further development of a cheap, continuously and ecologically working cell for the direct electrochemical reduction of dispersed vat dyes.

## 3.7.4.2 Indirect reduction

Direct electrochemical reduction of dispersed indigo for the dyeing process is somewhat complicated due to the electron transfer difficulties between solid electrode and solid particle of dye, and therefore indirect electrochemical methods have been suggested. In this system, dye reduction does not take place due to direct contact of dyestuff with the cathode, but it takes place through the mediator that gets reduced by contact with the cathode. Therefore, this system is known as indirect electrochemical dyeing. Bechtold and co-workers have patented the indirect electrochemical dye reduction method in 1993 and have published a number of other related patents since then (Bechtold, 1993; Bechtold et al., 2004; Bechtold and Burtscher, 1995, 2001).

In this method, a reducing agent that reduces the dye in the conventional manner is added, which in turn gets oxidised after dye reduction. The oxidised reducing agent is subsequently reduced at the cathode surface, which is then further available for dye reduction. This cycle is continuously repeated during the dyeing operation. In electrochemistry, the agent that undergoes both reduction and oxidation cycles is known as a reversible redox system and is called a mediator, which carries the electrons from the electrode to dye (Bechtold et al., 1997b, 1991, 1996; Anbu Kulandainathan et al., 2007b).

The general requirements of the mediator in the indigo reduction are that it has sufficient negative potential in the alkaline solutions, at least –600 mV versus Ag Ag/AgCl/3 M KCl to reduce the dyestuff and it has a reducible charge transfer and a high rate of electron transfer from cathode to the mediator and from mediator to the dyestuff (Bechtold et al., 1993).

Fe(III)-triethanolamine (TEA) complex, -bicine and HEDTA iron complexes and Fe3<sup>+</sup>-D-gluconate or Ca2<sup>+</sup>-Fe3<sup>+</sup>-D-gluconate complexes and anthraquinone derivatives have been investigated as mediators in the electrochemical reduction of indigo The reduction rate has been found to be dependent on the type of mediator system and the type of vat dyestuff (Bechtold et al., 1999; Bechtold and Turcanu, 2004). Complex mixtures of iron salt-triethanolamine-D-gluconate are of particular interest as mediators because it is possible to combine the advantages of both ligands (Mohr and Bechtold, 2001; Bechtold et al., 2002b).

Currently, the most suitable iron complex system (iron(II)-triethanolamine complex) shows reduction potentials up to -1050 mV versus Ag/AgCl/3 M KCl, giving a high rate of reduction of vat dyes, which is much faster than that with sodium hydrosulphite (Bechtold et al., 1998a). A great advantage of this technique is the direct information about the state of reduction in the dye bath, which is available by redox potential measurement, and that control by adjustment of the cell current is possible. However, the mediators are not entirely harmless from a toxicological point of view.

In order to carry out dyeing economically, a multi-cathode cell, where the cathode material used is stainless steel, is suggested as a possible solution to the problem of low cell current density. In this type of cell, several three dimensional cathodes are connected to a common anode and they produce the necessary high electrode surface area for the process (Bechtold et al., 1998b).

Such a cell was tested successfully for continuous dyeing of cotton yarn on a full scale indigo dyeing range using a 1000A multi-cathode electrolyser (Blatt and Schneider, 1999). However, the huge electrode surface of 500 m<sup>2</sup> is still necessary to achieve a feasible reduction rate on an industrial scale. Thus, it is impossible to use this technique for the complete reduction of a stock solution in the case of continuous dyeing, because the operating costs and the return on investment are not attractive enough for an application in the denim industry. Indirect electrochemical reduction can only be used in discontinuous exhaust dyeing processes (Bechtold and Turcanu, 2002) and to stabilise the dye bath in continuous dyeing by diminishing the amount of leuco indigo oxidised during dyeing by air contact.

The objective of the mediator system primarily is to generate a constant reduction potential in the dye liquor. Therefore, the addition of a conventional reducing agent is not essential and no accumulation of decomposition products of the reducing agents takes place. After the dyeing cycle, the unexhausted dye gets precipitated by air oxidation and can be removed by ultrafiltration. After the dye removal, the liquor containing mediator, ligand and alkali can be recycled for subsequent dyeing operations. The eco-friendliness of the process has yet to be established as some of the mediator systems are toxic. However, there are still several technical problems to be dealt with. Therefore, the mediator technique remains under development even after many years, and at present, production trials are performed only in one pilot plant (Anon., 2002). Thus, there is still a continuing need for new alternatives improving the eco-efficiency of the application of vat dyes.

## 3.7.4.3 Electrocatalytic hydrogenation

The electrocatalytic hydrogenation method for reduction of vat and sulphur dyes appears to be a promising and attractive alternative in terms of economic and ecological aspects (Roessler et al., 2003b). Electrochemical hydrogenation is a process in which adsorbed hydrogen, produced in situ by electrolysis of water, reacts with adsorbed organic substrates (i.e. vat dye) at the electrode surface. The industrial feasibility of this novel route has been studied recently in a divided flow cell using Raney nickel electrodes. Several vat dyes could be reduced with this method. In the case of indigo, optimisation of conditions in the system was attempted, and in scale-up an indigo concentration to 10 g/L was achieved. However, a huge electrode surface of more than several hundreds of square metres would be necessary to attain an industrially feasible reduction rate for stock solutions. Probably the method will be only powerful enough for dye bath stabilisation.

Raney nickel was chosen as electrode material, because it is readily available at low cost and stable in an alkaline medium. The stability of platinum black electrodes – which are among the most active ones – was shown to be poor, so that their industrial application is not practical. Recently, noble metal particles supported on graphite granules have been investigated as electrode material in a fixed and fluidised bed reactor. However, noble metals are very expensive and the long-time behaviour of the catalyst was shown to be poor (Roessler et al., 2002c,d). Excellent reviews covering various aspects of chemical and electrochemical reduction of vat dyes are available in the literature (Blackburn et al., 2009; Roessler and Jin, 2003; Anbu Kulandainathan et al., 2007a; Vuorema, 2008; Teli et al., 2001).

## 3.8 Traditional and modern dyeing methods

## 3.8.1 Traditional methods

Natural indigo is one of the ancient dyes, and therefore the traditional methods of dyeing based on the fermentation process vary from country to country and were evolved over a period of time. The following brief description provides some information about the typical dyeing procedures used in India, Japan and Europe.

## 3.8.2 Indian method

The steps involved in this process are as follows:

- 250 g locally available lime (chuna) in lump form, mixed with 2L water to make a smooth slurry.
- 500 g wood ash mixed with 2 L water.
- 500 g of casetora seeds (methi), boil with 2L water for 1 h.
- 500 g of indigo paste.

The indigo paste is thoroughly mixed with 15L water in a mud pot followed by addition of the remaining ingredients. The mouth of the mud pot was closed with a piece of fabric and allowed to ferment for 7–10 days. The extent of reduction was checked by opening the mouth of the pot and lifting the solution from the top. Yellow-ish green colour indicated the complete reduction of indigo.

The fabric for dyeing was wetted and dipped into indigo solution, squeezed thoroughly and exposed to air for oxidation of indigo. The process of dipping and exposure to air was repeated 6–10 times depending on the depth of blue shade required. The same vat is used for several months with the fresh addition of the ingredients and indigo dye (Salim).

## 3.8.3 Japanese method

In Japan, polygonum or tade was used in the natural indigo dye process known as ai-zome. There are five basic materials used in Japanese indigo dyeing: sukumo (composted tade leaves), fusuma (wheat bran), sake, hardwood ash and lime. Sake and fusuma facilitate the fermentation process. Wood ash and lime are used to control the alkalinity. All these materials are mixed in a large vat (about 540 L). The vat was buried in the ground for control of temperature. The entire mixture was fermented for one week. The fermentation process, a sponge like foam (called ai-no-hana or indigo flowers) formed at the top of the vat.

Fabric was soaked in the fermented vat for 15–30 min, taken out, squeezed and exposed to air. Just after the cloth was removed from the vat it looked dark green; it turned blue upon oxidation. Soaking and oxidation steps were repeated depending on the depth of blue colour desired and could be as many as 30–40 times for the darkest blue (Deep, Rich Japan Blue).

#### 3.8.4 European method

The indigo was dissolved in stale urine in Europe. Perhaps the urine vat was the easiest fermentation process because it often worked with additions of indigo and urine only. The process was carried out on a small scale due to difficulty of collection of large volumes of urine. Urine contained nutrients for bacterial fermentation which reduced indigo, and the bacteria also converted the nitrogenous waste product (urea) into ammonia (ammonium hydroxide and carbonate), which dissolved the reduced indigo white.

Natural indigo in the paste or powder form was mixed with urine in a vessel. The mouth of the vessel was closed and kept in sunlight. In cold weather, the vessel was kept near the fireplace. The fermentation process took 3–5 days, as indicated by the blue colour changing to yellow green. The fabric was then dyed by repeated soaking and air oxidation. The method was more suitable for wool because of mild alkalinity of fermented vat (Liles).

## 3.8.5 Modern method

Even in modern dyeing techniques the basic concept of dye application remains the same as in ancient techniques except for differences in the method of reduction and the choice of machines. In the modern methods, dyeing of cotton is carried out in yarn form using rope, slasher or loop dyeing methods.

In different areas of the world, the same depth of shade is produced using different concentrations of indigo on a weight of yarn. In the United States, a dark indigo colour is produced by using 1.2% indigo concentration, whereas the same depth of shade is produced by using 2% indigo in Latin America and 2.4–2.8% indigo in Asia. Very dark shades of indigo are in demand currently around the world. Many companies use

4% or more indigo on a weight of yarn. Dyeing indigo in light shades results in a sky blue, which is impossible with any other dye. This is useful for shirting fabrics that are not strong enough for stone washing, bleaching or cellulase treatments. Such light shades can be produced using an indigo concentration as low as 0.4% and reducing the number of dips. The indigo dyeing process begins with a concentrated mixture of indigo, sodium hydroxide and reducing agent. Typical stock solution consists of:

| Indigo dye           | 70–90 g/L |
|----------------------|-----------|
| Caustic soda (50%)   | 100 g/L   |
| Sodium hydrosulphite | 70 g/L    |

The concentrated stock solution is delivered by pipes to the indigo dye tanks, where the dye concentration is lowered to 1-4 g/L for dyeing the cotton. The dye in dyeing vats is maintained in reduced form at appropriate pH by a chemical feed solution consisting of:

Caustic soda (50%) 120 g/L Sodium hydrosulphite 60 g/L

The feed rate is typically 1.4L per minute (Mercer).

## 3.9 Future trends

A growing awareness for health and environment protection has translated into consistent efforts to reduce the ecological impact of production processes. Worldwide, consumers are also demanding goods with eco-friendly credentials. The denim industry is responding to this trend by modifying in-house practices and encouraging academic research. Future trends in indigo synthesis and its application for denim dyeing are likely to focus on technologies related to microbial synthesis of indigo, marketing of eco-friendly indigo and reduction techniques, revival of natural indigo and alternate environmentally friendly technologies for denim production devoid of indigo. Some of these trends are briefly highlighted.

While synthetic indigo has enjoyed a virtual monopoly for nearly a century, another method for production of an environmentally friendly indigo is under development. At the end of the twentieth century, enzymes required for cellular indigo synthesis were cloned into bacteria. When these genetically modified bacteria are fed tryptophan, they synthesise indigo and secrete it into the growth medium. Researchers at Genencor International, New York have proved that the bacteria themselves do not turn the dye blue. Instead they convert sugar (usually corn syrup) into a reddish amino acid called tryptophan. Genencor researchers spliced a gene into the bacteria to eliminate the red tones and created a substance called 'bioindigo'. The research was done using funding from Levi Strauss. Genencor produced 400,000 square yards of bacteria dyed jeans material. Indigo produced by microbial synthesis is chemically the same as the regular synthetic dye and behaves identically in dyeing tests. However, at this stage the

technology is expensive and production costs might be prohibitive. However, scientists continue to enhance the growth conditions of these biological indigo factories. Genencor is seeking a major market partner to work with them in the development of this new technology. It is hoped that an increasingly environmentally conscious consumer might someday pay for the 'blue' in blue jeans produced by genetically engineered bacteria (Microbial production of indigo, 2001; Scientists Make Bacteria-Dyed Jeans).

The use of sodium hydrosulphite as a reducing agent for vat dyes is associated with several environmental issues. Alternate reducing systems such as organic reducing agents, biological reduction, electrochemical reduction and catalytic hydrogenation of indigo have been explored. In 1993, BASF introduced a catalytic hydrogenation technique to pre-reduce the indigo. The product is now marketed by DyStar as DyStar Indigo Vat 40% Solution. It is a patented pre-reduced indigo ready for use on the dyeing range. It is synthesised by catalytic hydrogenation, which causes only water as a by-product. Due to the specific production process, it is the cleanest pre-reduced indigo available. It shows better fixation, and fewer chemicals are required in denim production, resulting in low pollution load in the effluent. Moreover, since DyStar Indigo Vat 40% Solution is available in solution form and stored at a closed circulating system, a cleaner working environment is achieved, as handling of chemicals in powder form by operators is avoided, which greatly reduces the dangers of exposure to chemical dust harmful to health (Holme, 2008; Cleaner Indigo Dyeing).

DyStar indigo 40% solution still requires the use of sodium hydrosulphite, although in smaller quantities, to keep indigo from oxidising prematurely in the dyeing bath. Through its partnership with DyStar, RedElec, a Swiss Company established in 2007, is promoting electrochemistry as a means of completely eliminating the reducing agent (RedElec). The process is based on the use of a three dimensional electrode made of carbon particles with quinine like structures on their surfaces. Electrons from the power source alter these structures to be similar to the reducing agent hydroquinone. RedElec claims the electrode remains stable over months of operation and is cheaper than electrodes that contain precious metals. RedElec's partnership with DyStar is being watched with interest by industry veterans, but they are also wary of being the first to adopt a new technology with uncertain costs.

In recent years, the demand for natural dyes has been increasing in many countries, particularly in the West. This trend is due to health hazard and environmental pollution issues associated with many synthetic dyes. Therefore, there is revival of interest in natural dyes. Presently, indigo is still cultivated for dyeing on a small scale in India, Bangladesh and in some parts of Africa and Central America. It is frequently grown as a secondary crop. There are quite a few national and international companies offering natural dyes in powder form ready to use for dyeing (Chavan, 2004).

In order to overcome the environmental issues associated with the conventional indigo dyeing process, Archroma has developed the Advanced Denim concept, a groundbreaking new dyeing process adapted to current needs that operates completely without indigo. It also needs much less water and energy, greatly reduces cotton waste and produces no effluents. Furthermore, it offers a greater variety of colours, better colour quality and new fashion effects. Experts feel that Advanced Denim will revolutionise jeans production. The Pad/Sizing-Ox process uses a new eco-friendlier

generation of concentrated sulphur dyes such as Diresul<sup>®</sup> RDT. In the first step, the dye is reduced using an eco-friendly sugar based reducing agent. Since sulphur dyes have a different chemical structure than indigo, they bond much better with the cotton; therefore a single dyeing box is sufficient for yarn dyeing. The dye is then oxidised without rinsing with efficient fixing agents to make it adhere to cotton. In the same immersion bath, using Arkofil<sup>®</sup> DEN-FIX, the yarn is sized and dried, and is then ready for weaving. The technology of Advanced Denim Pad/Sizing-Ox therefore greatly simplifies and shortens the production process. The trendy used look or vintage style can be achieved with eco-friendlier ozone and laser treatment without using aggressive chemicals. Extensive tests already conducted by all major textile manufacturers have shown that the Advanced Denim concept is successful in practice. During the course of 2012, the first jeans creations produced with the revolutionary process will be entering the market.

Advanced Denim is ushering in a new era of jeans production and fashion: more eco-friendly in manufacture, with more colours and new design effects. The dyed jeans will look fresher even after several years due to the good fastness properties of Diresul RDT sulphur dyes.

# 3.10 Conclusion

There are several environmental issues associated with the conventional process of denim dyeing with indigo. Worldwide, consumers are demanding goods with ecofriendly credentials. Future research and development activities will focus on microbial synthesis of indigo and environmentally friendly technologies for indigo reduction. At present, technologies are available for biosynthesis of indigo and total replacement of sodium hydrosulphite in indigo dyeing, but their commercial acceptability is yet to be established, because technologies featuring environmental benefits sell only in combination with cost reduction. There are trends towards the revival of natural dyes in general to overcome health and environmental issues associated with many synthetic dyes and also to keep alive the cultural heritage.

An entirely new concept of denim production without using indigo is emerging. If this concept is accepted by the industry, only the future will tell the fate of age old indigo dye. However, the author believes that the age old technologies based on traditional knowledge and cultural heritage have a much longer life than science based technologies, and that indigo will survive for the ages to come.

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# Indigo dyeing technology for denim yarns

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## 4.1 Introduction

Denim continues to be popular with men and women of all ages and social classes. Jeans are worn by both sexes. Much of the popularity of denim is mainly attributable to the attractiveness of its blue colour and the finishing effects that develop when the fabric is laundered repeatedly. The blue colour characteristic of denim fabric is related to cotton warp yarns that are dyed traditionally by indigo (Paul, 2004).

Although there is a long history of dyeing denim yarn with indigo, the process of dyeing with indigo remains largely an art (Zhou, 2001). In fact, indigo is a solid blue pigment that is insoluble in water with no substantivity for cellulose fibres. The dye requires four fundamental steps for application and development on cellulose fibres. First, it is necessary to reduce indigo to its leuco soluble form (leuco indigo form) using a suitable reducing agent with an alkaline compound in order to prepare the dyeing bath. The reduction, called also as vatting process, changes the chromophore of the molecule. Leuco indigo is a pale yellow solution having substantivity for cellulose fibres through van der Waals and dipole forces, which cause its absorption in cellulose fibres (Hughey, 1983). When the textile material is impregnated with reduced dye, leuco indigo is adsorbed in the fibre. It is then oxidised in situ to its original insoluble form. This is usually accomplished by exposing the fibre to the oxygen of the air, but can be also accomplished with other chemical oxidising agents such as hydrogen peroxide. The cycle (impregnating in the dyeing bath/oxidation in air) should be repeated many times to obtain the desired shade. Finally, the dyed material is subjected to an after treatment consisting of rinsing and washing in hot water.

The dyeing of cotton warp yarns with indigo is usually seen as key to the denim fabric manufacturing process (Paul and Naik, 1997a). Hence, in this chapter, a great deal of attention is paid to this important step in order to explain it in detail. Various methods of indigo dyeing that have been used in the past and others that are currently used for indigo dyeing are examined. Then the chapter focuses on the principal industrial dyeing techniques, especially rope dyeing, slasher dyeing and loop dyeing, as well as the different types of indigo dyeing machines now available in the market.

Since the colour variation and the reproducibility of shades (Xin et al., 2000; Westbroek et al., 2003) represent the most important problems of the industrial indigo dyeing processes, the main factors affecting their dyeing performances are discussed and several methods of controlling the quality of indigo dyeing are given. Finally, the future trends in this field are presented.

## 4.2 Evolution of indigo dyeing

## 4.2.1 Fermentation vats

The use of indigo as colouring matter for textile materials can be traced to ancient times when natural plants and animal derivatives were the only known sources of dyes. Wonderful linen fabric with fine indigo dyed borders has survived to the present from Egyptian tombs dating from around 2400 BC. From these times and until the end of the nineteenth century, indigo was produced exclusively from various plants such as Indigoferra tinctoria, Indigoferra caroliniana, Polygonum tinctorium, Nerium tinctorium, Lonchocarpus cyanescens and the woad plant (Isatis tinctoria). The first indigo dyeing procedures used fermented or bacterial indigo dyeing baths (Matthews, 1920; Blackburn et al., 2009). It was discovered long ago that if indigo leaves were left to rot in urine, colour was realised and a green solution was created. The urine provides both the nutrients to grow the bacteria that reduce indigo, and also the ammonia that produces the alkaline solution. When natural textiles such as cotton, linen, wool and silk were impregnated in this dyeing bath, they turned green. However, when they were taken out and exposed to air, the green colour quickly changed to blue. Each region of the world developed its own dyeing methods from this process, which depend especially on the kind of indigo bearing plants present as well as the design of its traditional garments.

In the course of time, various developments were made in fermented indigo dyeing baths. Probably this was achieved in order to avoid or decrease the worst smell caused by urine fermentation. Many substances were introduced in dye baths to create and accelerate the fermentation process, such as wheat bran, madder roots, dates, raisins, honey, plant seeds and glucose. The alkalinity of the medium was ensured by adding of lime or soda ash. Soda ashes were exclusively obtained from plants including glasswort, saltwort, kelp and mangrove (Bird, 1978). The dye bath that was used took about a week to ferment. The colour of the dyeing bath was light greenish yellow. However, people understood later that if it is bright yellow, it means too much alkalinity and more indigo should be added. If the colour is too dark, it needs more lime or other alkali. This vat could be maintained in a functional state for many months.

#### 4.2.2 Chemical vats

Indigo bearing plants were the only source of blue dye in the world. With increasing world trade, demand for blue garments rose. The fermentation dyeing technique was time consuming (Chakraborty and Chavan, 2004). This presented an important difficulty in rapidly fulfilling merchants' orders. However, since 1730, this situation has been improved with the development of the Copperas vat (Matthews, 1920). In this technique, prepared indigo is added to a mixture of Copperas (ferrous sulphate) with lime or potash (Beech, 1901; Fox, 1946; AATCC, 1953; Blackburn et al., 2009). The reduction to the leuco indigo proceeded without heating and it took only 24 h. This lowered the overall cost as well as the time of dyeing. The Copperas vat was exclusively applied for dyeing of cotton skein yarns because it was too alkaline to be used with wool. Its principal advantage is that it is easy to prepare and keep in condition.

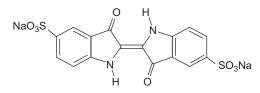


Figure 4.1 Indigo carmine.

However, a large quantity of indigo is habitually lost due to an over reduction phenomenon and the formation of an insoluble complex between dye and iron (Matthews, 1920).

Another change to the employment of indigo in the eighteenth century came with the invention of the Saxon blue vat by Johann Christian Barth in 1743 (Matthews, 1920; De Keijzer et al., 2012). The innovative step of the Saxon blue technique was the sulfonation of indigo in oil of vitriol (sulphuric acid). The result of this addition step is that the dyeing technique is converted from that of an insoluble vat dye (indigo) to that of a soluble acid dye: indigo carmine (Figure 4.1). In the eighteenth century, this conversion reduced the dyeing time as well as the quantity of energy consumed. The Saxon blue dyeing technique offers bright and beautiful colours visually somewhat different from those obtained with the traditional indigo dyeing methods. However, the disadvantages of this dyeing process are poor light-fastness and wash-fastness (De Keijzer et al., 2012).

In 1845, the zinc–lime vat appeared. This technique used zinc dust as a powerful reducing agent in place of the Copperas (Matthews, 1920; Fox, 1946; AATCC, 1953; Blackburn et al., 2009; Prideaux, 2003). This technique was very advantageous because it avoided the large amount of precipitated iron oxide that always forms in the Copperas vat and leads to loss of dye and muddiness and dullness of colours.

## 4.2.3 Modern methods

This era was marked by two principal events that disrupted the field of traditional indigo dyeing. The first one is the production of synthetic indigo in 1880 by Adolf von Baeyer (1880). This led to the industrial synthesis of this dye in 1897 by Badische Anilin- und Soda-Fabrik (BASF) in Ludwigshafen, Germany. This event resulted in the rapid decline of traditional dyeing with natural indigo (Matthews, 1920). The second event was the development of sodium hydrosulphite (dithionite), a powerful reducing agent able to achieve a rapid reduction of indigo, therefore enabling the dyeing process to be relatively short in comparison with other reducing methods. Once this reducing agent became available in industrial quantities, the continuous indigo dyeing range was developed. This inorganic reducing agent was used to produce the reduced indigo stock vats, which were then pumped into the dyeing range for dyeing of cotton yarns.

For the first 20 years of the twentieth century and due to the success of blue jeans garments, the use of the 'hydrosulphite vat' in indigo dyeing increased, particularly when employed with sodium hydroxide, as there were no precipitation products and no loss of indigo within the dyeing bath (Fox, 1946; AATCC, 1953).

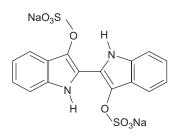


Figure 4.2 Indigosol O.

Nevertheless, an attack on indigo and its new dyeing process came in 1924 with the discovery of Indigosol O (the diester sulphonic acid salt of indigo) (Figure 4.2) by Marcel Bader and Charles Sunder from National Higher School of Chemistry of Mulhouse (Brunello, 1973). The use of Indigosol O allows the dyer to eliminate the vatting step of indigo. In fact, this dye is soluble in water, which makes it possible to apply it directly to cotton. Then, the blue colour is developed by hydrolysis and oxidation of the Indigosol O under acidic conditions and in the presence of an oxidising agent such as potassium dichromate. This process offers some advantages. It can be used in the dyeing of wool, silk and rayon. It can also be applied for piece goods by padding and jigger dyeing. However, due to the high cost and the low affinity of Indigosol O to cellulosic fibres, this dye can be only applied for the production of light to medium shades. Besides, precautions must be usually taken when handling this dye because it is very sensitive to moisture, light, heating and the action of acids.

In the last century, improvements reached various levels of the indigo dyeing process. Many dyeing techniques such as rope dyeing, slasher dyeing and loop dyeing were developed and applied in order to improve the performances of the indigo dyeing process. In the early 1990s, the pre-reduced indigo (alkaline leuco indigo solution) was prepared by catalytic hydrogenation using Raney nickel as a catalyst and was commercially available in stock vats. The use of pre-reduced indigo avoids the need for a separate vatting stage during the indigo dyeing process. This leads obviously to rapid dyeing, provides satisfactory indigo coloration of cotton yarns and could achieve the minimum of dyeing effluents. The evolution and the change of the world of jeans fashions influenced significantly the indigo dyeing process. As a result, new dyeing steps by sulphur dyes (sulphur bottom and sulphur top processes) and by other dye classes such as vat and reactive dyes were included in the continuous indigo dyeing process in order to achieve the more recent appearances of jeans that fascinate consumers.

## 4.2.4 Green indigo dyeing

Since the beginning of the twentieth century, the hydrosulphite vat has presented the dominant method of indigo reduction due to its high performing and economic properties. However, little by little, dyers started to feel the ecological drawbacks of hydrosulphite: low stability, corrosive effect, risks of fire and health problems during its storage, generation of toxic by-products (sulphate, sulphite and thiosulphate compounds) that have harmful effects on the environment, etc. So, many attempts are being made to improve the environmentally unfavourable hydrosulphite process by eliminating or minimising the production of inorganic waste from chemical reducing agents. These include the use of iron (II) complexes (gluconic acid complexes) (Semet et al., 1995), borohydride (Meksi et al., 2007, 2010),  $\alpha$ -hydroxycarbonyls (Ben Ticha et al., 2013; Meksi et al., 2012; Vuorema, 2008) and biotechnological reduction (Padden et al., 2000; Bozic et al., 2009a,b) as well as electrochemical reduction (Roessler and Jin, 2003; Bozic and Kokol, 2008; Roessler and Crettenand, 2004; Bechtold et al., 1996, 1997; Bechtold and Turcanu, 2009). For technical and economic reasons, most of these are still being studied at the laboratory scale stage, and probably the electrochemical dyeing method developed by Bechtold et al. (1996, 1997) and Bechtold and Turcanu (2009) is until now the only method that is the subject of a wide range of investigations at industrial pilot scale. However, this does not necessarily mean that the cleaner processes of indigo dyeing will not be soon industrially introduced.

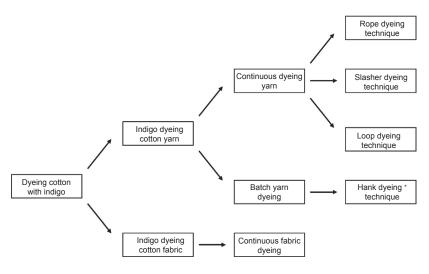
On the other hand, increasing awareness of the environmental and health hazards associated with the synthesis, processing and use of synthetic dyes has generated a renewed worldwide interest in textiles dyed with natural substances. In this context, organic denim is a fabric that is made with entirely organic cotton and free from chemical fertilisers and pesticides. The whole production of organic denim adheres rigorously to ecological standards: from spinning, preparation and dyeing until finishing of the denim. It involves non-toxic fibre processing, dyes and fabric treatments guaranteeing that no pollution was caused to the environment for the production of the collection. During the last decade, there has been an increase in consumer demand for organic denim, reviving interest in the use of the primitive indigo dyeing methods. Therefore, many projects have recently been undertaken in order to reach commercial growing and extraction of natural indigo. Furthermore, novel processes of indigo dyeing for the organic denim industry using green biotechnological methods are currently under development.

## 4.3 Indigo dyeing techniques

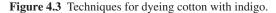
This section provides a detailed description of the main techniques used for dyeing cotton with indigo. These dyeing techniques can be illustrated in the schematic diagram of Figure 4.3.

## 4.3.1 Batch dyeing technique

Until 1915, most indigo dyeing was conducted using the batch dyeing technique, which is also called skein or hank dyeing (Matthews, 1920). The batch dyeing technique can be carried out artisanally in pots on gas burners or in specialised machinery. These machines are generally classic machines of cotton hank dyeing that were modified by artisans in order to be more adaptable for the specificity of indigo dyeing. With this technique, dyeing occurs in skeins or hanks generally 110 m in length, which may be suspended in the dye machine. Every skein is first looped over a hook and washed



\* In most situations, this activity is artisanal.



in water, opening the fibres in order to receive the dye. Then it is dipped into the dyeing bath. After dipping, it is exposed to the air for oxidation. It is possible to dip the skeins up to 20 times in order to reach a deep shade.

This technique is a laborious and time consuming process. However, it achieves a good and rich colour penetration. Furthermore, this dyeing technique is less deteriorating to the textile material, and the yarns retain a softer and loftier feel.

On the other hand, contrary to other yarn dyeing techniques (rope dyeing, slasher dyeing and loop dyeing), which provide a *ring dyeing* effect (a characteristic of indigo dyeing whereby only the outer ring of the fibres in the yarn are indigo dyed, while the inner core remains white), hank dyeing produces a core dyeing effect.

Skein dyeing of indigo is still the useful method of dyeing with indigo on very fine yarns for delicate high fashion fabrics. Recently, it has been largely applied for dyeing organic denim with natural indigo.

## 4.3.2 Continuous dyeing techniques

## 4.3.2.1 Continuous yarn dyeing techniques

The continuous dyeing techniques of cotton yarns by indigo are mostly used for producing denim products. Denim fabrics are 100% cotton with blue face and white back. Traditionally, they are a  $3 \times 1$  twill woven structure where the warp yarns are indigo dyed and the weft yarns are non dyed cotton. The dyeing of warp yarns is done continuously using three major methods: rope dyeing, slasher dyeing and loop dyeing (Paul and Naik, 1997a). Figure 4.4 shows a schematic diagram that clearly represents the position of the steps of these dyeing methods in the manufacturing process of denim fabrics.

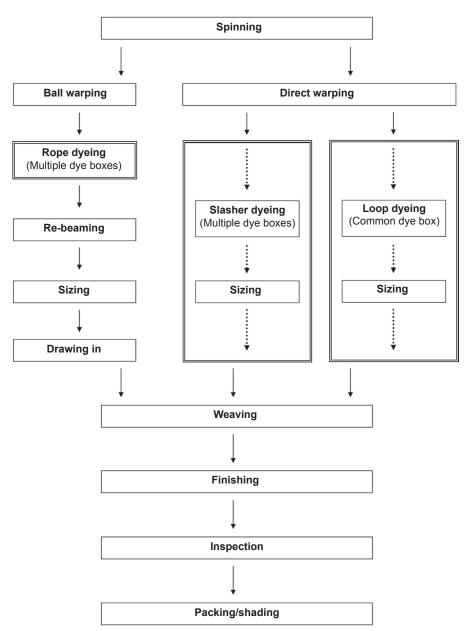


Figure 4.4 Position of rope, slasher and loop dyeing steps in denim manufacturing.

## Rope dyeing

This dyeing technique dates from 1915, when the first rope dyeing machine appeared. A typical example of a rope dyeing range is shown in Figure 4.5. With the rope dyeing technique, 350–400 warp threads are bound on the ball-warper machine to very thick cables of 10,000–15,000 m in length (sometimes the length of cables may exceed

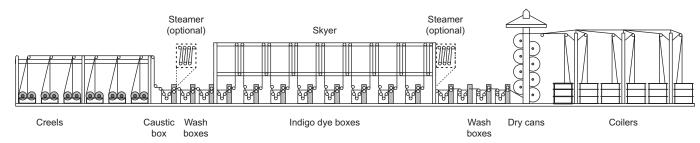


Figure 4.5 Typical scheme of a rope dyeing range.

25,000 m). Generally 12–36 cables are first fed into one or more scouring baths containing wetting agents, detergents and sodium hydroxide (BASF, 1995; Cotton Incorporated, 2004). The scouring baths are used to remove naturally occurring impurities found in cotton fibres such as dirt, minerals, ash, pectin and naturally occurring waxes. It is very important to remove these substances in order to achieve uniform wetting and uniform dyeing. Then, the cables are fed into one or more water rinsing baths.

After that, the cables are dipped into a bath of leuco indigo with an immersion time of 12–20 s, and then are squeezed to give 70%–80% wet pick-up after each dip, followed by exposure to air for oxidation, multiple times. The oxidation time takes at least 80 s. Generally, four to eight dyeing vats are used for dipping. This results in the fine layer of indigo on the surface of yarn. The cables of yarn are washed in various water baths to eliminate the non-fixed dye. Next they pass through a softener box, which assists in obtaining a better opening of the cables in the long chain beamer. Finally, they are dried on Teflon covered cylinders and coiled into large cans.

#### Slasher dyeing

Slasher dyeing was introduced in 1970 to be more rapid and flexible in response to changes on the denim market. This kind of dyeing works well, especially with lightweight denims, and the corresponding dyeing machines require less floor space and enable smaller production runs. Basically, in slasher dyeing, direct warping beams are employed instead of the ball warping logs used in the rope dyeing technique. A schematic diagram of a typical slasher dyeing unit is shown in Figure 4.6. During slasher dyeing, section beams of warp yarn are forced into a sheet of yarns (approximately 4000 yarns), which is first fed into a scouring section to remove natural impurities as in rope dyeing (Chakraborty and Chavan, 2004; BASF, 1995; Cotton Incorporated, 2004). Then the sheet passes through the multi-dip/nip indigo dyeing section with an immersion time of 4-15s in order to achieve fairly deep shades. The oxidation time takes at least 45 s. Some slasher dyeing ranges do not allow for multiple dip/nip applications, and so only light and medium shades can be obtained from indigo in this case. After rinsing, the sheet is dried on cylinder dryers. Next, the sheet passes through the size box containing the sizing agent. The yarns pick up the required quantity of size solution and the excess size is removed by squeezing. Then, the sheet is dried on cylinder dryers using hot steam rolls. In the end, the yarns are wound onto a loom beam for weaving. Using slasher dyeing, it can be seen that the handling of yarns is minimised since the warp sheet is directly processed and then sent to the weaving section for its conversion to fabric. A slasher dyeing range may consist of either the indigo dyeing range alone or a continuous indigo dyeing range with an integrated sizing range. It is possible to simultaneously treat two or more layers of warp sheet using this technique.

#### Loop dyeing

This dyeing technique, known as 'Loopdye one for six', was developed in 1980 by Eckhardt Godau and his company Looptex in order to solve many problems associated with both slasher and rope dyeing (Chakraborty and Chavan, 2004). A typical example of a loop dyeing range is shown in Figure 4.7. In comparison with the other

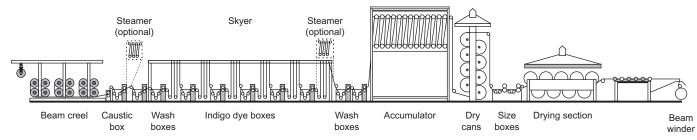


Figure 4.6 Typical scheme of a slasher dyeing range.

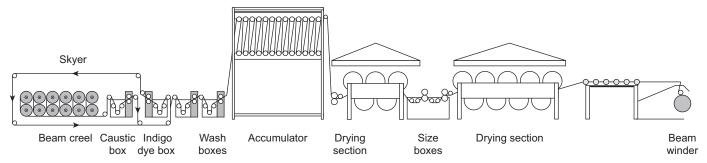


Figure 4.7 Typical scheme of a loop dyeing range.

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indigo dyeing methods with six or eight dye baths, in the loop dyeing process, the yarns are dyed in only a single bath with one squeezing unit, after passing through the pre-treatment boxes. When the yarns exit the dyeing bath, instead of moving forward, the yarns are carried to the rear of the machine, around the top and rear of the yarn creel from where they started, to pass under the yarn creel, where they return to the indigo dye bath for another dye passage. This continuous passage of yarns that occurs between the yarn creel and the dye box represents a 'loop' form. According to the desired shade, the yarns can make multiple loops through the indigo dye bath. Next, they are conducted through the wash boxes and then onto the drying cylinders. After drying, the indigo dyed yarns pass directly to the sizing unit. It can be seen that loop dyeing has various advantages in terms of handling, rapidity and flexibility of process, floor space and investment cost. To further clarify the difference between rope dyeing, slasher dyeing and loop dyeing, a comparative study between both the performance and the limitations of these continuous dyeing techniques is summarised in Table 4.1.

#### Bottoming and topping

The additional processes of bottoming and topping were included in the dyeing of denim fabrics especially due to fashion effects. Bottoming dyeing is applied before dyeing by indigo. In fact, after scouring, the yarns are fed originally into a bath of a reduced sulphur dye. The purpose of bottoming is to produce a much deeper and darker shade with less indigo for lower cost, or to slightly change the shade of the blue yarn in order to make it unique (Cotton Incorporated, 2004). Now, the bottom dye range is expanded to other classes of dyes like reactive and vat dyes in order to produce new shades.

On the other hand, topping dyeing is a process in which the warp yarns are dyed first with indigo and then they are washed and dyed generally with sulphur dye (Cotton Incorporated, 2004). Although the sulphur dye will migrate towards the core of the fibre/yarn, the sulphur top gives a different type of yarn colour performance when the garment is washed than a sulphur bottom. Similar to the bottom dyeing process, it is possible to use other dyes for topping such as reactive and vat dyes. Another process called 'bottoming indigo topping' is also used in denim dyeing. In this case, the warp yarns are first dyed with bottom dye. After washing, they are dyed with indigo, followed by washing and a second dyeing with another dye such as sulphur dye.

## 4.3.2.2 Continuous fabric dyeing technique

The continuous fabric dyeing technique consists of passing the fabric through successive baths of leuco indigo (Figure 4.8). After each dipping, the fabric is squeezed between rollers followed by exposure to air for oxidation, multiple times. Then the fabric is washed, passes to the drying section and wraps as a roll. This technique is not common industrially, probably for technical reasons. In fact, taking into account the specificity of indigo dyeing, it will be extremely difficult to achieve in practice a good level of dyeing and a good depth of shade as well as acceptable dyeing fastnesses when using this technique.

|            | Rope dyeing  | Slasher dyeing   | Loop dyeing   |
|------------|--|--|---|
| Advantages | <ul> <li>Rope dyeing can handle a dyeing capacity of more than 15,000 m.</li> <li>No centre to selvedge shade variation.</li> <li>This technique offers a good depth of shade and lower wash down.</li> <li>No need to stop operation of the machine even in the case of yarn breakage.</li> <li>In rope dyeing, ropes are dipped into the dye pads with identical tension and angle; therefore there is no risk of 'side-to-side' problems.</li> <li>The dyeing machine does not have to stop while feeding new dyeing parties, which means high productivity.</li> <li>Yarn wastage is not that much.</li> <li>Possible to mix yarns of different colours. One can get denim stripes at rebeaming.</li> <li>In rope dyeing, there is an opportunity at rebeaming to repair broken ends.</li> </ul> | <ul> <li>This technique is characterised by a one-stage production process from the back beam to the weaving beam.</li> <li>The slasher dyeing machines are smaller and require less floor space compared to rope dyeing machines.</li> <li>The yarns wet more rapidly, which decreases the dipping and the wetting times during dyeing.</li> <li>The dipping and skying times are shorter.</li> <li>The short slots are possible with this technique.</li> <li>Dyeing can be performed with climatic control thanks to temperature controlled air oxidation.</li> <li>The energy requirements are lower for this technique (optimised drying technology).</li> <li>This technique can be applied also for fine yarns.</li> <li>Slasher dyeing is more specialised for producing lightweight denims.</li> <li>This technique requires small volumes of dyeing bath (1500–8000 L).</li> </ul> | <ul> <li>This technique may be characterised<br/>by a one-stage production process from<br/>the back beam to the weaving beam.</li> <li>The loop dyeing machine is smaller and<br/>requires less floor space than slasher<br/>dyeing and rope dyeing machines.</li> <li>The loop dyeing machine presents the<br/>lowest investment costs for continuous<br/>indigo dyeing machinery.</li> <li>The dipping and skying times are shorter.</li> <li>Maintenance and energy costs are<br/>approximately 20% lower with loop<br/>dyeing compared to slasher dyeing and<br/>rope dyeing.</li> <li>The short slots are possible with this<br/>technique.</li> <li>Dyeing can be performed with climatic<br/>control thanks to temperature<br/>controlled air oxidation.</li> <li>This technique can also be applied for<br/>fine yarns.</li> <li>Loop dyeing is able to produce<br/>lightweight denims.</li> <li>This technique requires small volumes<br/>of dyeing bath (1500 L).</li> <li>Less chemical consumption.</li> </ul> |

# Table 4.1 Advantages and limitations of rope, slasher and loop dyeing

| Limitations | <ul> <li>This technique is characterised by three stages up to production of the weaving beam (dyeing, long chain beamer, sizing).</li> <li>The rope dyeing machine is more expensive than slasher dyeing.</li> <li>The short slots are not possible with this technique.</li> <li>Rebeaming is required after process, hence more time consuming.</li> <li>The oxidation time is greater.</li> <li>This technique is applied only for coarse yarns, as the tension of the rope breaks the yarns.</li> <li>Dyeing is performed without climatic control.</li> <li>This technique offers little flexibility due to the important volumes of the dyeing bath (30,000 L).</li> <li>This technique presents other additional costs of softening treatment for opening of cables.</li> </ul> | <ul> <li>Slasher dyeing can only handle a dyeing capacity of over 5000 m.</li> <li>There is a problem of centre to selvedge shade variation.</li> <li>Consumption of sodium hydrosulphite is significantly higher due to the greater surface area of the textile material.</li> <li>When the slasher dyeing machine slows down at the end of each yarn set, the wash down shade will be altered.</li> <li>During the change of lots, machine stoppage is time consuming.</li> <li>The obtained depth of shade is not that good.</li> <li>Yarn wastage is very important.</li> </ul> | <ul> <li>The productivity is essentially equivalent to a multi-boxed slasher machine.</li> <li>This dyeing method produces more warp yarn breakage in weaving, which decreases productivity as well as fabric and garment quality.</li> <li>Loss of elasticity of yarns.</li> <li>There is a problem of centre to selvedge shade variation.</li> <li>During the change of lots, machine stoppage is time consuming.</li> <li>Limits in the production of very dark shades.</li> </ul> |
|-------------|---|---|---|
|-------------|---|---|---|

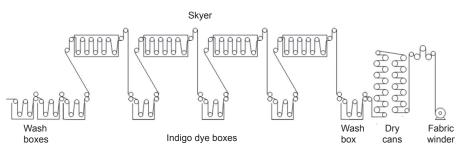


Figure 4.8 Typical scheme of a continuous fabric dyeing range.

# 4.4 Indigo dyeing machinery

In this section, the main machines used in indigo dyeing and that are currently available in the market are illustrated. The data reported in this section are a synthesis that is developed on the basis only of accessible information provided by the manufacturers. The choice of dyeing technology depends on several factors such as the production volume, the investment cost, the desired quality and the flexibility of each customer.

## 4.4.1 Rope dyeing machinery

In the market, six companies generally produce the indigo rope ranges for the production of denim fabrics. These companies are Morrison Textile Machinery (USA), Master S.r.l. (Italy), Karl Mayer Textilmaschinenfabrik GmbH (Germany), Looptex Company (Italy), Komatsubara Iron Works Ltd. (Japan) and Smartec Machinery & Engineering Inc. (China).

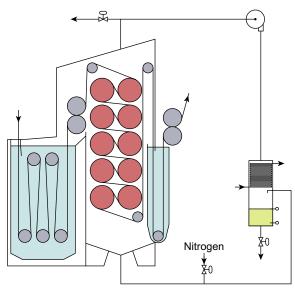
## 4.4.1.1 Morrison technology

Morrison Textile Machinery is one of the leading companies in textile processing machinery. This company is particularly famous for its long history in the design and manufacturing of rope dyeing machines. In fact, Morisson installed over 200 rope dyeing machines for denim fabrics worldwide.

Generally, Morrison supplies classical indigo rope ranges with minimum waste and maximum flexibility (Anon., 2009a). But it has recently developed the Spectrum<sup>TM</sup> Indigo Rope Dye Range. This range is equipped with additional wash/dye boxes, pre-dryers and dye steamers sections in multiple locations. This process flexibility makes it possible to obtain the highest production targets while meeting fashion demands of deep/dark shades, sulphur bottoming and topping, and the application of all other cotton dyes such as vat, reactive and direct dyes. The company offers also the optional FCS (Flexible Control System) on the Indigo Dye Box, which continuously monitors the critical dyeing parameters and alerts operators to deviations from recipe set points.

## 4.4.1.2 Master technology

Master S.r.l. is an emerging company specialised in designing and manufacturing yarn dyeing machines. Its first indigo rope dyeing machine, called IndigoRope<sup>®</sup>, was



**Figure 4.9** Integrated module Genius/C (Pat.). Reproduced from Anon. (2013b), with kind permission from The Indian Textile Journal.

produced in 2005. Currently, the company offers a new machine for continuous rope dyeing with indigo and other dyes of denim fabric warps. In order to have a flexible adaptation to the quickly changing fashion trends, this machine is designed to achieve various pre-treatments and post-treatments as well as dyeing of several kinds of cotton yarns (ring spun, open end, heavy or light) and blends. The basic version of this dyeing range is equipped with the dryers and coiler, but it is arranged for possible future upgrading with steamers and other additional sections. Moreover, it possesses computerised dosing and automatic monitoring systems to ensure a good quality of dyeing.

There were some reports (Anon., 2013a,b) that Master S.r.l. has developed a new indigo rope dyeing machine, the IndigoRope Genius/C<sup>®</sup>, in which it has combined its IndigoRope<sup>®</sup> rope dyeing machine with a new integrated dyeing module called Genius/C (Pat.) (Figure 4.9). This integrated dyeing module is made up of a combination of a dyeing vat with a special group of dyes, diffusion/fixation at soluble condition (leuco form) in the yarn, adjustable through heat activation and timing variation in an inert environment. According to the company, its new technology offers several ecological and economical advantages over traditional dye vats: dye bath number and volume reduction, better fixation of dyes in the fibre, reduction in caustic soda and hydrosulphite consumption, reduction of sulphites and sulphates in the wastewater, etc.

## 4.4.1.3 Karl Mayer technology

Karl Mayer Textilmaschinenfabrik GmbH is famous worldwide in the field of warp knitting technology. Actually, the activities of this company include not only the

manufacturing of warp knitting machines and Raschell machines but also the manufacturing of warp preparation machines for weaving (beaming machines, sectional warping machines, sizing machines, assembling machines, indigo dyeing machines, etc.), machines for the production of technical and medical textiles, etc. Karl Mayer Textilmaschinenfabrik GmbH increases its market presence in indigo dyeing machines especially after the acquisition of Ira L. Griffin Sons Company (USA) and Sucker-Muller-Hacoba GmbH & Co. (Germany), which are very old and well known companies in the sector of warp preparation machines.

Indig-O-Matic (IOM-R) is the machine designed by Karl Mayer for indigo rope dyeing. This machine contains the following main components (Karl Mayer Textilmaschinenfabrik GmbH, 2011; Anon., 2009b):

- Vario Double troughs, which can be used flexibly for both conventional and nitrogen or reactor dyeing. According to the company, this module offers improved handling, reduced cleaning time and stable liquor baths during machine downtimes. Moreover, thanks to efficient liquor exchange at the textile material, the consumption of chemicals can also be reduced by 25%.
- A rapid oxidation system for stabilising the climatic conditions during processing. It is a blowing unit that is controlled by means of temperature and pressure. This accelerates the oxidation process during indigo dyeing and improves fixing of the indigo into the yarn.
- The eco-wash trough, which operates with roughly 10–15% less wash water than similar systems.
- The Kamcos<sup>®</sup> control system, which supplies the operators with accurate information on the tension and elongation behaviour throughout all of the various chemical treatment stages.
- The Indigo Pilot ancillary system, which is equipped with integrated online titration as well as evaluation and calculation software. This guarantees accurate starting recipes and constant dyeing bath concentrations for indigo, alkali and reducing agent.

#### 4.4.1.4 Looptex technology

Looptex is a subsidiary of the HTP Unitex Group (an Italian firm manufacturing textile machines) which is intended to indigo warp dyeing and denim finishing machines. Looptex markets a classical indigo rope range designed to provide minimum waste and maximum flexibility. This rope dyeing range, which is called Rope Dye, offers various benefits: dyeing multiple yarn weights with multiple dye classes, running short or long production lots as well as production with light or heavy depth of shade.

For Rope Dye, the pre-treatment stages consist of counter flow scour and wash boxes. This machine is set also for possible future upgrading with an optional mercerising section that could improve dye affinity, lustre, strength and fashion effects.

On the other hand, the dyeing stage in this machine can be performed in multiple dips of leuco indigo with the classic oxidation method in the skyer section or with the nitrogen indigo dyeing reactor technology (Pat.) (Figure 4.10). The company claims that this technology makes it possible to save up to 20% of indigo for obtaining the same shade of a traditional rope indigo dyeing. Dosing and monitoring of the range are totally automatic, based on a PLC control system. The average of its production speed is estimated at 30 m per minute (Anon., 2008).

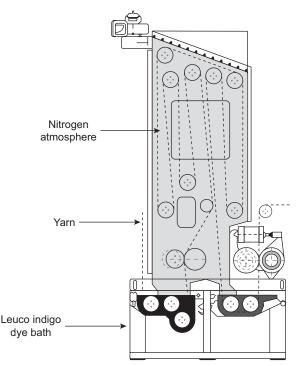


Figure 4.10 Nitrogen indigo dyeing reactor for a rope dyeing machine (Pat.).

## 4.4.1.5 Komatsubara technology

Komatsubara Iron Works Ltd. is a Japanese manufacturer of industrial machinery such as textile dyeing and finishing as well as continuous rubber curing machines. Komatsubara Iron Works provides an indigo rope dyeing machine that has the following principal features:

- · Dyeing cisterns have a low liquor ratio for saving chemical agents, steam and water.
- The dyeing and the airing processes are properly programmed.
- A system is provided for circulation of the dyeing solution.
- An ergonomic designed plaiting-down system is provided.
- The rope end can be connected with the next rope form without stopping the machine, but by reducing the speed.

# 4.4.1.6 Smartec technology

Smartec Machinery & Engineering Inc. is a denim machinery manufacturer in China. Unlike the previous companies, which produce both rope and slasher dyeing machines, Smartec is specialised only in the manufacturing of rope dyeing ranges. The most important characteristics of the rope dyeing machines provided by Smartec (Model LHJ3689) are:

- A metering pump and flow meter for auto feeding control.
- · A drying unit with temperature, pressure and moisture control.

- Stainless steel dye boxes with a 35 m oxidation zone for each dye box.
- A process control system equipped with Hi-Tech PLC, inverter control and SOPCS<sup>®</sup> software. According to the company, this system offers quick, easy, precise and reliable control. Furthermore, thanks to the remote access system, the range machine can be connected to the Smartec Service Centre via the Internet for quick troubleshooting and maintenance remotely.

# 4.4.2 Slasher dyeing machinery

The number of companies that manufacture slasher dyeing machines is slightly greater than those producing rope dyeing machines. In addition to the companies cited above for the production of the indigo rope range machines, there are other companies from various countries that are specialised in producing slasher dyeing ranges, such as Benninger AG (Switzerland), Texima S.A. Industria de Maquinas (Brazil), Memnun Makina (Turkey) and Jupiter Comtex Pvt Ltd. (India).

## 4.4.2.1 Morrison technology

Morrison Textile Machinery Co. designs and manufactures sheet dye ranges that require a small investment. They are destined only for short dye runs or lighter weight yarns. These dyeing range machines are equipped with a flexible flow control for various dye types and a high accumulator capacity to reduce waste due to a set of changes for dye class changeovers.

## 4.4.2.2 Master technology

For slasher continuous dyeing, Master S.r.l. supplies two types of dyeing machines.

IndigoFlow<sup>®</sup>. This is a machine based on the indigo flow technology. This technology consists of special pad troughs with an optimised shape and efficient double flow bath circulation. The machine is equipped also with TwinFlow<sup>®</sup> (Pat.) vats, which can be used for producing 'colour denim' with sulphur, vat and reactive dyeing. The RapidSky<sup>®</sup> module allows a thorough oxidation with a shorter distance between dips leading to fewer wasted meters of warp at lot change. Ecowash<sup>®</sup> washing units in this machine are also available to enhance the washing efficiency with notable water savings.

This machine is characterised by maximum operative flexibility to meet fashion trends. In fact, this machine is designed to achieve various pre-treatments and post-treatments as well as dyeing of several kinds of cotton yarns (ring spun, open end, heavy or light), blends and also elastic with various colour shades of blue, black and others. IndigoFlow<sup>®</sup> is a fully computerised machine that allows process data collection and data feeding. It works with a capacity of 34 m per minute.

IndigoGenius<sup>®</sup>. This is a novel range machine designed by Master S.r.l. for slasher continuous dyeing with indigo and other dyes of denim fabric warps. Instead of the classical number of six to eight dyeing vats, this new machine is equipped with the integrated Genius <sup>®</sup> (Pat.) dyeing module (Anon., 2013a,b). The use of this technology offers several technical, ecological and economic advantages, which were reported previously for IndigoRope Genius/C<sup>®</sup> (see Section 4.4.1.2).

# 4.4.2.3 Karl Mayer technology

Indig-O-Matic (IOM-S) is the indigo slasher dyeing machine manufactured by Karl Mayer Textilmaschinenfabrik GmbH. In addition to the components available in the rope dyeing range of this company (called Indig-O-Matic (IOM-R)), this machine also contains the following functions (Anon., 2009a,b):

- The WarpLink system for automatic beam changing yarn to yarn, which makes it possible to run the machine continuously without loss of productivity. This system allows reducing the yarn wastage by about 50% when changing the sets.
- The compact size box CSB formed by a size box with triple dip and double nip squeezing technology to ensure the uniformity and the surface oriented size pick-up.
- Cylinder driers available as full warp or sectional warp versions (with partial Teflon coating) for rapid drying after sizing without damaging the yarns.

# 4.4.2.4 Looptex technology

Similarly to the Looptex Rope Dye machine, the Looptex slasher dyeing machine is also equipped with the patented Nitrogen Indigo Dyeing Reactor<sup>®</sup> (Pat.) (Figure 4.10) with optimised shape in order to improve dyeing performance (Anon., 2008). The reactor could be also supplied in the reactor steamer version. Furthermore, according to the manufacturer, this range can be used in dyeing with indigo in an inert environment, sulphur and vat and reactive dyes. It is also equipped with several options to follow the market demands.

# 4.4.2.5 Benninger technology

Benninger AG is one of the oldest companies specialised in the manufacturing of textile finishing and cord production ranges. Benninger AG has developed and successfully introduced the indigo slasher dyeing ranges in closed nitrogen filled troughs. According to the company, this technology, called Ben-Indigo, ensures high production flexibility for various colour shades and offers various ecological benefits such as reduction of the hydrosulphite and alkali consumption as well as the reduction of sulphites and sulphates in wastewater. The Ben-Indigo machine features a number of components (Anon. 2003):

- Dye baths under nitrogen atmosphere (Figure 4.11), which make it possible to reduce the total number of required dye baths to about one-third lower than that of traditional process designs.
- The Ben-Direct Warper, equipped with the CleanVac dust extraction system to remove the maximum amount of dust and fly.
- The Ben-Link is an automatic yarn to yarn joining system. It allows running the machine continuously during lot changes without decreasing the dyeing speed (which can reach up to 40 m per minute).
- The Ben-Sizetec sizing machine ensures high sizing performance.

# 4.4.2.6 Texima technology

Texima S.A., the leading machinery builder in Brazil, provides the Multicaixas slasher dyeing machine for indigo. Multicaixas technology offers high production flexibility for

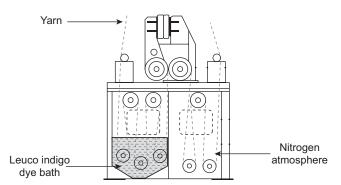


Figure 4.11 Ben-Indigo dye bath.

various types of yarns and colour shades such as deep/dark shades, sulphur bottoming and topping. This slasher dyeing machine contains the following main units:

- A dyeing unit that is equipped with several Cilflex rolls padders. The circulation and the liquor level are controlled by a frequency variator on the circulation pump. The oxidation process can be performed by 'Skying' or 'Quick Oxidation'.
- An automated sizing unit that contains a size padder with double immersion and an intermediate nip. The drying is generally carried out using Teflonate dryer cylinders.

In addition, the company offers many options such as a mercerisation unit, predyeing steamer, intermediate dryer, TinaFlex system for dyeing in colours with or without the steamer, FastOxid system to accelerate the oxidation process, heat recovery system and monitoring system.

# 4.4.2.7 Memnun technology

Memnun Makina is a Turkish company established in 1979 and specialised in the production of textile machines. This company manufactures slasher dyeing machines that have the following main functions:

- A caustic process unit for swelling of cotton fibres and getting brighter and deep colours.
- A hot water washing unit for the caustified yarns.
- Teflon coated drying cylinders with controlled heat and moisture.
- Vessels for sizing and preparing the size.
- Driving head system.

Memnun Makina claims that their slasher dyeing ranges provide continuous working and a time saving of 5.5 min with the help of an accumulator. Moreover, these machines allow the application of different combinations of colours (blue/black, black, smoke coloured, blue/blue, black/black) in order to respond to fashion trends.

## 4.4.2.8 Jupiter Comtex technology

Jupiter Comtex Pvt Ltd. is a family group from India specialised in textile machinery and manufacturing activity. Jupiter Comtex Pvt Ltd. supplies multi-colour warp dyeing ranges. These ranges are equipped with:

- A size box with a positive feed device and size circulation device as well as a pair of squeezing rollers/rubber coated immersion rollers.
- Dyeing tanks that are used for topping or dyeing with different classes of dyes such as sulphur, direct, reactive, naphthol and vat dyes.
- A dosing system for dyes and chemicals.
- · A quick oxidation/aeration section with constant air flow and controlled temperature.

## 4.4.3 Loop dyeing machinery

The loop dyeing technique was developed by Echardt Godau and his company Looptex in 1980. Although the process is also under license by other companies such as Kusters Zima Corporation (USA) and Texima SA (Brazil), there is only Looptex, which now markets the loop dyeing machine under the Loopdye brand name. With a compact layout, this machine is equipped with the famous Looptex technology Nitrogen Indigo Dyeing Reactor (Pat.) (Figure 4.10; Anon., 2008). It can produce various colour shades requested by the market such as sulphur bottoming and topping, blue or 100% black sulphur shades. According to the company, thanks to the reduced length and to the nitrogen atmosphere, Loopdye can dye in half of the space of a classic machine and reaches the darker shades with very good fastness. The short layout of the machine allows reducing hydrosulphite, water and energy consumption. The company also claims that this machine is the cheapest in the category and the simplest, which enables it to be operated by minimally skilled personnel.

## 4.4.4 Fabric dyeing machinery

Since the continuous technique of fabric dyeing with indigo faces several difficulties in practice to achieve an acceptable dyeing quality, there are no companies that currently manufacture and market machines for this kind of dyeing. The only common company in this field is probably Memnun Company, which offers a machine for fabric dyeing by indigo with various advantages. The Memnun range machine is designed to dye cotton fabrics, cotton/lycra fabrics and fabrics that are formed from 50/50 cotton/polyester blends. The machine also contains an integrated sanforising section that makes it possible to achieve shrinking and fixing treatments on the woven fabric in both length and width. These treatments reduce the shrinkage that would otherwise occur after washing of cloths and articles made from this fabric. The machine is equipped with four dyeing vessels and one washing vessel. According to the fabric area density and the speed situation, approximately 1500 m of fabric may be dyed in an hour when using this machine.

# 4.5 Factors affecting indigo dyeing

In denim manufacturing, the factors influencing the effectiveness of the indigo dyeing process are many and varied, but ultimately the most important factors involve the

quality of the preparation of cotton yarns, the composition of liquor (dye baths) and other parameters that are related to the dyeing procedure (Paul et al., 1996).

#### 4.5.1 Effect of cotton pre-treatment

Before dyeing, denim warp yarns pass traditionally through scouring baths, which generally contain wetting agents, detergents and sodium hydroxide. This step aims to improve the absorbency and the whiteness of textile materials, removing the non-cellulose natural matter, that is fats, waxes, pectins and proteins from the fibres. Waxy materials and pectins are responsible for the hydrophobic properties of the raw cotton. To ensure the success of the dyeing process, the scouring step must be efficient. The performance of this step may be improved by the addition of a caustification or mercerising stage prior to indigo padding, which enhances fabric appearance and handle and offers higher yarn strength, higher indigo uptake and more intensive ring spun yarn dyeing with shorter and more efficient stone washing (Chakraborty and Chavan, 2004).

#### 4.5.2 Effect of pH

The pH of the dyeing bath is one of the crucial parameters that influence significantly the indigo dyeing process. The importance of this parameter may lie in the fact that it affects not only the structure of leuco indigo but also the morphology and the ionic character of the cellulose of cotton.

It is well known that the reduction of indigo by sodium hydrosulphite in basic medium leads to a bienolate form (see Figure 4.12). The pH of the dye bath strongly influences the stability and the hydrolysis of the bienolate form (Abozin and Karpov, 1964; Etters, 1993a). Depending on the medium pH, the reduced form of indigo can exist in the dye bath in three different forms (Figure 4.13):

- The bienolate form, which has very good water solubility but relatively low affinity for cotton.
- The monoenolate form, which has limited solubility but relatively high affinity for cotton.
- The non-ionised acid leuco form, which has little water solubility or affinity for cotton.

As shown in Figure 4.13, the monoenolate form results from the addition of alkali to the acid leuco indigo and, as pH increases with the further alkali addition, the bienolate form develops. The proportion of each species present at a given pH can be calculated using the following equations (Blackburn et al., 2009; Fromherz, 1964):

$$P_{\text{acid leuco indigo}} = \frac{1}{1 + 10^{(\text{pH} - \text{pK}_1)} + 10^{(2\text{pH} - \text{pK}_1 - \text{pK}_2)}}$$
$$P_{\text{Monoenolate form}} = \frac{1}{1 + 10^{(\text{pK}_1 - \text{pH})} + 10^{(\text{pH} - \text{pK}_2)}}$$
$$P_{\text{Bienolate form}} = \frac{1}{1 + 10^{(\text{pK}_1 + \text{pK}_2 - 2\text{pH})} + 10^{(\text{pK}_2 - \text{pH})}}$$

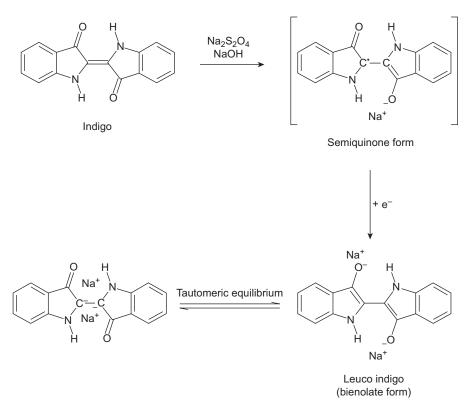
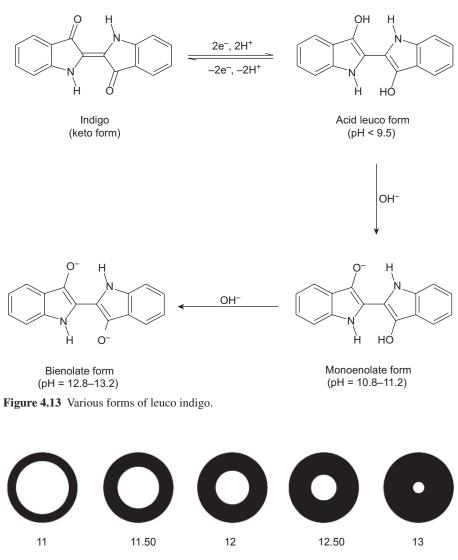


Figure 4.12 Mechanism of indigo reduction by sodium hydrosulphite.

where  $pK_1$  and  $pK_2$  represent the first and the second ionisation steps from nonionised acid leuco form to the monoenolate and bienolate forms, respectively.  $pK_1$ and  $pK_2$  values were determined by Etters et al., and were equal to 7.97 and 12.68, respectively (Etters, 1993b).

The monoenolate form of leuco indigo has a much higher affinity for cellulose than the bienolate form (Etters, 1995). Etters reported that the colour yield is greatest within a pH range of about 10.8–11.2, and it is within this pH range that the monoenolate form of indigo predominates (Etters, 1993a, 1995).

In practice, for denim yarn dyeing, when the pH of the indigo dyeing bath increases, the dye penetration increases. Consequently, the ring dyeing effect decreases (see Figure 4.14), and the shade becomes difficult for subsequent stone washing. Moreover, the shade becomes redder and brighter. However, when the pH of the dyeing bath decreases, the ring effect is accentuated, and the shade becomes easy for subsequent stone washing. It also becomes greener and duller (Paul and Naik, 1997b).



Dye bath pH

Figure 4.14 Effect of dye bath pH on ring dyeing.

## 4.5.3 Effect of sodium hydrosulphite

Sodium hydrosulphite or dithionite ( $Na_2S_2O_4$ ), in the presence of sodium hydroxide, is the reducing agent that is commonly used to prepare the leuco indigo solution for denim dyeing. It was reported that the reducing action of sodium hydrosulphite is complex (Broadbent, 2001). It depends upon the formation of the dithionite radicals

 $(SO_2^-)$  formed by breaking the weak bond between the two sulphur atoms in the dithionite as follows:

$$O_2S - SO_2^- \rightleftharpoons 2SO_2^-$$

The mechanism of the reduction of indigo by sodium hydrosulphite was described in the literature as a two-step process in which the formation of semiquinone radical is followed by a reduction of the radical to bienolate form (Figure 4.12; Zhou, 2001).

Sodium hydrosulphite gives an effective and rapid reduction of indigo. However, it has a low stability. It is extremely sensitive to atmospheric oxygen (Etters, 1989; Camacho et al., 1997). Moreover, the stability of its alkaline solutions reduces with the increase of temperature even in the absence of oxygen. So large amounts of hydrosulphite and sodium hydroxide are needed over the stoichiometric requirements of the reduction process (Vuorema, 2008). Besides, these large amounts of hydrosulphite that are needed become higher in summer than in winter.

Thus, this clearly shows that sodium hydrosulphite concentration plays an important role in the indigo reduction. The role of sodium hydrosulphite becomes more and more important, especially when operating a continuous indigo dyeing process of cotton yarns, because this reducing agent is employed not only to reduce indigo but also to preserve and stabilise the leuco indigo form in the dyeing bath and avoid its decomposition. So an excess of hydrosulphite is necessary to ensure that a complete reduction is reached and also to maintain leuco indigo in the dyeing bath. In the course of dyeing, the concentration of hydrosulphite in the dyeing bath must be controlled because it directly affects the shade of dyeing. Generally, there are three cases:

- The concentration of hydrosulphite is low whatever the dye bath pH is. In this situation, the indigo reduction is not complete. So the shade gets reddish and unfixed indigo is observed on the cotton surface.
- The concentration of hydrosulphite is high but the dye bath pH is low. In this situation, hydrosulphite is not able to achieve a complete reduction of indigo. Thus, the shade is reddish with a low penetration degree of indigo.
- Both the concentration of hydrosulphite and the dye bath pH are high. In this case, the degree of penetration of indigo is important. The shade gets lighter and bluer.

## 4.5.4 Effect of dye

In continuous indigo dyeing processes, the effect of dye depends on the form and the amount of the indigo pigment as well as the concentration of the leuco indigo present in the dyeing bath.

## 4.5.4.1 Effect of indigo pigment

At first, the effect of the indigo pigment intervenes in the reduction step. The reduction yield depends upon the size distribution of indigo particles as well as the habit of the

crystals in dispersion. The crystalline form affects the rate of reduction more than the size. However, in general, the rate of reduction is higher for finer particles due to the increase of the specific surface area.

On the other hand, the use of pre-reduced indigo avoids the need for a separate vatting stage during the indigo dyeing process. This leads obviously to rapid dyeing with minimum of dyeing effluents. Currently, several forms of indigo are available in the market in order to meet the industrial requirements for denim dyeing, such as:

- Indigo powders, supplied by Tianjin Green Chemical Co. (China).
- Indigo granules, supplied by Dystar (Germany), Bezema AG (Switzerland), Mastone Chemicals Co. (China) and Tianjin Green Chemical Co. (China).
- Indigo paste 20%, supplied by Tianjin Green Chemical Co. (China).
- Indigo paste 30%, supplied by Bann Química Ltda. (Brazil), Mastone Chemicals Co. (China) and Tianjin Green Chemical Co. (China).
- Indigo paste 40%, supplied by Bann Química Ltda. (Brazil) and Tianjin Green Chemical Co. (China).
- Pre-reduced indigo vat 30%, supplied by Bann Química Ltda. (Brazil).
- Pre-reduced indigo vat 40%, supplied by Dystar (Germany).

The effect of the indigo pigment intervenes also in the dyeing step. A high amount of indigo pigment in the dyeing bath leads to a fall of the dyeing fastnesses and the contrast of denim after wash down. Nevertheless, when the amount of indigo pigment decreases, the dyeing fastnesses are improved.

# 4.5.4.2 Effect of leuco indigo concentration

Increasing the leuco indigo concentration in the dyeing bath enhances the colour yield. However, a decrease in the leuco indigo concentration leads to a decrease of the colour yield.

# 4.5.5 Effect of immersion time

The longer the immersion time, the better will be the penetration degree and the higher the colour yield, but the lesser will be the ring dyeing effect. Consequently, the shade becomes easy to subsequently stone wash in this case.

# 4.5.6 Effect of number of dips

The increase of the number of dips in the dye baths leads to an increase of the colour yield.

# 4.6 Testing and quality control

# 4.6.1 Monitoring dye bath parameters

To achieve a continuous dyeing of cotton yarns with indigo in a reproducible way usually constitutes a complicated task. The reasons for errors and irreproducible dyeing are commonly related to the lack of control quality during the dyeing process. So it is vital to control dye bath parameters or at least the most important of them, which are indigo and hydrosulphite concentrations as well as the pH dye bath value. This control should be performed at least hourly, and a good dye bath circulation is indispensable when taking the representative liquor specimens. In case of any remarkable change, necessary precautions and corrections must be taken. Although the ability to maintain the values of these parameters at a constant level is undoubtedly a difficult task that requires a lot of experience and skills from dyers, the control of the indigo dyeing process minimises the large variations in dyeing quality and avoids tailing problems.

In this section, the principal techniques are presented that are used in continuous dyeing with indigo in order to control and manage the most important dyeing parameters.

## 4.6.1.1 Evaluation of pH

Acidimetric titration is not convenient for determining the pH of the dye baths. The pH of the dye baths is only determined with pH meters that are marketed for industrial use. In this procedure (BASF, 1996), the electrode is rinsed with distilled water before it is dipped in the dye bath sample and briefly agitated. The pH value can be recorded when the display on the pH meter has stabilised. If the measuring value of the electrodes fluctuates, the pH meter must usually be calibrated. For calibration purposes, two different buffer solutions are required. The first buffer solution has a pH of 7 whereas the second buffer solution should have a pH similar to that of the dye baths. A buffer solution of pH 12 is generally used by industrials. Besides, the electrodes of the pH meter must be replaced at intervals of no longer than 60 days. On the other hand, checking the pH of dyeing baths by online measurement is very advantageous because it offers a precise and reliable control.

#### 4.6.1.2 Sodium hydrosulphite concentration

Measurement of the redox potential represents an easy method of determining whether hydrosulphite exists in the dye bath, but it cannot provide any indication about its concentration. Currently, various methods are used to determine the hydrosulphite level in dye baths. The most important methods are iodine titration, potassium ferricyanide titration, titration by the Vatometer method and indigo carmine titration.

#### **lodine titration**

The main advantage of this volumetric titration method is its selectivity to dithionite anions. Upon addition of an excess of formaldehyde to the dye bath in the presence of acetic acid, only the dithionite anions react quantitatively to form complexes as follows (Kilroy, 1980):

$$S_2O_4^2 + 2HCHO + H_2O \rightarrow HCHOHSO_2^- + HCHOHSO_3^-$$

The obtained sulphinate is then titrated with a standard solution of iodine, as follows (Kilroy, 1980):

$$HCHOHSO_2^- + 2I_2 + H_2O \rightarrow HSO_4^- + HCHO + 4HI$$

This titration makes it possible to determinate the concentration of hydrosulphite. However, this method has many drawbacks, such as the relatively complicated procedure, the long time and effort that the experiment requires (response time of at least 60 min), the high cost and the low accuracy.

#### Potassium ferricyanide titration

The hexacyanoferrate (III) method (BASF, 1996) is a redox titration performed using potassium ferricyanide as the oxidising agent. The reaction involved is

$$S_2O_4^{2-} + 2[Fe(CN)_6]^{-3} + 4OH^- \rightarrow 2SO_3^{2-} + 2[Fe(CN)_6]^{-4} + 2H_2O^{-}$$

This method offers several advantages over the iodine titration method: rapidity and high precision. Furthermore, in addition to the reducing agent, it allows simultaneous measure of the leuco indigo concentration. In the presence of an excess of reducing agent, two end points are recorded with redox electrodes. The hydrosulphite content is shown by the first end point, whereas the leuco indigo content can be determined from the difference between the two end points. Titration must be performed in the absence of oxygen. The working electrode should periodically be dipped in a chromic sulphuric acid cleaning solution and a ZoBell's solution can be used for standardisation of the measuring instrument.

It is important to note that sulphide and sulphur dyes interfere with this method of titration, which means that the values recorded in the presence of these dyes are not correct.

#### Titration by the vatometer method

The vatometer method offers simplicity, speed and accuracy. The vatometer is a device that contains a rounded glass flask and a measuring tube (Figure 4.15). The principle of this method consists of dosing the hydrosulphite content of the dye bath sample (present in the glass flask; see Figure 4.15) with oxygen from the air,

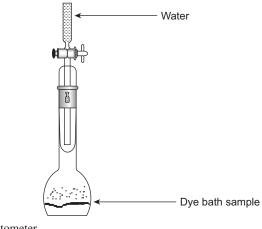


Figure 4.15 Vatometer.

exactly with the oxygen trapped in the vatometer flask. This oxygen reacts with hydrosulphite, which creates a low vacuum in the flask. So when the water is introduced to the measuring tube and the spigot of the measuring tube is opened, an amount of this water is pulled into the flask to equalise the pressure. This amount of water is equal to the amount of oxygen consumed. However, the oxygen consumption does not refer only to the hydrosulphite oxidation but also to the oxidation of leuco indigo. Thus, a second test in the presence of an excess of formaldehyde should be performed in the same manner as previously described. The oxygen consumed in this case refers only to the oxidation of indigo. The difference between the two obtained volumes of water corresponds to the amount of oxygen consumed by sodium hydrosulphite. This makes it possible to calculate the concentration of hydrosulphite in the dye bath.

#### Indigo carmine titration

This method is very rapid and cheap but not very precise. It consists of titrating the hydrosulphite content of the dye bath sample with an indigo carmine solution until the colour of the sample passes from blue to yellow. The yellow colour indicates that all the amount of hydrosulphite is consumed in the indigo carmine reduction. Titration must be carried out in the absence of oxygen. The determination of the amount of indigo carmine at the end point of titration allows us to determine the concentration of hydrosulphite.

#### Other methods

It can be seen that all of these methods of analysis of hydrosulphite are not continuous, which means that the control of the sodium hydrosulphite concentration cannot be done properly. Several trials of automating these methods (e.g. with titration equipment) resulted in only a limited success owing to the poisoning of the detection system (e.g. potentiometric electrodes) and blocking of the valves and the peristaltic pumps used for pumping the dye solution to the analysis cells (Westbroek and Kiekens, 2005).

From the successful continuous methods of analysis of hydrosulphite, we can cite the sensor system developed by Westbroek and Kiekens (2005). This sensor system is based on multistep chronoamperometry and it is used for online and inline measurement of the concentration of hydrosulphite in the indigo dyeing processes. The authors claimed that their method is characterised by high precision, accuracy and small response time (less than 0.5 s).

Enscada Company has recently presented a new automatic analyser for commercial use. This analyser is able to measure both the concentration of hydrosulphite and the concentration of leuco indigo. According to Enscada, this method offers various advantages:

- Rapidity (5–7 min for each analysis).
- No use of analytical grade reagents.
- · Sodium hydrosulphite and leuco indigo measurements are independent.
- Low cost of ownership.

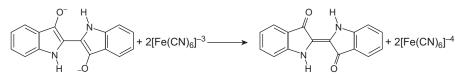


Figure 4.16 Redox titration of leuco indigo with hexacyanoferrate (III).

#### 4.6.1.3 Leuco indigo concentration

Some of the previous methods used for measuring the concentration of hydrosulphite can also be applied to determine the concentration of leuco indigo in dye baths. For example, the difference in standard potential of indigo and sodium hydrosulphite is about 150 mV. This allows the determination of both concentrations in the same titration by the hexacyanoferrate (III) method as explained previously (BASF, 1996). Redox titration of leuco indigo with hexacyanoferrate (III) is based on the equation given in Figure 4.16.

The sensor system developed by Westbroek and Kiekens (2005), which was described previously, is also able to simultaneously determine the concentration of hydrosulphite and the concentration of leuco indigo in dye baths. Since the absorption of the oxidised indigo to the electrode surface can disturb the measurement, multipulse potential steps were used to reduce the dye to its soluble form and to clean the surface. However, in the semi-continuous determination of leuco indigo concentration at -0.6V versus SCE, a small interference was observed due to the presence of hydrosulphite.

The automatic analyser commercialised by Enscada Company also permits the concentration of hydrosulphite and leuco indigo to be determined simultaneously. According to Enscada, this analyser covers the leuco indigo concentration range between 0 and  $30 \text{ gL}^{-1}$  and it provides very precise measurement even at low concentrations.

On the other hand, it is well known that leuco indigo is very sensitive to air and pH variation; the direct spectroscopic technique has not been successfully employed to determine the concentration of leuco indigo in the dye bath. This has encouraged researchers over the years to develop novel spectroscopic techniques in order to measure and monitor the leuco indigo concentration. At first one was suggested by BASF (BASF, 1996) for determining the concentration of leuco indigo in dye baths, which requires a lot of experience and effort to achieve better precision of results. This method involves the use of 1-methyl-2-pyrrolidone as solvent for the preparation of the calibration solutions and the dilution of the dye bath sample. This allows preventing the indigo skin formed on the surface of the coloured solution, which leads evidently to wrong results. The measurements were performed using a spectrometer at 408 nm, which represents the absorption maximum of the leuco indigo.

Sahin et al. (2004) reported a continuous spectroscopic method using a laser diode spectrometer that is coupled with a continuous dilution system for monitoring indigo concentrations. First, the principle of this method consists of pumping continuously the leuco indigo solution into a mixing cuvette, where it is diluted by a factor of 80 and oxidised to its initial form. Next, this solution is pumped into the sampling cell of the laser diode absorption spectrometer. The absorption measurements were carried out at 635 nm to measure the indigo absorption. Sahin et al. (2004) reported that this method is inexpensive, highly accurate and reliable. Furthermore, they claimed that there is no interference due to sulphur compounds present in the dye bath, which constitutes the main problem of the electrochemical titration methods.

Another method for monitoring indigo is flow injection analysis (FIA) (Merritt et al., 2001). FIA is a real-time analytical technique for determining the leuco indigo concentration in dye baths. The sample is introduced in FIA and diluted with five different reducing agents. The absorbance measurements are made at 406 nm (the maximum absorption of leuco indigo) by the fibre optic coupled spectrometer. Nevertheless, this method is very sensitive to atmospheric oxygen, and therefore the concentration of leuco indigo decreases as the reduced molecules come into contact with atmospheric oxygen and are oxidised. So, nitrogen gas must be continuously bubbled into the solution to prevent this oxidation of leuco indigo.

The extraction of indigo on yarns and fabrics was historically used to determine the amount of indigo in textiles. Various mediums were reported in the literature for extracting indigo from textiles such as pyridine (Zhou, 2001; Etters and Hou, 1991) and ferrous sulphate/triethanolamine/sodium hydroxide (Chong et al., 1995). Next, the concentration of indigo is determined spectroscopically after preparation of the calibration solutions. However, the extraction methods are especially applied in the research field because they are time consuming.

## 4.6.1.4 Temperature of the dye bath

The control of temperature is very important in the indigo dyeing processes because it affects significantly the rate of diffusion of leuco indigo in cotton fibres and consequently the quality of ring dyeing. Moreover, the temperature affects the pH and the hydrosulphite consumption. When the dyeing bath temperature varies, it becomes very difficult to achieve reproducible dyeing results. This is very observable with the change of temperature from cold weather to hot weather. So in order to avoid or minimise the effect of temperature on the performances of indigo dyeing, online measurements must be checked. Besides, the dyeing bath temperature in the hot season of the year should be taken as the controlled parameter for dye baths. According to that, the dye baths should be heated during the cold season.

## 4.6.2 Quality control of indigo dyed yarns

This control is obviously carried out after the dyeing step. In denim dyeing, it involves two levels: colourimetric control, which is related to the quality of the shade; and the control of the degree of the ring dyeing.

#### 4.6.2.1 Colourimetric shade control

After dyeing and drying, the colour of the dyed yarns can be checked visually or instrumentally. In fact, with many modern indigo dye ranges, the colour of the dyed

yarns is continuously monitored by colourimetric instruments, which are connected to the control systems of the indigo dye baths.

The most important colourimetric parameters used to control continuously the quality of the shade are the *CIELAB* coordinates  $L^*$ ,  $a^*$ ,  $b^*$ .  $L^*$  represents the degree of lightness. The attribute  $a^*$  indicates the degree of redness and greenness (when  $a^*$  increases, the redness of the sample increases, and vice versa). The attribute  $b^*$  indicates the degree of yellowness and blueness (when  $b^*$  increases, the yellowness increases, and vice versa). Each denim manufacturer has its own uncertainty intervals for these colourimetric parameters. Colour measurements are performed by specific spectrophotometers in which the nature of the illuminant and the angle of observation are fixed. Generally, the illuminant  $D_{65}$  and 10° observer are used by industrials. In this case, an automatic adjustment of the moisture is absolutely necessary.

The colour yield (*K/S*) can be also used as a colourimetric parameter to evaluate and control the quality of shade. The value of the colour yield is determined at  $\lambda_{max}$  according to the Kubelka–Munk equation (Kubelka, 1948, 1954):

$$\frac{K_{S}}{2R} = \frac{(1-R)^2}{2R} - \frac{(1-R_0)^2}{2R_0}$$

where R is the decimal fraction of the reflectance of dyed fabric,  $R_0$  is the decimal fraction of the reflectance of undyed yarn, K is the absorption coefficient and S is the scattering coefficient.

In some cases, when the colour yield is very high, the maximum absorption wavelength shifts and the evaluation of the quality of shade using the *K/S* value becomes incorrect. So many researchers suggest calculating the *Integ* value, which is determined according to the following equation (Xin et al., 2000; Derbyshire and Marshall, 1980):

Integ = 
$$\sum_{\lambda=400}^{700} \left[ \left( \frac{K}{S} \right)_{\lambda} E_{\lambda} \left( \overline{x_{\lambda}} + \overline{y_{\lambda}} + \overline{z_{\lambda}} \right) \right]$$

where  $\lambda$  represents the wavelength,  $E_{\lambda}$  is the spectral power distribution of the illuminant  $\overline{x_{\lambda}}$  and  $\overline{y_{\lambda}}$  and  $\overline{z_{\lambda}}$  are the standard observer functions. *Integ* is the integration of the Kubelka–Munk constant (*K/S*) weighted by spectral power distribution of the illuminant and the standard observer functions over the visible spectrum.

#### 4.6.2.2 Control of ring dyeing

Ring dyeing is characterised by the inner layer of fibres containing little to no indigo whereas the outer layer is highly pigmented. This characteristic is a desirable part of denim dyeing and produces the aesthetic high and low or uneven shade on the final product after garment washing. Furthermore, an efficient ring dyeing leads to a faster washing process.

During indigo dyeing, the degree of ring dyeing can be regulated by the pH of the dye bath or also by some pre-treatment steps that can be added during pre-scouring

such as caustification or mercerising. Typically pH 11 displays better ring dyeing, while pH 13 exhibits much greater penetration (see Figure 4.14). To control the ring dyeing property of indigo dyed yarns, analyses of yarn cross-section must be performed using a microscope or hand lens. The results of these analyses must be compared according to a reference sample (Paul and Naik, 1997b).

## 4.7 Future trends

Looking to the future, several actions will be undertaken in order to accelerate and succeed the ecological transition in the indigo dyeing processes. The principal aim of these actions is to produce sustainable and fashionable denim that fascinates more and more consumers. Among these actions, the most important ones are:

- The use of new chemical products and non-indigo dyes in conventional indigo dyeing processes that gives new fashion effects but minimises environmental impact.
- The development of clean indigo dyeing processes: electrochemical dyeing, dyeing by αhydroxycarbonyls, etc.

On the other hand, the dyeing of organic denim remains usually challenging for dyers because it is time consuming and needs to be carried out by highly skilled workers. This leads to a high processing cost, which prevents organic denim from currently being more popular. Many attempts have therefore recently been undertaken in order to develop novel green processes of organic denim dyeing that should be more efficient, more rapid, cheaper and easy to be applied.

## 4.8 Conclusion

Indigo dyeing usually remains the crucial step in the manufacturing process of denim fabric. The success of this key step determines closely the denim fabric qualities and therefore their market value. During the last century, various indigo dyeing processes were developed in order to produce denim fabrics that meet the requirements of consumers in terms of quality and price. From now on, the producers of denim fabrics will be faced with new kinds of market demands that will be more severe, especially in terms of costs. This will certainly require the development of innovative dyeing processes with indigo based on a synergy between technology, ecology and fashion trends. In this situation, the challenge faced by denim fabric producers, in the next decades, will be inevitably an eco-efficiency challenge. They should produce competitively priced denim fabrics using these innovative dyeing processes, which will need important investments in the research and development, the hiring of skilled and experienced employees, the maintaining of novel patents, the obtaining of standard certifications and eco-labels, etc and in the meantime acquiring a solid position in the world market.

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# Dyeing of denim yarns with non-indigo dyes

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# 5.1 Introduction

Since Levi Strauss started to commercialise waist overalls that eventually became jeans, blue has been the traditional colour for articles that were developed to meet the requirements of miners and other workers. The brown duck cotton that Levi Strauss also commercialised, parallel to trousers made of *serge de Nimes*, could be considered, to a certain extent, the ancestor of current colour denim fabrics (Downey, 2007). For decades, the only tone in the jeans was the standard indigo blue, which could be in different depths. Interest in incorporating dyes other than indigo to dye denim started in the early 1970s. Along with high demand for denim garments, with denim firmly established as a symbol of youth and rebellion, the oil crisis caused a lack of availability of indigo. Major denim producers confronted this by including black in one of the rinsing boxes after indigo impregnation to boost the depth and obtain darker indigo. This type of process would become eventually known as topping and was adopted for changing the colours and casts of indigo blues.

The fact that the denim was neither prewashed nor washed in garment form helped to make the presence of the sulphur black dyestuff optically undetectable. Interest in darker shades led to exploration of the possibilities of producing a true black denim, which began to be commercialised in the mid 1970s. Other colours (browns, greens and oranges) started to be offered by some brands in the United States. The first half of the 1980s saw denim achieve its current status of flexibility, innovation, multifunctionality and so forth. Although some stone wash treatments had already been performed in the mid 1970s, wash downs became a top fashion trend, in which blue denim was treated with chlorine to obtain a pale blue (sometimes even white) and with the introduction of mechanical abrasion treatments and cuts to produce 'destroyed' effects. Figure 5.1 shows the destroyed effect with aggressive and localised wash down.

The possibility of creating new effects and tones through wash down treatments created interest in changing the cast or even the colour of the denim fabric, thus amplifying the scope of obtainable looks. Along with the known topping of indigo, the possibility of dyeing the cotton warp while pre-scouring it for subsequent indigo dyeing helped create bottoming effects. Double colour contrasts were then easily obtainable. By the end of the 1980s and early 1990s, real colour denim (in a wide variety of tones) was available, mostly from European producers. Always considered premium denim, all important denim groups usually have two or three colour denim shades in their collections to show to potential customers their ability to produce these high quality articles.

Other options were explored in the 1990s to produce different, more brilliant shades and special new effects, such as steady colours. Hence, by modifying dyeing equipment in the required way, it was possible to use reactive dyes of different reactive groups, vat dyes and pigments and azoic colours for specific shades. The last one was sporadically used until it was banned owing to ecological considerations in the beginning of the 2000s.

Today denim is not only an all colour product, with blue and navy still the main tones; it is possible to find all shades in the collections of many denim producers and brands. New application possibilities for dyes and pigments in the form of paste or foam coatings have even further expanded the colour options and effects (making it possible to create double colour denim by coating the back face of the fabric). Nowadays, denim fashion is not just about colour effects. The touch and feel of denim in the form of fake leather, paper touch, oily rubber and many others keep denim a unique fabric for imaginative designers to express lifestyles and attitudes and to make every pair of jeans special for every person. This feeling is strengthened with daily use of the garment.

# 5.2 General considerations

Before explaining in detail current available options for dyeing denim warp with non-indigo dyes, it is important to know the basic technical, chemical and ecological aspects that have an important role in deciding the recipes and application procedures to be implemented when looking for a colour, cast or effect.

## 5.2.1 Technical aspects

As in continuous warp denim dyeing with indigo, mechanical conditions are critical in non-indigo dyes to obtain regular tones along the dyed batch as well as good reproducibility from lot to lot and good general performance. Every type of non-indigo dye to be used requires a specific set up to get the most out of the dyestuff or pigment used. Not all denim dye ranges are suitable for all applications and it is usual to design the machine anticipating the type of yarn, colours and dyeing conditions required for effects that will be visible only when the garment has been made up and washed.



Figure 5.1 Destroyed effect with aggressive wash down (© Archroma).

Whereas bottoming and topping of indigo with sulphur dyes can basically be done in the same range used for 100% indigo dyeing, in which only some minor mechanical modifications might be required, pure non-indigo dyes and pigments applications require specific set ups. There are basically three types for denim warp dyeing in continuous form: rope form, slasher and loop. The rope and slasher type ranges dye 95% of produced denim yarn worldwide. Differences among the three technologies can be summarised as follows.

# 5.2.1.1 Rope dyeing range

In this type of denim range, warp threads are extended along the range in the form of a rope. Yarn groups are composed of 300 or 400 ends forming ropes or cables. The total width of rope ranges is taken up by a number of ropes ranging between 12 and 48, depending on the width of the machine. The total number of ends, depending on the number of ropes, can range between 3,600 and 19,200. A dye box in the denim warp rope dyeing range is shown in Figure 5.2.

# 5.2.1.2 Slasher dyeing range

In this type of dyeing range, warp yarns are extended flat and separately and are arranged parallel to each other, with a millimetric gap between them in individual layers. The width of the range corresponds to the sum of all warp yarn. The number of yarns per beam ranges between 300 and 750, whereas the total number of threads that make up the warp yarn vary between 3,500 and 9,500, according to the thickness and diameter of the yarn, the type of warping range and the denim fabric design in the weaving process. A general view of a slasher warp dyeing unit is shown in Figure 5.3.

# 5.2.1.3 Loop dye range

The system for preparing beams as well as circulating yarn in the loop range is the same as in the slasher range, which means that parallel threads enter and



Figure 5.2 View of a dye box in a rope dyeing range (© Archroma).



**Figure 5.3** General view of a slasher dyeing range (Picture: Archroma). Indigo flow by Master S.a.s., Italy.



**Figure 5.4** General view of a Looptex<sup>®</sup> dyeing range (Picture: Archroma). Looptex.

circulate in one layer. In the loop range, as opposed to the slasher range, yarn does not circulate along a machine composed of various boxes. After the impregnation with a solution of dyestuff and squeeze, the yarn passes through a closed circuit to reenter the single (sometimes double) vat. This lap of yarn passes as many times as required through the single dyestuff impregnation vat. The number of times the lap passes through the same indigo vat is determined by various factors: type of yarn used, number of strands of this yarn, number of strands of yarn forming the warp and desired intensity. A general view of a Looptex<sup>®</sup> warp dyeing unit is shown in Figure 5.4.

## 5.2.2 Chemical aspects

Some chemical issues should be considered when dyeing denim warp with non-indigo dyes. With some specificity that will be discussed in forthcoming sections, sulphur dyes are based on a chemical balance of reduction–oxidation similar to that of indigo. That makes it

possible, in general, for sulphurs and indigo to be dyed in-line, which produces toppings or bottomings by sequentially dyeing sulphurs first or after indigo in the same range.

Other types of dyes such as reactives are generally unstable under chemical reduction conditions. This means that it is impossible to dye indigo and reactive dyes in-line, as mentioned for sulphurs. Reactive dyes are then normally used for pure colour denim. Indigo belongs to the generic family of vat dyes. Its actual Colour Index name is C.I. Vat Blue 1. This does not mean that the possibility of in-line dyeing vat plus indigo is automatic. There are different subfamilies in the vat dye groups, depending on their stability in reduction and affinity for cellulose in reductive conditions.

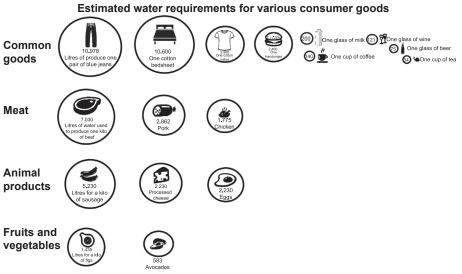
Other common products used for non-indigo dyeing of denim warp, such as pigments, require special dyeing conditions because they do not have direct affinity for the cellulose and are physically left over the fibre for fixation with binders and special resins. Owing to drawbacks in their continuous application, direct dyes, which are extremely unusual for dyeing denim warp, also have high sensitivity to reducing conditions that are required for indigo dyeing, and are hence not recommended for bottoming and topping effects and basically are not used for pure colour denim.

#### 5.2.3 Ecological aspects

A new factor to be considered, which has become critical in modern textile production and especially in denim dyeing, is sustainability. This is an important part of the equation when deciding on the types of dyes, chemicals and processes along the line to obtaining the final denim garment ready for the shop window. The use of water is particularly of concern because, among other studies on the topic, The National Geographic Magazine<sup>®</sup> published their Water Issue in 2010. Within an exhaustive analysis of water required to produce different materials for human consumption and use, National Geographic claimed that the production of a pair of jeans requires 11,000 L of water if the entire production frame is considered. Figure 5.5 shows a scheme of the water requirements for different consumer goods.

On the other hand, some relevant non-governmental organisations have also carried out intensive analytical work on resources required for textile and denim production and generated global concern about how these garments are produced. Figure 5.6 shows the ZDHC visual for the Zero Discharge Hazardous Chemicals campaign.

Brands and retailers, denim producers and chemical companies are facing this important challenge by introducing innovative solutions throughout the textile chain. Here it is possible to start from the use of fibres that require less water to be produced, maybe from natural polymers, continue with the adoption of dyes and chemicals with the highest eco-profiles, and work with application processes in which the use of water is controlled and reduced through new mechanical solutions in the design of dyeing and washing boxes and water reuse and recycling procedures. This low water and



**Figure 5.5** Water requirements for different consumer goods. Scheme © Archroma; graphics from Shutterstock; National Geographic, April 2010.



Figure 5.6 Zero Discharge Hazardous Chemicals campaign. http://www.roadmaptozero.com.

general resource consumption can be complemented with wash down treatments in which the use of water is also minimised, as, for instance, ozone treatment of the use of laser beams for localised effects.

# 5.3 Options for non-indigo dyeing

Based on an analysis of denim production carried out in 2012 (PL Special Dyes, Archroma), the percentage of different dyes used to obtain the colour palette is shown in Figure 5.7.

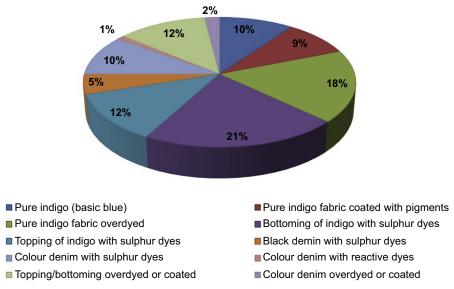


Figure 5.7 Percentage shares of different types of denim (© Archroma).

- Pure indigo (basic blue): 10.0%.
- Pure indigo fabric coated with pigments: 9.0%.
- Pure indigo fabric overdyed: 18.0%.
- Bottoming of indigo with sulphur dyes: 21.0%.
- Topping of indigo with sulphur dyes: 12.0%.
- Black denim with sulphur dyes: 5.0%.
- Colour denim with sulphur dyes: 10 0%.
- Colour denim with reactive dyes: 1.0%.
- Topping/bottoming overdyed or coated: 12.0%.
- Colour denim overdyed or coated: 2.0%.

Other products such as pigments are currently used in small proportions for straight dyeing of denim warp. From these detailed data, it can be seen that the families of dyes used more or less in proportion are sulphur and reactive dyes. Pigments are used to coat woven material either in paste or foam forms. Vat dyes are currently seldom used and direct dyes have never been considered a real option for long production runs.

## 5.3.1 Sulphur dyes

Chemical News Magazine, in October 1874, announced the 'New Dyes of Messrs. Croissant and Bretonniére from Laval (France), comprising all shades of brown, yellow and grey, some tints of lilac, greys and violets, also a colour very nearly approaching black ...' and considered them to be 'specially suited for fashion colours (*Modefarben*)' (Chemical News and Journal of Industrial Science (1874:30)).

Sulphur dyes are one of the first families of dyes developed by synthesis and probably the oldest still in wide use. They are characterised by a low dyeing yield and good light, washing and cross dyeing fastness and are adaptable to different dyeing conditions (Shankarling et al., 1996). Although some relatively brilliant elements (red and green) are currently available, the shade palette of sulphur dyes is composed mostly of brown, olives, blues and navies and other dull shades. A special element owing to its global importance is black (C.I. Sulphur Black 1), with an estimated yearly sale of 120,000 tons (powder equivalent) (PL Special Dyes, Archroma 2012).

Once considered to be a range of dyes of unpleasant applications, modification of dyestuff formulations, reduction to a minimum of the proportion of sulphide derivatives in the dyestuff itself, and adoption of glucosides as reducing agents for their application have allowed sulphur dyes to be considered completely safe and environmentally friendly (Teli et al., 2001).

In addition, new application processes exist such as the 'pad-sizing/ox' for denim, in which the dyestuff applied to the yarn is fixed in the same sizing box without the need for intermediate washing off of unfixed product, allowing water savings higher than 90% compared with standard denim dyeing based on indigo (PL Special Dyes, Archroma 2012).

## 5.3.1.1 Chemistry of sulphur dyes

Sulphur dyes are so named because they contain the element, however, it is in a completely different state to what is found in direct dyes such as thiazoles. According to A. Green (Discussion on Theories of Dyeing, 1918), the difference between other dyes containing sulphur and real sulphur dyes is that in the latter the sulphur atoms form a chain.

In many aspects sulphur dyes are similar to substantive dyes, and in other aspects, they are like vat dyes. Similar to substantive dyestuffs, they dye cellulosic fibres directly when reduced. On the other hand, like vat dyestuffs, they are insoluble in water (or slightly in alkaline solutions) when in their oxidised form. Even though it is not yet well defined, the oxidation–reduction of a sulphur dye molecule may be depicted as shown in Figure 5.8.

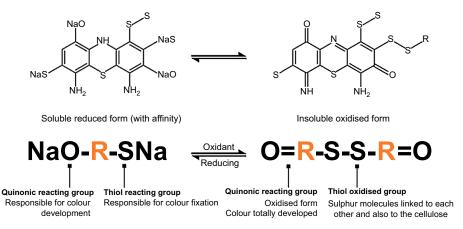


Figure 5.8 Oxidation-reduction of C.I. Sulphur Black 1 molecule (© Archroma).

These molecules are often long and contain few solubilising groups. As in the case of indigo, sulphur dyestuffs are insoluble in their pigmented form, which is their oxidised state. Sulphur dyestuffs transform into their soluble pre-reduced form when reacting with reducing agents, normally in an alkaline medium.

The application of these dyestuffs to cellulose fibres is thus based on the oxidationreduction balance of their molecules. Contrary to indigo, which requires high energy for its reduction and becomes completely oxidised just by air passage (skyings), sulphur dyes normally require mild reducing conditions and strong chemical oxidation by impregnating the dyed yarn in a solution with some oxidising agent. In the oxidising bath, the dye not only returns to its original insoluble chemical form, it becomes fixed to the fibre. The type of fixation of the sulphur dyes and the cellulose is based on secondary types of links such as hydrogen bonds and van der Waals forces. The large size of the formed molecules, which have a polymeric character, and therefore the high number of bonds of dye to cellulose explain the good general fastness that sulphur dyes possess (Cegarra et al., 1992; Shankarling et al., 1997).

## 5.3.1.2 Technical features

The substantivity of sulphur dyes makes it possible to reach deep shades with relatively short impregnation times. Usually one or two dye bath boxes are required to obtain the desired strength, which means an actual dye bath–fibre contact time of 4–10 s. This allows one to set up very compact processes with a short number of application boxes.

Bottoming or topping processes are hence possible because the same range section used for the pre-wetting (consisting usually of four boxes) can be used to dye the yarn before the indigo, bottoming, or the final washing off section of the range (also consisting of four to five boxes in standard ranges) can be used for the topping and no important range modifications are required.

In the case of pure colour or black denim, the dyeing conditions required for the dyestuff (alkalinity, reduction, presence of dispersing and wetting agents and high temperatures) allow the possibility of simultaneously scouring and dyeing the cotton, increasing its hydrophilicity and improving the evenness of the colour along and across the dyeing and preparing the cotton for eventual overdyeing or after treatments. Sulphur dyes are not based in a trichrome concept like other dyestuff families. The recipes should be defined by selecting one basic element and adjusting to the final desired colour with suitable shading elements.

#### 5.3.1.3 General principles of application

In general, the application process of sulphur dyes in denim is simple. After impregnation of the yarn in a dye bath containing the required auxiliaries to ensure stable conditions throughout dyeing, it is usually washed off and the dye is fixed by means of oxidation with a suitable chemical. The most important parameters in dyeing and oxidation are:

**Dyeing conditions** Conditions of the impregnation dye bath: Temperature, pH, degree of reduction (mV), dye bath level control and feeding solution (concentration and rate).

**Oxidation conditions:** Temperature, pH, bath level control and feeding of oxidant solution (concentration and rate). All specified conditions must be kept constant throughout the dyeing of the complete set. It is also necessary to keep mechanical conditions stable. One important factor to keep in mind when dyeing denim warp is that in many cases, a processing problem in the yarn is perceptible only when the final garment has been made up and washed down, when it is too late to think about potential corrective actions.

**Affinity factor** As already mentioned, in a reduced form, sulphur dyes have high dyeing capacity (build up) compared with indigo; this is similar to direct (substantive) dyes. According to Cegarra (The Dyeing of Textile Materials, 1981), chemically speaking, the affinity is an intrinsic property of matter by virtue of which a body tends to react with another. Considering the dye bath as a chemical system, the reduction in absolute value of a chemical potential of the system is the measurement of the driving force of the reaction: for example, of the affinity.

This variation in chemical potential is commonly denominated as the affinity factor and corresponds to the amount of additional dyestuff that in given conditions will be attracted by the fibre, compared with what it is taken purely because of mechanical reasons, such as the pick up or impregnation rate. Affinity factors have a value of 1 as the starting reference if the dyestuff has no affinity for cellulose at all, and increases depending on the degree of attraction. Hence, an affinity factor of 1.20 means that under given dyeing conditions and a starting concentration of dye, 20% more of dyestuff will be taken up by the cellulose if only the pick up is considered. This factor is basic for calculating the concentration of dyestuff in the feeding solution that is dosed at a calculated rate, which has to be the right one required to keep the level constant in the dye bath in all impregnation boxes.

If this affinity factor is not considered, problems such as the tailing effect will likely appear. This consists of a gradual reduction in colour strength during the initial part of the dyeing until a certain equilibrium is reached. From this point, the depth will stay constant because the dyeing system has been gradually changing until the point where the feeding solution (initially calculated to contain the same concentration of dye as the starting dye bath) has become relatively stronger with regard to the weakened dye bath, enough to compensate for the actual amount of dyestuff actually taken up by the fibre. Figure 5.9 shows a graphic representation of the tailing effect according to the Marshall equation (Diresul RDT Sulphur Dyes in Pre-reduced Form, 2009). The affinity factor depends on several parameters:

- Specific dyestuff family.
- · Concentration of dyestuff.
- Temperature.
- Volume of dye bath.
- Speed.
- Special treatments before dyeing.

**Migration capacity** Compared with indigo, the stability of the reduced form of sulphur dyes is higher. This means that the dye can maintain solubility over a longer time so it has a higher capacity of diffusion to the core of the fibre once impregnation

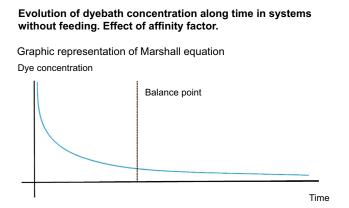


Figure 5.9 Representation of the tailing effect by the Marshall equation (© Archroma).

has taken place. Conditions when dyeing with sulphur dyes can be modified so that different degrees of migration and thus ring effects are possible. Factors that have an influence on the diffusion capacity of the sulphur dyes are:

- Degree of reduction in the dye bath: Sulphur dyes maintain a high solubility only when the redox potential (degree of reduction) in the dye bath is sufficient. In general terms, this is fixed in the range of -600/-700 mV.
- Alkalinity in the dye bath: Sulphur dyes are usually applied in the presence of reducing conditions working at an alkaline pH. The average working pH when using sulphur dyes is 11.5–12.5.
- Preparation of the dyed material and special pretreatments: The removal of impurities from cotton and the subsequent increase in its hydrophilicity is a key factor for good migration of the dye solution to the core of the fibre.
- Special after impregnation processes: As in other continuous processes for dyeing woven materials, treatment of the dyed yarn with saturated steam accelerates the migration of the dyestuff to the core of the fibre. This type of treatment takes place in a steamer unit, where the chamber is full of saturated steam at 102–104 °C and 99% humidity.
- Presence of cations in water or dyed material: Having the sulphur dyes in reduced form a strong anionic character it is important to avoid the presence of cations, especially metallic ones that can be present in the used water or directly on cotton fibre, such as Ca and Mg.
- Wet on wet applications: Wet on wet applications, when referring to denim, consist of a sequence of processes in which the fabric is first treated in a bath (either pretreatment or dyeing) and goes into a second bath with no intermediate drying. This material, wet with solution A or water, is impregnated with solution B. This type of process is usual to obtain low penetrated dyeing in the ring dyeing style of indigo, as the water/solution applied in the first instance, and still remaining in the core of the fibre, blocks the migration of the second solution (normally a dye bath), forcing the dyestuff to stay on the surface.

**Recipes for sulphur dyes** A general recipe for dyeing with sulphur dyestuffs should be designed in a way that considers all of the previously mentioned critical aspects. Hence, the dyestuff has to be under the right reducing conditions and its

dyeing behaviour should not be affected by the presence of impurities in the cotton affecting hydrophilicity or chemical species that may affect dyestuff stability or performance. The following products are thus required (Global Product Line Special Dyes, 2007):

- Dyestuff.
- Reducing agent.
- Alkali.
- Wetting agent.
- Dispersing/sequestering agent.

The second part of the application process of a sulphur dyestuff, as already mentioned, is fixation and final shade development by means of an oxidation treatment. For this, the following chemicals are required:

- Oxidant agent.
- Chemical to adjust the required pH: an organic acid (usually acetic acid) for acidic conditions and sodium carbonate for alkaline conditions.
- Additional after treatments to improve fastness may be carried out, normally by applying a cationic fixing agent as the last step in the actual dyeing process.

## 5.3.1.4 Application procedures

Each application process of a sulphur dyestuff must be adapted to the mechanical conditions and desired effect. The large number of factors with an influence on the final outcome of the dyeing makes it impossible to give specific recommendations. The general recipes and conditions mentioned here are only informative and cannot be extrapolated to all cases.

## Black denim

The stability of sulphur black (C.I. Sulphur Black 1) under all kinds of dyeing conditions, including processes involving simultaneous caustification and dyeing, is unique. It can be basically applied in any type of available equipment and with a wide variety of processes for different effects.

Two standard processes of sulphur black are available, with two different options for each, depending on the degree of fibre penetration (ring effect):

- · Caustisised (mercerised) black denim.
  - Solid dyeing.
  - Ring dyeing.
- Non-caustisised (mercerised) black denim.
  - Solid dyeing.
  - Ring dyeing.

The type of dyeing effect obtainable for each option is depicted in Figure 5.10 (Global Product Line Special Dyes, 2007).

**Mercerised black denim** The processes of caustisising/mercerising and subsequent dyeing are used to achieve high colour intensity by increasing the hydration capacity of the cotton fibre. When the dyestuff is applied in the same bath, under suitable

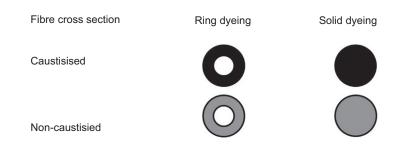


Figure 5.10 Fibre cross section of different dyeing methods (© Archroma).

wetting conditions, the intention is to obtain solid dyeing for a non-fading look. This effect is normally called 'mercerised solid' denim and the machine set up and general conditions of application are detailed in Figure 5.11 (Diresul RDT Sulphur Dyes in Pre-reduced Form, 2009).

- A. Simultaneous caustification and dyeing.
- B. Washing off.
- C. Neutralisation/oxidation.
- D. Rinsing.

The degree of diffusion in the fibre can be increased by a steaming step after the dye bath impregnation. This opens more the fibre micropores used by the dye bath for migration, and thus deeper and more penetrated dyeings can be reached. Black is the only colour dyed this way. The reason is the high stability of C.I. Sulphur Black 1 in strong alkaline solutions, when the high alkali concentrations help to maintain and stabilise the reduction of the dyestuff.

A more popular type of caustisised/mercerised black denim is the so-called mercerised ring, which is obtained by impregnating the dye in wet on wet conditions after a previous caustification/mercerisation step and subsequent washing off of the excess of alkali from the fibre. This wet on wet application produces a saturation of water in the core of the fibre to be dyed that acts as a barrier for the dye solution eventually impregnated, impeding its diffusion and creating a film of saturated dye solution around the fibre (Figure 5.11).

- A. Caustification.
- B. Rinsing.
- C. Dyeing (one to three boxes).
- D. Washing off.
- E. Neutralisation/oxidation.
- F. Rinsing.

This mercerised ring effect is the base for the salt and pepper look obtained by a wash down treatment of the made up garment that removes some superficially fixed dyestuff by friction, exposing the white core of the fibre. A cross section view of fibres with a ring dyeing effect is shown in Figure 5.12.

Other colours have become popular for the salt and pepper effect in other tones, such as browns and greens. Because the dyestuff is applied under standard dyeing conditions, with no simultaneous caustisising/dyeing, all sulphur dyes are suitable for the mercerised ring effect.

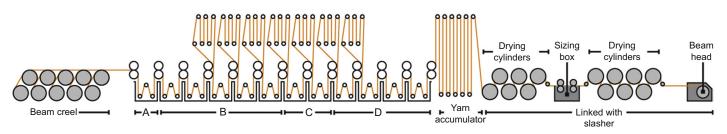


Figure 5.11 Dyeing range for non mercerised solid with sulphur black (© Archroma).



Figure 5.12 Cross section view of fibres with ring dyeing effect (© Archroma).

**Non-mercerised black denim** Non-mercerised black denim was the first type of black denim to appear on the market. However, currently it is not common as a straight colour because the achievable blacks are limited in depth, and normally only a dark grey can be reached. As in the case of the mercerised black denim, the process and dyeing conditions can be modified to adjust the level of ring/solid effect desired. The options are then:

- Dyeing crude/raw yarn with sulphur black directly in the first preparation or pre-wetting vat. The process in question is at a technical level called the dry/wet process because the yarn enters the dye bath without undergoing a previous wetting treatment. Figure 5.13 shows the machine set up and process sequence for non-mercerised solid dyeing with sulphur black.
  - A. Dyeing.
  - B. Washing off.
  - C. Neutralisation/oxidation.
  - D. Rinsing.
- Applying sulphur black to a yarn that was presoaked or partially scoured in the first vat for a wet on wet process, because the yarn is already treated in the first box. Then the process sequence can be as follows (Figure 5.13):
  - A. Pre-wetting.
  - B. Rinsing.
  - C. Dyeing (one to three boxes).
  - D. Washing off.
  - E. Neutralisation/oxidation.
  - F. Rinsing.

#### Colour denim

The denomination 'colour denim' is usually applied to all denim dyed on a shade that is neither blue nor black and is considered a high end type of article. In this case, it is difficult to control the dyeing parameters in terms of depth and shade consistency, unlike in standard indigo or black. This is because the dyes are normally used at

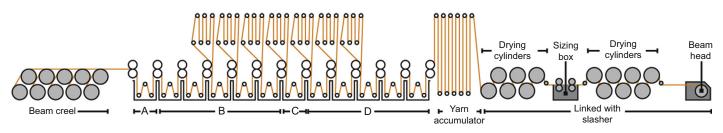


Figure 5.13 Dyeing range for non mercerised solid with sulphur black (© Archroma).

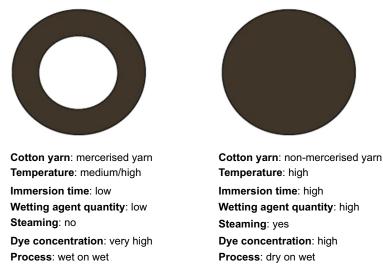


Figure 5.14 Fibre cross section of solid and ring dyeing (© Archroma).

concentrations not appropriate for fibre saturation (as usually happens in black denim) and are more sensitive to reduction–oxidation conditions and other dyeing parameters.

As in the black denim, mercerised and non-mercerised processes are possible, with either a ring or solid effect. A representation of cross sections of fibres showing the differences between solid and ring dyeing is shown in Figure 5.14.

**Mercerised colour denim** When considering mercerised/solid dyeing, only a few dyes other than black are stable under the strong alkaline conditions of the caustisising bath, so previous tests are required to confirm the appropriate element to be used as well as actual application conditions. The mercerised ring effect is more popular. Caustification/mercerisation pretreatment of the yarn produces bright final colours and nice colour contrasts. On the other hand, the feeding solution requires a high affinity factor because the dyestuff has a much higher substantivity for mercerised cotton.

**Non-mercerised colour denim** Also as in black denim, the dry on wet process (direct impregnation of the dye solution of raw cotton warp) is much more standard than the wet on wet process and is used especially for fine qualities of yarn that will not stand a pre-mercerisation process. Nevertheless, the wet on wet process is important when used as a topping of indigo.

### Bottoming of indigo

**Principle of the process** The bottoming of indigo consists of dyeing the yarn with a sulphur dyestuff for eventual dyeing with indigo. In this way, it is possible to change the cast of the indigo to any desired tone. Depending on the shade of the sulphur dye used, it is possible to modify the indigo cast to be 'dirty', 'bright', 'greenish' or 'reddish'. With a wet on wet process, the cross section of the final dyed fibre would look as shown in Figure 5.15 (Diresul RDT Sulphur Dyes in Pre-reduced Form, 2009).



Cotton yarn: non-mercerised yarn Temperature: high Immersion time: long Wetting agent quantity: high Steaming: recommended Dye concentration: medium/high

Yellow sulphur dye Diresul<sup>®</sup> RDT liq ● Interface indigo - yellow sulphur dye Diresul<sup>®</sup> RDT liq ● Indigo
 Figure 5.15 Representation of fibre cross section in indigo-bottoming (© Archroma).

The dyestuff used in the bottoming bath has saturated the fibre and prevented migration of the indigo, leaving a ring effect where the core of the fibre is not white. On the other hand, the colourimetric addition of the shade of the sulphur dyestuff and that of the indigo has modified its colour, so it is not the classical standard pure blue. As a general guide, the tones of the indigo can be modified by using sulphur dyes in bottoming in the following way:

- Black dull blue and navy.
- Yellow and olive greenish cast.
- Yellow brown and orange dirty cast.
- Red, reddish brown and burgundy reddish cast.
- Brilliant green and greenish blue bright cast.
- Reddish blue and navy deep blue cast.

**Application process** The bottoming of the indigo is the pre-wetting of the yarns, but with a coloured dye solution. Once the yarn has been impregnated with the bottoming dye bath, a short skying takes place even though it is also usual to proceed to a steaming step if the equipment integrates with a steamer chamber. This secures complete diffusion of the dyestuff in the fibre and its saturation. Before the indigo impregnations, the unfixed dye is washed off in two to three washing boxes before entering the first box of indigo and continuing with the process as usual for this dye. The final section of the range is used to remove the unfixed indigo. Mild oxidation with hydrogen peroxide at acid conditions is possible, to completely fix the sulphur dyestuff that remains in the core of the dyed fibre. The process continues with the standard final drying, sizing, etc. Figure 5.16 shows the diagram of a machine

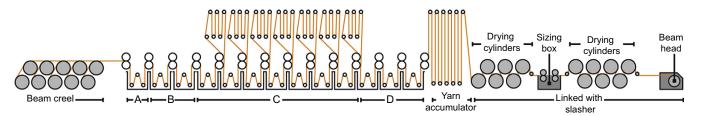


Figure 5.16 Dyeing range for bottoming of indigo with sulphur dyes (© Archroma).

set up for bottoming of indigo dyeing with sulphur dyestuff (Diresul RDT Sulphur Dyes in Pre-reduced Form, 2009).

- A. Sulphur dyeing.
- B. Washing off.
- C. Indigo dyeing.
- D. Washing off. It is also possible to wash off followed by oxidation and final rinsing.

Standard ranges for applying bottoming of indigo are those denominated slasher. This type of range minimises the risk of unevenness and streakiness in the final woven fabric that may happen in rope ranges.

#### Topping of indigo

**Principle of the process** In indigo topping the sulphur dyestuff is applied after the sequence of indigo dyeing has been completed, so the yarn is coloured blue and is wet. This impregnation normally takes place once some of the unfixed indigo has been removed in one to two rinsing boxes. As the fibre is overdyed wet on wet, diffusion of the sulphur dyestuff is blocked by the presence of the previously applied solution. In the case of conventional indigo dyeing this means that the core of the fibre is still natural white and that the sulphur dyestuff applied will combine with the indigo to produce a new shade. Similar casts can be obtained as explained in the previous section, but the wash down look of the obtained denim will be distinctly different because some white core will be exposed. The typical fibre cross section of the topping of indigo dyed yarn will look as shown in Figure 5.17 (Diresul RDT Sulphur Dyes in Pre-reduced Form, 2009).

A three colour effect is perceptible. The white core has been covered by sulphur dyestuff that managed to migrate more to the core of the fibre than the indigo, whereas the tone of this dye has been altered by its combination with the sulphur dye.



Cotton yarn: indigo dyed yarn Temperature: high Immersion time: long Wetting agent quantity: high Steaming: not required/optional Dye concentration: high

Yellow sulphur dye Diresul<sup>®</sup> RDT liq Interface indigo - yellow sulphur dye Diresul<sup>®</sup> RDT liq Indigo Figure 5.17 Representation of fibre cross section in indigo-topping (© Archroma). **Application process** Application of sulphur dye in a topping process is also done at standard conditions of reduction and alkali. It is usual to increase the temperature of application and use a wetting agent to increase the absorption factor of the sulphur dye bath by the indigo dyed yarn, increasing the depth and enhancing the three colour effect mentioned previously. In ranges with several boxes (five to six) after the indigo application section, it is possible to achieve complete sulphur dyeing as defined, including oxidation and final rinse. In more basic ranges, normally with three boxes, sulphur dyeing takes place in the first box after the indigo application section, with a final two washing off boxes and no oxidation. The machine set up details of general sulphur topping of indigo can be seen in Figure 5.18 (Diresul RDT Sulphur Dyes in Pre-reduced Form, 2009).

- A. Pre-wetting.
- B. Rinsing.
- C. Indigo dyeing.
- D. Washing off.
- E. Sulphur dyeing.
- F. Washing off. It is also possible to wash off followed by oxidation and final rinsing.

After washing off and drying, the process continues as usual with direct sizing or, if the yarn has been dyed in rope form, to rebeaming in preparation for sizing. Both slasher and rope denim dyeing ranges are in principle suitable for a topping of indigo process. In the case of the rope, the different threads composing each rope have been separating from each other, and so become a kind of slasher after the several paddings and squeezings required for indigo so that the risk of marks, unevenness or streakiness is minimised.

#### Special applications: Advanced Denim

As it is today, the textile industry consumes a huge quantity of water. Here the problem is double: in some steps of the process to convert fibre into a final article, water is required to dissolve and apply chemicals, and eventually to remove those that are unfixed or not required for subsequent treatments. In this sense, the operations of pretreatment, dyeing and finishing of the fibres and fabrics are critical. The World Bank (2008) estimates that 20% of industrial pollution comes from these three processes.

The water required for each type of article depends greatly on the number of steps required for its production. National Geographic made an estimation of the litres required for whole processing of common items used every day, including some basic textiles, from obtaining fibre until the article is ready for final use. Denim is on top of the pyramid of water consuming textiles, with a total volume of approximately 11,000 L per pair of jeans.

**Water in the denim industry** Special efforts are being made in the denim industry to reduce the amount of water required, starting from the production of cotton itself, through different means such as the Best Cotton Initiative, the use of recycled fibres or the adoption of artificial fibres from natural polymers. The same is valid for methods used to obtain final effects in jeans. Options include new generation enzymes to replace traditional stone wash or sandblasting wash downs and the use of technologies

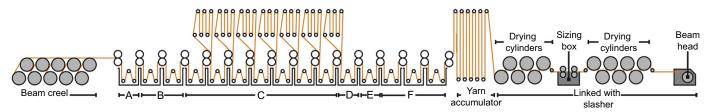


Figure 5.18 Dyeing range for topping of indigo with sulphur dyes (© Archroma).

based on ozone or laser beams to replace chemicals such as sodium hypochlorite or potassium permanganate for localised contrast effects, thus saving water and preventing the contamination of effluents with hazardous chemicals.

Nevertheless, the part involving colouring the warp, which is the base for the desired depth, cast and final contrast effects, still mainly depends on traditional dyeing technologies involving the use of indigo and associated chemicals such as sodium hydrosulphite. The total volume of water required to dye and remove unfixed dyestuff requires volumes of water between 15 and 25 L/kg for dyes in a slasher denim range.

**Applications for water saving** Under standard conditions, after dyeing the warp in the denim range, rinsing off is carried out to remove unfixed dyestuff before it is fixed with the use of an oxidant agent. However, there is a particularity in sulphur dyes that allows one to skip rinsing before oxidation. It is possible to completely insolubilise the dyestuff to a stable form by using a cationic fixing agent. In this way, after impregnation with the dye bath and with no intermediate rinsing, an immediate cationic treatment can be carried out. This is possible owing to the presence of thiol groups in the basic molecule of a sulphur dye. Figure 5.19 shows the functional groups in a C.I. Sulphur Black 1 molecule.

Because of the ionic character of the thiol group in the dyestuffs, a strong ionic bond is formed with a bi-reactive cationic agent. Thus there are two types of dye cationic compound forms:

CEL – Dye – Cationic agent – Dye – CEL – Cationic agent – Dye – Cationic agent –

Unfixed dye, normally in the surface of the fibre, stays in a stable insoluble form.

Dye - Cationic agent - Dye -

**Advanced Denim concept** Based on the chemical features of the sulphur dyes, the company Archroma has developed innovative application systems to reduce the

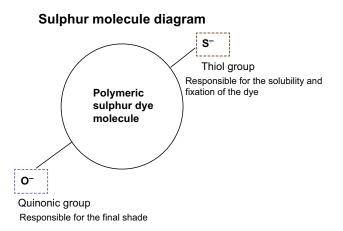


Figure 5.19 Functional groups in C.I. Sulphur Black 1 molecule (© Archroma).

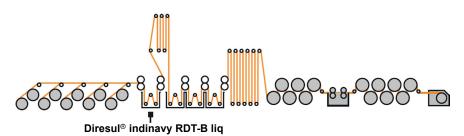


Figure 5.20 Dyeing range for Denim Ox process (© Archroma).

impact on the environment of producing denim fabric. The Advanced Denim concept is intended to fulfil three critical requirements in the modern denim industry:

- · New options for special effects.
- · Increased performance in terms of fastness.
- · Cleaner dyes and chemicals and more sustainable application processes.

Two new processes have been introduced so far for denim warp dyeing within the umbrella of Advanced Denim:

- Denim Ox.
- Pad-sizing/ox.

*Denim Ox process*. Based on the previous explanations, it is possible to develop a simple process in which no washing off of unfixed dyestuff is required before fixation. This process is usually called Denim Ox and its application steps are as follows:

- · Impregnation of fibre with dye solution containing reducing agent, alkali and auxiliaries.
- Short air oxidation (skying).
- Fixation bath containing an oxidant agent and a cationic fixing agent. The pH is adjusted to the type of oxidant product, normally acidic (pH 4–5).

A simple scheme of the Denim Ox process is shown in Figure 5.20.

*Pad-sizing/ox process*. Preparation of the warp for weaving the denim fabric requires a sizing intended to protect fibres from friction forces that occur at the loom, and thus to obtain good weaving efficiency. The pad-sizing/ox process is based on the possibility of combining oxidation–fixation of the dyestuff with the sizing. This process reduces the water input to a mere 7% of what is required for a conventional denim dyeing process, with the additional feature of completely preventing the generation of wastewaters, because no rinsing is required before oxidation/fixation/sizing. This is technically possible with the use of a sizing agent that combines good fibre coverage and elasticity with fixing properties. The fixation is carried out in acidic (pH 4–4.5) conditions.

Additional advantages of the pad-sizing/ox process, along with extremely high water savings, are the reduction in energy required for dyeing in 25% and generated cotton waste in more than 60%. In slasher ranges, in which the yarns run continuously from the dyeing range to the sizing, the pad-sizing/ox can be directly implemented. In rope dyeing ranges, the dyed warp is re-beamed for eventual oxidation/fixation/ sizing in the separate sizing unit. A schematic representation of a machine set up in the pad-sizing/ox process is shown in Figure 5.21.

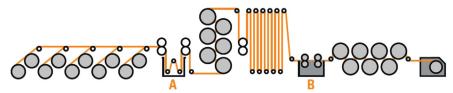


Figure 5.21 Dyeing range for pad-sizing/ox process (© Archroma).

Advantages of Advanced Denim technologies:

- Sustainability. Less water required for dyeing denim means less effluents to be treated.
- Performance.

High fastness levels for washing are achieved by means of ionic bonds formed between the dye and the fibre through a cationic fixing agent.

• New colours and effects.

Pre-reduced dye Diresul<sup>®</sup> RDT, specially designed for environmentally friendly applications, allows one to obtain a wide variety of shades and casts. The 'Indi' colours offer the possibility of on-tone fading after oxidative wash downs, including hydrogen peroxide, thus avoiding the use of hypochlorites or potassium permanganate.

## 5.3.1.5 Technical considerations

For successful application of the Advanced Denim concept, the following points must be considered:

- Dyestuffs should contain minimal sodium sulphide.
- Only glucosides can be used as reducing agents in the dye bath.
- Bifunctional fixing agents give the best results in the Denim Ox process.
- Double function sizing products (such as Arkofil Den-Fix) are essential to obtain the right degree of dye fixation in the pad-sizing/ox process.

Because of the wide scope of applications and variability in the parameters to be considered for each type of desired effect, it is advisable to contact the technical departments of the manufacturers of the dyes and chemicals to be used.

## 5.3.2 Reactive dyes

Reactive dyes are currently the most used group of dyestuffs for standard dyeing of cellulose at a global level. This is explained by their complete palette of shades, flexibility in all applications (exhaust, continuous and semi-continuous) and general performance. They currently represent 30% of all dye family sales worldwide. Nevertheless, their use in denim colouration is relatively small because the requirements are different. Reactive dyes require specific equipment for their application, such as intermediate drying sections or steamers, which are not always available in standard denim dyeing ranges. On the other hand, they have a limited ability to obtain wash down looks because the dyeing tends to be completely solid; on the other hand,

this can be interesting for stable shades, which do not fade after repetitive use and washing.

Another factor is the limited build up achievable compared with standard cotton materials, because the preparation of the fibre limits the amount of dye that can be fixed to the fibre. Normally just scouring is needed as pretreatment before dyeing. Reactive dyes in denim are normally used for medium shades requiring a certain level of brilliancy, and also for the mentioned solid dyeings. Black (for so-called 'steady' or 'stay' black) is also a popular tone for reactive dyes.

### 5.3.2.1 Chemistry of reactive dyes

In 1954, Ratee and Stephen discovered that the dye contained in a dichlorotriazinyl group could form covalent bonds with the cellulose at an alkaline pH and moderate temperatures. The reactive dye is composed of two chemical species: the chromophore and the reactive ring. The union of the two molecular groups is brought about by means of the reaction with an amine of the chromophore. In turn, the compound fixes to the cellulosic fibre by means of the reaction with a hydroxyl group of the cellulose ring. A schematic representation of parallel reactions of a reactive dyestuff in the presence of alkali is shown in Figure 5.22 (Cegarra et al., 1992).

Reactive dyes are so named because they actually react with the cellulose to form a new molecule that is the product of the reaction. The classical way to depict this reaction is  $CEL + DYE \rightarrow CEL - DYE$ , where the link between the cellulose and the dye is of a covalent character. Each of these reactive groups gives different technical properties to the final dyestuff, according to the degree of hydrolysis and fastness.

From a dyeing point of view, the cellulose and the dye are in contact with the water, which is also capable of reacting with the reactive group of the dyestuff, causing the formation of the denominated hydrolysed dye. This hydrolysed dye has lost its ability to form covalent bonds with the cellulose and is absorbed like any other substantive dye with more or less affinity. Because it is not strongly linked to the cellulose and has relatively small structures, the fastness levels (washing in particular) are low compared with the actual covalent bond linked dyestuff. Alkali is required to obtain a high degree of hydroxyl groups dissociated in the cellulose, with which the dyestuff

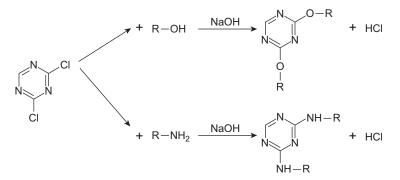


Figure 5.22 Parallel reactions of reactive dye in the presence of alkali (© Archroma).

actually reacts, and it also increases the amount of free hydroxyl groups in the water, with which the dyestuff also reacts, producing a hydrolysed form. The reason why the dyestuff reacts more with the fibre is that the ratio between hydroxyl in groups in cellulose and the water is 30. This means that the speed of reaction of the dye and the cellulose is 30 times faster. In all cases, precautions must be taken to minimise formation of the hydrolysed form of the dyestuff, to maximise build up and increase washing fastness.

## 5.3.2.2 Technical features

Reactive dyes in denim are a good option for solid dyeings on tones that are not achievable with indigo, sulphurs or their combination. Because the covalent bonds formed between the dye and the fibre are much stronger than the secondary forces that link substantive dyes such as directs or sulphurs, fastness to repetitive washing is usually better than that for other dye groups. That makes reactive dyes suitable for steady colours.

Achievable depths are normally light to medium, owing to the mechanical requirements needed to obtain good dye fixation in the standard types of denim warp ranges usually available and the difficulty of removing unfixed dye by soaping (sometimes more than one) because of the number of boxes required in the final section of the range. Dyeing with reactive dyes takes place through three different steps (Reactive Dyes for Cellulosic Dyes, Catlow et al., 2011):

- Neutral dyeing absorption: The dyestuff after impregnation diffuses toward the interior of the fibre, where it is absorbed by the cellulosic chains by secondary force.
- Absorption and reaction in alkaline phase: Once equilibrium at neutral pH is reached, alkaline treatment is carried out. This starts the reaction of the dye and cellulose (and also water).
- Elimination of unreacted dye: Aggressive treatment with the use of dispersing agents is required to remove hydrolysed dye weakly linked to the fibre. This type of process is normally called soaping.

## 5.3.2.3 General principles of application

With some exceptions, such as deep blacks, in which saturation of the fibre is intended, the most advisable type of denim warp dyeing range is the slasher. Reactive dyes in denim are commonly used by one of these two processes:

- Pad-dry/chemical pad-steam: The fibre is impregnated with the dye solution and dried. Then it is saturated in a bath containing alkali required for the reaction and steamed for complete diffusion of the alkali through the fibre and good fixation of the dye. Washing off of unfixed dye and soaping eventually follows for good removal of unfixed dye.
- Pad-wet steam: The fibre is impregnated with a dye solution that contains a weak alkali to prevent quick hydrolysis of the dyestuff. The fabric is steamed wet on wet (no intermediate drying) at 102 °C for 60–90 s with saturated steam.

Important parameters to be considered in general for either of these two processes are:

• Preparation of the yarn to be dyed. Usually efficient pre-wetting by scouring is required before dyeing.

- Dyeing conditions. It is necessary to work at room temperature and to have neutral pH.
- Stability of dye liquor.

Whereas in the pad-dry/pad-steam process the stability of the dyeing solution is perfect because no alkali is added to it, alkali can be added and dosed (with or without a metering pump) in the wet-pad/steam process.

- Drying (pad-dry/chemical pad-steam process).
   The fabric is first passed through an infrared pre-drier to reduce the fabric moisture content to below ~35%. It is then cooled before subsequent steaming.
   Because denim dyeing is a full continuous operation, the machine running speed is governed by the time required to pre-dry the fabric. This is determined by the fabric weight, the moisture content of the wet fabric, the drying temperature, the airflow speed and the machine capacity.
- Use of electrolyte (pad-wet steam process). As mentioned earlier, this type of process is suitable only for light to medium shades. To increase the substantivity of the dyestuff for the fibre, it is usual to add heavy amounts of a neutral electrolyte to the dye bath (200–300 g/L).
- Steaming (pad-dry/chemical pad-steam and pad-wet steam process). In both cases steaming at 102–104 °C with saturated steam for 60–90s is required.
- Washing off and soaping.

Optimum fastness properties can only be achieved for a perfectly washed off material. If a neutral electrolyte has been used for dyeing, it is important to remove it efficiently before proceeding to soaping, so that any hydrolysed dyestuff can be removed. The soapings are normally carried out with a good dispersing agent, usually at mild alkaline pH with the addition of sodium carbonate.

**Recipes for reactive dyes** There are two recipes: one for pad-dry/chemical padsteam and the other for the pad-wet steam process (Catlow et al., 2011).

*Recipe for pad-dry/chemical pad-steam* The dye bath contains the following products:

- Dyestuff.
- Anti-migrating agent (to secure evenness during the drying step).
- Wetting agent.
- Dispersing/sequestering agent.

The alkali liquor applied after the drying contains:

- Sodium sulphate or sodium chloride (to prevent transfer of the dye from the fabric to the bath).
- Sodium carbonate.
- Sodium hydoxide.
- Anti-reducing agent.

Soaping requires:

- Dispersing/sequestering agent.
- · Sodium carbonate.

Recipe for pad-wet steam The dye bath contains the following products:

- Dyestuff.
- Sodium carbonate (for high reactivity dyes, sodium bicarbonate is recommended).
- · Sodium sulphate.
- Wetting agent.
- Dispersing/sequestering agent.

Soaping requires:

- Dispersing/sequestering agent.
- Sodium carbonate.

## 5.3.2.4 Application procedures

Each application process of a reactive dyestuff must be adapted to the mechanical conditions and desired effect. The large number of factors with an influence on the final outcome of the dyeing makes it impossible to give specific recommendations. The general recipes and conditions mentioned here are only informative and cannot be extrapolated to all cases.

### Pad-dry/chemical pad-steam process

A schematic representation of the machine set up for a complete process of dyeing denim warp with reactive dyestuff by the pad-dry/chemical pad-steam process is shown in Figure 5.23.

- A. Scouring.
- B. Rinsing.
- C. Drying.
- D. Dyeing.
- E. Drying.
- F. Impregnation with alkali solution.
- G. Steaming.
- H. Washing off.
- I. Soaping.
- J. Rinsing.

After pre-wetting the yarn, which usually consists of simple scouring, the material is washed off and neutralised to pH 7. The yarn is then dried and cooled down by air passage (skying) before impregnation with the dye bath. The dye-stuff solution is applied cold and at a neutral pH in a small box (padding trough) that should have a volume of around 60 L (or smaller) for best results. This produces a quick dye bath turnover and reduces the possibility of tailing resulting from the affinity of unreacted dye for cellulose. The number of impregnations can be two or three, depending on the configuration of the boxes and the set up for the feeding solution.

The process continues with pre-drying and skying to cool down the fabric before entering the chemical box that contains the alkali required to accelerate the reaction between

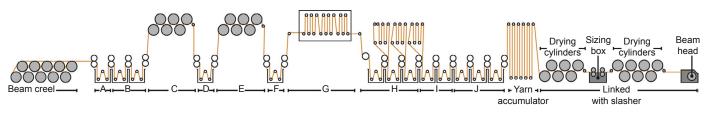


Figure 5.23 Reactive dyeing range for pad-dry/chemical pad-steam process (© Archroma).

the dye and the fibre. The target pick up here should be the highest possible allowed by the padding unit. Diffusion of this solution in the fibre is enhanced by steaming the treated yarn for 60–90s with saturated steam at 102-104 °C. A cold rinse is carried out in four to five boxes to remove alkali and electrolyte before soaping treatment at 80–85 °C with a dispersing agent. The process continues with standard drying and eventually sizing.

#### Pad-wet steam process

In this process the denim warp is dyed wet on wet after pretreatment with a solution that contains the dyestuff, the alkali and the auxiliary chemicals. Figure 5.24 shows a schematic representation of the machine set up for the complete process for dyeing denim warp with reactive dyestuff by the pad-wet steam process.

- A. Scouring.
- B. Rinsing.
- C. Drying.
- D. Dyeing.
- E. Steaming.
- F. Washing off.
- G. Oxidation.
- H. Rinsing.

Considerations for pretreatment of the material to be dyed mentioned in Pad-dry/ chemical pad-steam process are also applicable here. The pre-dried yarn is impregnated with the dye bath for a pick up of 60-70%. The process continues with steaming at 102-104 °C with saturated steam for 60-90 s. Previously mentioned conditions for washing off and soaping are applicable here.

# 5.3.2.5 Technical considerations

To minimise possible problems related to the stability of the dye bath or fixation of the dyestuff, it is recommended to check the following parameters regularly throughout denim dyeing with reactive dyes:

- Temperature of the dye bath: Variations of ±5 °C produce perceptible changes in the depth of shade and diffusion degree of the dye bath.
- Dye concentration: The concentration of dyestuff in the dye bath must be regularly checked. There are different systems for this.
- Speed: This parameter has an influence on the contact time of the fibre with the bath. The longer the contact, the deeper are the achievable depth and dye diffusion in the fibre. The speed should be set so the drying and steaming times are sufficient for proper dye fixation.

A large variety of reactive dyes are available on the market based on different reactive groups; each has its own particularities. For the correct selection of the type of reactive dyestuffs and the type of trichromy to be used, based on the criteria of stability and performance mentioned in this section, it is recommended to contact the technical departments of the dye suppliers.

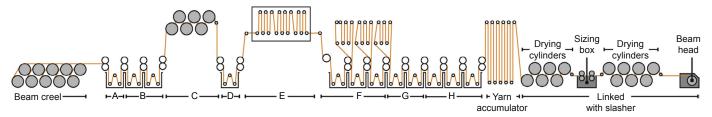


Figure 5.24 Reactive dyeing range for pad-wet steam process (© Archroma).

### 5.3.3 Pigment dispersions

It is possible to obtain liquid (sometimes called paste) forms of pigments by fine grinding that reduces the particle size of the original pigments to diameter values <3 microns. Combined with adequate dispersing agents, this produces a form of pigment that is stable for a certain time in liquid media. This type of product is called pigment dispersion, to be differentiated from standard pigments that might be presented in different granular forms.

Because it has no inherent capacity to chemically link to the fibre, fixation of pigment dispersion is achieved by using binders, resins that are self cross linking that can be from different types from acrylic to butadiene and combinations. Application of pigment dispersions in denim is usually done in two to three boxes to reach a certain depth based on optical density, with the liquor also containing the binders and the rest of the auxiliaries. The pigment bath is applied cold because the reactivity of the resins increases with the temperature and some polymerisation may occur.

## 5.3.3.1 Chemistry of pigment dispersions

A wide variety of pigments comes from many different types of chemistry. A basic summary of the origin of main pigment families is mentioned here. Pigments can be based on organic or inorganic chemistry. Organic pigments may have a natural or synthetic origin. Organic natural pigments (examples are haem or even indigo, if not reduced in its insoluble form) usually belong to the porphyrin family and are not used for simple colouring applications. However, molecules imitating porphyrinic structures containing a metal are important for industrial use and are the origin of important pigment families such as the metal phthalocyanines. Copper or nickel phthalocyanines are the base for brilliant blues, turquoises and brilliant greens.

Organic pigments in the group of reds, yellows and oranges are based on azo or carbonyl (such as quinones) chemistry, whereas bright blues belong to the cyanine family usually coming from metallised molecules forming chelates. Inorganic pigments used today are metal (normally Fe) salts such as oxides or in the form of iron hexacyanoferrate or ferric cyanide, the classical Prussian blue. Lead chromate gives yellows and oranges whereas lemon yellows can be obtained from barium chromate. Titanium dioxide is the standard base for whites. Pigment blacks are usually based on carbon black (C.I. Pigment Black 7), which can be obtained from oil as a residue or from charred vegetal origins (Hawthorne and Solomon, 1983).

#### Particle size and dispersion

In addition to its chemical structure, the application properties of a pigment are given by its crystal properties and its ability to embed into the surrounding medium. Some important terms in this context are crystal form and size, specific surface, aggregates, agglomerates, primary particles and distribution of the particle size.

Insoluble molecules cluster together to form crystals. This process depends directly on the production conditions in the synthesis of the molecules. However, matters do not rest with these so-called primary particles. Based on their surface energy, the primary particles tend to cluster into larger formations; the smaller they are, the more rapidly they do this. Here two conditions should be differentiated: aggregates and agglomerates. Aggregates are primary particles that have grown together, whereas agglomerates consist of primary particles that are attached at their surfaces. Only the latter condition (agglomerates) can be separated by a mechanical grinding process.

It is precisely this separation that is desired, because the size of the pigments has a decisive influence on the properties of the pigment. Thus, for example, the colour strength of the pigment increases along with a reduction in the particle size. This is because smaller particles have a larger surface in relation to their volume. Thus, more light can be absorbed by the same amount of pigment and the pigment appears to be stronger in colour (Sabat, 2003).

However, not only is the absolute size of the particles decisive, but also the distribution of the particle size. The particles are not all of the same size but are subject to a Gaussian normal distribution. If this consists of a very wide curve, that is the particles exist in different sizes, many slightly different colour depths and shades will exist, leading to a reduction in brilliance. The nearer the maximum and the minimum of the particle size are to each other, the more brilliant and intense the hue will be.

In the production of pigment dispersion the pigment agglomerates are broken up into primary particles by high speed stirring mills and/or bead mills. These are wetted at the particle surface and then stabilised so that no re-agglomeration can occur. The stability of the dispersion is ensured by means of dispersants that are added to the solvent (water) used to wet the primary particles.

### 5.3.3.2 Technical features

Pigment dispersions are used in denim especially when bright tones with a marked ring dyeing effect are required. Because pigment dispersions are presented in the form of small insoluble particles, they do not possess substantivity for the cellulose or the capacity of reacting with it. Their lack of solubility prevents actual diffusion of the coloured solution in the fibre, so they tend to stay on the surface of the yarn, producing the mentioned ring effect.

Pigments offer the possibility of obtaining a wide range of shades but only for light to medium depths. The fact that they have no affinity for the fibre makes them suitable for pale and bright tones with the additional advantage of good light fastness, which they have in general. Other types of fastness depend on the degree of adherence of the pigment dispersion to the fibre achieved with the use of a binder. The amount of this binder cannot be too high because the yarn will become too stiff after pigment application and will make fabric weaving problematic. It will affect the softness and flexibility of the final garment, which are essential for a final even wash down look. This restricts the level of washing fastness achievable to medium.

The general application process of pigment dispersion in continuous colouration is simple because only impregnation with the pigment liquor and after drying is required. This simplicity makes it a good option for short runs. On the other hand, it is necessary to take precautions to achieve even colouration with good fastness:

• The preparation of the yarn before the colouration has an important role in the depth, shade and final fastness of the fabric. The yarn must be clean from impurities, paraffins and waxes,

so the colouration is even (pigments do not have migration capacity), the degree of binder fixation is sufficient and the final shade is not affected by the basic colour of grey cotton, an important point for bright shades. For medium to dark shades two to four boxes of impregnation are needed so a certain depth is achieved by optical density.

• The pH of the pigment dispersion bath must be neutral. An alkaline pH will hinder the fixation of the binder on the fibre. Neutralisation at pH 7 in the yarn is required after the scouring treatment.

## 5.3.3.3 General principles of application

There is basically one type of application process for colouring denim warp with pigment dispersions. It consists of a number of impregnations with the colouring solution, for a kind of multi 'painting', once the yarn has been pretreated for even hydrophilicity, and dried. The process is then pad-dry/pad-dry. Precautions for pretreatment of the yarn to be coloured are the same as for reactive dyeing, as described in Section 5.3.2.3. Once the material is dry and neutralised at pH 7, it is impregnated in several boxes (normally two to four, depending on the desired depth) with a liquor that contains:

- · Pigment dispersion.
- Binder.
- Anti-migration agent.
- Dispersing agent.
- · Diammonium phosphate.
- Diammonium phosphate is used as a pH adjuster for proper fixation of the binder resin.

## 5.3.3.4 Application procedure

The machine set up and general application process for colouring denim warp with pigment dispersions are schematically described in Figure 5.25.

- A. Scouring.
- B. Rinsing.
- C. Drying.
- **D.** Pigment liquor (two to four boxes).

The bath is stable for a long time as long as the temperature (cold) and pH (7) are kept constant. Standard drying conditions with steam heated cylinders are sufficient for the required fixation of the binder. Because a wash down treatment will eventually take place and binder will be partially removed, it is not necessary to work at conditions for full polymerisation.

## 5.3.3.5 Technical considerations

- Quality of pigment dispersions: Particle size is a critical factor for achieving deeper shades, improving fastness and obtaining a final material that is not too stiff owing to the addition of binder that may be needed to integrate all of the pigment particles deposited onto the fibre.
- Type of binder: A suitable binder for denim colouring with pigment dispersions should meet some important criteria, such as the formation of a colourless transparent film, good cross linking properties and softness.
- Recipe: When calculating the colouration bath recipe it is important to consider that the concentration of binder depends on the concentration of the pigment dispersion to be used.

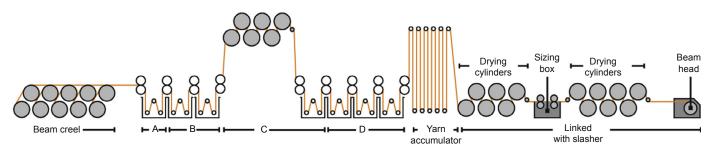


Figure 5.25 Application range for pigment dispersions (© Archroma).

| Pigment dispersion | Binder                              |
|--------------------|-------------------------------------|
| 0.1–5.0 g/L        | 25–40 g/L                           |
| 5.0–10.0 g/L       | 25-40 g/L<br>40-60 g/L<br>60-80 g/L |
| 10.0–20.0 g/L      | 60–80 g/L                           |
| >20.0 g/L          | 100–120 g/L                         |

Table 5.1 Typical pigment application recipes

For articles meant to be washed down eventually, as in this case, the generic rule is recommended in Table 5.1: Nevertheless, previous laboratory tests are required to confirm the exact amounts to be used.

• Type and number of application boxes: Standard application boxes in slasher ranges with volumes ranging from 300 to 700 L are suitable for application. The number to be used must be adjusted according to the actual range configuration, desired depth and running speed (determined by drying conditions).

It is usual for the used boxes to remain stained after the colouration. The binder in the colouring bath reacts gradually and can produce a film of pigment dispersion on the walls of the boxes and the additional parts in contact with the coloured group of yarns. It is recommended to begin cleaning as soon as the set has been coloured to make the operation more effective and less time consuming.

Owing to the relevance of technical factors concerning the type and quality of pigment dispersion as well as the binder system, it is advisable to consult technical literature released by the major pigment dispersion producers before preparing a colouring recipe, and to adjust the different parameters of the process.

## 5.3.4 Vat dyes

Vat dyes are an ancient family of dyes but still the most important ones in the textile industry when indigo, actually a vat dye, C.I. Vat Blue 1, is considered. They are normally used to dye cellulose but a selection, including indigo, can also colour other types of textile fibres such as wool. Vat dyes allow the possibility of obtaining a wide range of shades with high fastness levels. Selected vat dyes present high fastness to light and repetitive washing, and some are also fast to chlorine. The main uses are in working wear, military fabrics and camouflage, and in general whenever high overall fastness levels are required.

Vat dyes are usually presented as a dispersion of the oxidised form. This means that complete pre-reduction is required to confer solubility and affinity for the cellulose. This reductive reaction can be done in a separated bath, which is called 'vatting', to transfer the solution eventually with the reduced dyestuff to the impregnation boxes. This would be the standard method to work, that is with indigo. The dyestuff in the bath needs to be reduced to the right level so that it has good solubility and affinity for the fibre. The amount of reducing agent and alkali to be used depends on the actual type and amount of dyestuff and also the pick up of the reductive solution. The required calculation tables or expert programs are available from the companies commercialising the dyes.

### 5.3.4.1 Chemistry of vat dyes

Vat is actually a generic name for different dye families coming from different chemical constitutions. Like sulphur dyes, vat dyes are insoluble in water but by reduction in alkaline solutions they are converted into hydrosoluble derivatives (called 'leuco'). In this form, the dye possesses substantivity for the textile fibres on which the original colour is developed by subsequent oxidation.

The difference in sulphur dyes resides in the type of reducing agent required to obtain the water soluble form. The oxidised form of vat dyes is stable and requires high reduction energy achievable only by using strong reducing chemicals such as sodium hydrosulphite. On the other hand, the reduced form is easily oxidised, sometimes by simple skying (in the case of the indigo) or mild chemical oxidation. Sulphur dyes can be reduced with relatively mild reducing agents but require strong oxidants to fully develop the final shade and achieve good fixation.

Vat dyes are normally classified into two groups:

- 1. Dyes derived from indigo (indigoids).
- **2.** Dyes derived from anthraquinone (anthraquinoids).

Examples of the basic chemical structures of each dye group are represented in Figure 5.26 (Baptista, 2009). Indigo, thioindigo and bromindigo belong to Group (1). Derivatives from anthraquinone, indanthrone and other anthraquinoid structures belong to Group (2). Despite the different basic chemistry, application methods for both groups are the same. In general terms, indigoid dyes give brighter shades than anthraquinoids but with worse light and washing fastness.

#### Commercial forms

Because of the sensitivity to air oxidation of the reduced form, vat dyes are usually commercialised as a finely dispersed form of the oxidised dyestuff. As in the case of pigment dispersions, the insoluble dyestuff is ground to obtain small particles with a diameter <2 microns and combined with dispersing agents to obtain a stable liquid/ paste commercial form.

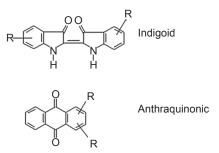


Figure 5.26 Schematic representation of vat dye classes (© Archroma).

# 5.3.4.2 Technical properties

Vat dyes are usually applied to denim in single elements as self-shades. In the case of using two or three dyes in the recipe, they must belong to the same group and be used in relatively similar concentrations, so calculations required for the reducing agent and alkali are relatively simple. As for other dyes and pigments used to colour denim, important parameters should be considered:

• The preparation of the yarn before dyeing has an important role in the depth, shade and final fastness of the fabric. The yarn must be clean from impurities, paraffins and waxes, so regular hydrophilicity helps to achieve good dyeing evenness and fastness. This is an important point for bright shades.

For medium to dark shades two to four boxes of impregnation may be needed to achieve dark tones.

• Dye bath temperature: Both the dye bath (for the pad-steam process) and the alkaline development bath (for the pad-dry/pad-steam process) should be applied at a cold (room) temperature. Heating of the bath accelerates the decomposition of the sodium hydrosulphite used as a reducing agent.

The yarn has to be evenly dry and cooled to room temperature before impregnation with the dye bath and reductive solution.

• Oxidation: Vat dyes require mild oxidation to fully develop their shade and obtain good fixation of the fibre. This oxidation can be sometimes carried out solely with water, but it is advisable to run the dyed yarn, after the washing off, in a bath containing some hydrogen peroxide or other types of oxidant agents such as aromatic sulphonic acid derivatives.

# 5.3.4.3 General principles of application

In denim, vat dyes are an option when bright and light to medium shades are required combined with a high level of light and repetitive washing fastness. Their use in denim dyeing is limited by the mechanical requirements when drying and steaming units are required for good dye fixation. In this aspect, the applications and required range set ups are similar to those used for reactive dyes. Another point when considering the use of vat dyes for denim is the economy of the process, because the recipe and production costs can be higher than those of other dyes families. Only slasher ranges are recommended for vat dyes in denim. Working on rope may lead to running marks, streakiness, and side to side shade variations, usually perceptible only on the woven fabric.

Vat dyes in denim are commonly used in one of two processes:

- Pad-dry/chemical pad-steam: The fibre is impregnated with the dye solution and dried. Then it is saturated in a bath containing the reducing agent and alkali required for the reaction and steamed for complete diffusion of the reduced dyestuff through the fibre and good fixation of the dye. Washing off of unfixed dye and soaping eventually follows for good removal of unfixed dye.
- Pad-steam: The fibre is impregnated with the dye solution, which contains the dyestuff and the reductive system. The fabric is steamed wet on wet (no intermediate drying) at 102 °C for 60–90 s with saturated steam.

**Recipes for vat dyes** The recipes for the pad-dry/chemical pad-steam and the padsteam process are distinguished here.

*Recipe for pad-dry/chemical pad-steam* The dye bath contains the following products:

- Dyestuff.
- Anti-migrating agent (to secure evenness during the drying step).
- Wetting agent.
- Dispersing/sequestering agent.

The reductive/alkaline liquor applied after the drying contains:

- · Sodium hydoxide.
- · Sodium hydrosulphite.
- Dispersing agent.
- Wetting agent.
- Sodium sulphate (to prevent transfer of the dyestuff from the dyed fabric to the reductive bath).

The amount of sodium hydoxide and sodium hydrosulphite to be used should be calculated by tables according to the type of dye and concentration used.

The oxidation bath requires:

- · Hydrogen peroxide or any other suitable oxidising agent.
- Dispersing agent.

Recipe for pad-steam The dye bath contains the following products:

- Dyestuff.
- Sodium hydoxide.
- Sodium hydrosulphite.
- Wetting agent.
- Dispersing/sequestering agent.

The oxidation bath requires:

- Hydrogen peroxide or any other suitable oxidising agent.
- Dispersing agent.

# 5.3.4.4 Application procedures

Each application process of a vat dyestuff must be adapted to the mechanical conditions and desired effect. The large number of factors that have an influence on the final outcome of the dyeing makes it impossible to give specific recommendations. The general recipes and conditions mentioned here are only informative and cannot be extrapolated to all cases.

## Pad-dry/chemical pad-steam process

A schematic representation of the machine set up for a complete process for dyeing denim warp with vat dyes by the pad-dry/chemical pad-steam process is shown in Figure 5.23.

- A. Scouring.
- B. Rinsing.

- C. Drying.
- D. Dyeing.
- E. Drying.
- F. Impregnation with reductive/alkali solution.
- G. Steaming.
- H. Washing off.
- I. Oxidation.
- J. Rinsing.

After pre-wetting the yarn, which can consist of simple scouring, the material is washed off and neutralised to pH 7. The yarn is then dried and cooled down by air passage (skying) before impregnation with the dye bath. The dyestuff solution is applied cold. The number of impregnations can be two to three, depending on the configuration of the boxes and the set up for the feeding solution.

The process continues with pre-drying and skying to cool down the fabric before entering in the chemical box that contains the alkali and the sodium hydrosulphite required to produce the reduction reaction that solubilises the dyestuff. The target pick up here is the highest possible allowed by the padding unit. The diffusion of this solution in the fibre is enhanced by steaming the treated yarn for 60–90 s with saturated steam at 102–104 °C.

A cold rinse is carried out in four to five boxes to remove alkali and remaining sodium hydrosulphite and then the fabric is oxidised cold with hydrogen peroxide (or another suitable oxidant agent). After a rinsing, and if the number of boxes in the last range section is enough, it is possible to make a soaping with a dispersing agent at 80–85 °C. The process continues with standard drying and eventual sizing.

#### Pad-wet steam process

In this process the denim warp is dyed wet on wet after pretreatment with a solution that contains the dyestuff, the alkali, the sodium hydrosulphite and the auxiliary chemicals. A schematic representation of the machine set up for a complete process for dyeing denim warp with vat dyes by the pad-wet steam process is shown in Figure 5.24.

- A. Scouring.
- B. Rinsing.
- C. Drying.
- D. Dyeing.
- E. Steaming.
- F. Washing off.
- G. Oxidation.
- H. Rinsing.

Considerations for pretreatment of the material to be dyed mentioned in Section Pad-dry/chemical pad-steam process are also applicable here. The pre-dried yarn is impregnated with the dye bath containing the dyestuff, alkali, sodium hydrosulphite and auxiliaries, for a pick up of 60–70%. The process continues with steaming at 102–104 °C with saturated steam for 60–90 s. Previously mentioned conditions for washing off and soaping are applicable here.

# 5.3.4.5 Technical considerations

To minimise possible problems related to the stability of the dye bath or fixation of the dyestuff, the following parameters should be regularly checked throughout denim dyeing with vat dyes:

- Temperature of the dye bath in dyeing or developing baths: It is recommended to work at a cold (room) temperature and to keep it constant. Variations of  $\pm 5$  °C in the dye bath or a chemical solution used to reduce the dyestuff may produce perceptible changes in the depth of shade and diffusion degree of the dye bath, with an eventual effect on the fastness and appearance of the final garment. In some cases, yarn coming from pre-drying that is not properly cooled down may be the reason for a gradual rise in temperature. Longer skying or setting up a system to force an air stream to be in contact with the yarn slasher may solve the problem.
- Dye concentration: The concentration of dyestuff in the dye bath must be regularly checked by the usual means of testing.
- Speed: This parameter has an influence on the contact time of fibre with the bath. The longer the contact, the deeper is the achievable depth and dye diffusion in the fibre. The speed should be set so the drying and steaming times are sufficient for proper dye fixation.

Because of the relevance of the technical factors concerning the type and quality of the vat dyes available in the market, it is advisable to consult the technical literature released by major producers and technical specialists before preparing a colouring recipe, and to adjust the different parameters of the process.

# 5.3.5 Other options for denim colouration

In an attempt to discover new effects and obtain special shades, dye families other than those mentioned so far have been applied, although marginally. Currently, they are not commonly used owing to technical, economical and ecological issues. Such dye classes as direct dyes and diazotable dyes are briefly discussed below.

## 5.3.5.1 Direct dyes

Direct dyes, also known as substantive dyes, are an ancient type of dye for cellulose. They are known for their wide palette of shades, ease of application and economy, but they have some restrictions in the fastness achievable through washing and potential application procedures. Direct dyes are currently mostly used in exhaust, particularly in garment form, on cellulose fibres and in polyester–cellulose blends, where they can be applied in a simple and economical way. In continuous applications, the low obtainable build up and washing fastness levels are important limitation factors.

Direct dyes in denim have been used for some bright colours as single elements for self shade tones. Only slasher ranges are appropriate for their application. The general application method is based on the pad-steam concept:

- Pretreatment of the yarn by scouring.
- Washing off, neutralisation of the treated cotton to pH 7 and drying.

- Impregnation with the dye solution (in two to four boxes) at 80–85 °C.
- Steaming with saturated steam for 60–90 s at 102–104 °C.
- Washing off of unfixed dyestuff.
- Fixation with a cationic agent at 40 °C.

A schematic representation of the machine set up for a complete process for dyeing denim warp with direct dyes is shown in Figure 5.23.

- A. Scouring.
- B. Rinsing.
- C. Drying.
- D. Dyeing.
- E. Drying.
- F. Impregnation with alkali solution.
- G. Steaming.
- H. Washing off.
- I. Soaping.
- J. Rinsing.

The dye solution contains:

- Dyestuff.
- Dispersing agent.
- Wetting agent.
- Anti-reducing agent.
- Urea or a chemical for moisture control.

Even after using a cationic fixing agent, the after washing temperature should not exceed 50 °C because bleeding of the dye will produce back staining problems and unevenness as a result of differential dye removal.

## 5.3.5.2 Azoic colours

Owing to modern ecological and safety regulations related to the presence of free amines in textile articles, azoic colours have completely disappeared from the market. The azoic insoluble colours, commonly known as naphthols, were special types of colouring products directly produced on the fibre by applying a compound that included amino and hydroxyl groups (usually hydroxyl derivatives of naphthalene) that was eventually reacted with a diazotised base or salt at a low temperature to produce an insoluble colour molecule within the fibre. Naphthol colours had good overall fastness but a limited range of shades, the most popular of which were brilliant reds, oranges and blacks. The process of application in denim is similar to that in other types of textile materials:

- Pretreatment of the yarn by scouring, combined scouring/bleaching or caustification mercerisation.
- Washing off, neutralisation of the treated cotton to pH 7 and drying.
- Impregnation at 80–85 °C with a bath containing the pre-diluted naphthol base at a cold temperature. Usually two to three boxes were required for even distribution of the base and to achieve the required depths.
- Washing off of naphthol base excess.

- Impregnation with the coupling bath containing also hydrochloric acid and sodium nitrite. The required coupling salt should be prepared previously. The impregnation should be carried out at a temperature never higher than 15–18 °C (ice is used to keep the temperature below these levels).
- Washing at cold in acid conditions.
- Soaping with a dispersing agent at a slightly alkaline pH.

A schematic representation of the machine set up for a complete process for colouring denim warp with azoic colours is shown in Figure 5.27.

- A. Pre-wetting.
- B. Washing.
- C. Drying.
- D. Naphthol.
- E. Salt.
- **F.** Washing.
- G. Soaping.
- H. Washing.

The process is complicated, with many points to control and risks of precipitation or decomposition of the bases or the coupling salts.

# 5.4 Non-indigo dyes for fabric overdyeing

An alternative to modify the shade of dyed denim fabric and open new possibilities of wash down looks is to overdye with dyestuffs using standard application methods. This allows a coloured weft to be obtained, which can be interesting for certain garment designs. The usual starting fabrics are blue indigo and black denims. Overdyeing can be applied on loom state denim fabric by continuous or semi-continuous routes or in the final garment by exhaust. The latter option is commonly known as 'tinting'. There are two basic methods for overdyeing denim fabric: using either sulphur or reactive dyes.

#### 5.4.1 Overdyeing with sulphur dyes

Although this type of application can be done by exhaust in a jigger machine, it is dyed by the continuous pad-steam method. Pad-steam is highly productive for long runs that are normally dyed and secures better consistency of shades along with dyeing and batch to batch reproducibility. A schematic representation of the machine set up for the complete process for overdyeing denim fabric by the pad-steam process with sulphur dyes is shown in Figure 5.28.

The denim fabric could be dyed in the loom state form, without desizing, so the dye bath is usually heated to 60–70 °C for better diffusion of the dyestuff in the fibre. This improves dye fixation and final fastness. Standard overdyeing combinations with sulphur dyes are:

- Blue and blue: sulphur blue or navy overdyeing blue indigo denim.
- Black and blue: sulphur black overdyeing blue indigo denim.

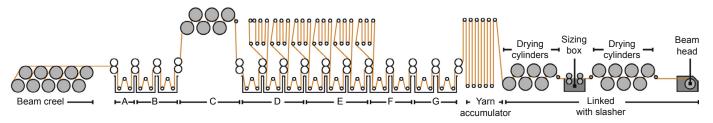


Figure 5.27 Application range for azoic colours (© Archroma).

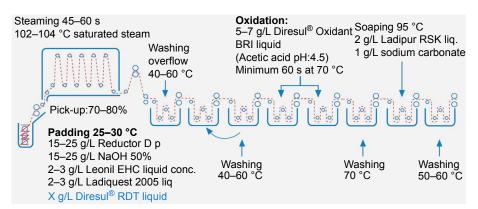


Figure 5.28 Sulphur overdyeing range for pad-steam process (© Archroma).



Figure 5.29 Scheme of pad-batch process with reactive dyes (© Archroma).

- Black and black: sulphur black overdyeing black denim.
- · Browns and olives overdyeing blue indigo denim are also shown in collections for a 'dirty' look.

### 5.4.2 Overdyeing with reactive dyes

Reactive dyes can be used to overcast the indigo with bright shades. The original shade of the reactive dyestuff is visible on the back face of the denim fabric for special garment designs or wearing styles. A usual process of application, particularly for short runs, is pad-batch. The pad-batch process is a semi-continuous dyeing method that is extremely interesting from the point of view of both the machinery and the application technique. The only machines required are a padder, batching device and washing off equipment.

The principle of the pad-batch process is to pad the goods at room temperature with a dye solution that also contains the necessary alkali for fixation and any other chemicals. The fabric is rolled upon a beam and wrapped in plastic film ready for the fixation step. Dye fixation takes place during batching at room temperature. Slow rotation of the fabric batch is necessary during batching to avoid unevenness and draining of the dye liquor. The fabric is batched for the required fixation time before the unfixed dye is removed from the fibres by rinsing then soaping at boiling. A schematic representation of a pad-batch application process with reactive dyes is shown in Figure 5.29.

The fabric should have even hydrophilicity and be free from impurities that may affect the performance of the dyestuff and the stability of the dye bath. Because of the sensitivity of reactive dyes to organic matter, which may generate some reduction in the bath, it is advisable to carry out desizing of the denim fabric before overdyeing.

# 5.5 Modern colouration possibilities

New application technologies allow the dyestuffs to be applied in the form of layers or 'skins', thus dyeing one face (or both) of the denim fabric with a lack that stays on its surface. The ease to remove this lack from the dyestuff by mechanical means gives the possibility of having differential colour effects after wash down treatments. This type of process is known by the generic name of 'coating'. The colouring product can be applied in the form of a paste or foam. In both cases, preparation of the dyestuff or the pigment dispersion is done with some additives to produce the desired form to be used.

Coating is a continuous application process. The prepared paste, a liquid with an oil like viscosity, or foam is deposited evenly across the running fabric and the thickness of the micrometric layer is adjusted by a device (floating knife) that leaves the required amount, normally calculated as a percentage over the weight of coloured goods. Standard types of products used in this type of application are pigment dispersions and solubilised sulphur dyes. A schematic representation of a general coating application process is shown in Figure 5.30.

### 5.5.1 Coating with pigment dispersions

The process is based on a simple application of the coating paste followed by drying and polymerisation. The paste to be prepared for coating with pigment dispersion contains:

- · Pigment dispersion.
- Binder.
- Thickener.
- Softener.
- Dispersing agent.

The thickener provides the viscosity required so the paste remains on the coloured surface of the fabric and does not diffuse into the back face. The softener helps to

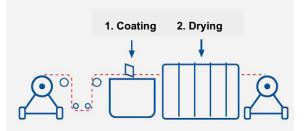


Figure 5.30 Scheme of a general coating process (© Archroma).

provide better running properties of the paste, acting as a lubricant. This gives an even and homogeneous look to the coloured material.

The recipe for foam application is based on the same recipe. In this case, a product is required that generates a fluid, stable and consistent foam paste. The concentrations of the rest of the auxiliaries are reduced according to the actual concentration of pigment dispersion used. The coated material is dried and treated at the temperatures and times required for polymerisation of the binder. This is done in a stenter. The number of available fields in the stenter determines the running speed, which has to be adjusted to reach the polymerisation time in accordance with the temperatures in each field.

### 5.5.2 Coating with sulphur dyes

The procedure of application is as follows (Diresul RDT Sulphur Dyes in Pre-reduced Form, 2009):

- · Coating with prepared paste.
- Drying.
- Fixation.
- Drying.

The dyeing recipe contains:

- · Solubilised sulphur dyestuff.
- Hydrogen peroxide.
- Pick up improver.
- Dispersing agent.
- pH stabiliser.

The fabric is dried at 110–150 °C. Fixation–oxidation takes place in the same range, with a solution that contains:

- Cationic fixing agent.
- Dispersing agent.
- pH adjusted to 4–5.

Application in a foam form is based on the same recipes and process. It is necessary to use a product that generates a fluid, stable and consistent foam paste. The concentrations of auxiliaries are adjusted to the actual amount of dyestuff to be fixed on the fibre. The fabric is subsequently dried and fixed at the same conditions mentioned for the paste application.

## 5.6 Future trends

Denim dyed with non-indigo dyes has become important in the collections of designers and fashion trendsetters. Indigo will continue to be the king of the dyes and will remain associated with denim as the standard dyeing product but the permanent search for new effects and the flexibility that denim has for continuously reinventing itself will require the exploration of new application methods and the development of new chemicals and dyes. In the future, another important factor to be considered is that of sustainability regarding not only how denim fabrics are produced and processed but also the characteristics of the dyes and chemicals to be used. This trend for more sustainable denim has started with the way in which cotton is grown and alternative options for obtaining it, such as the use of recycled fibres and other fibres alone or in combination with cotton.

Dyeing processes will have to consider the water and energy consumption required to manufacture the fabric and treat the final garments. In wash down treatments, the use of stones, sand blasting and hazardous chemicals such as sodium hypochlorite or potassium permanganate will come to an end and will be replaced by cleaner and safer alternatives. In any case, denim will continue to be an actual global type of textile article, in continuous evolution but as close, charming and special as always.

## 5.7 Conclusion

Denim is a wide playground for designers and fashion trendsetters, and dyes other than indigo provide options for continuous innovation. Although indigo has been linked to denim since the early days of jeans production, back in the nineteenth century, and its use today is almost exclusive for denim wear, other dyes have become complements and even alternatives to it. Continuous requirements for new effects in terms of shades and effects and for more sustainable ways to dye denim warp open the way to dyestuffs of a different chemical character. Also the dyeing equipment, originally meant only for indigo, is in transformation to provide conditions required to apply these new dyes. Nowadays, the proportion of 100% indigo dyed denim warp is very small because it is commonly combined with other types of dyes in the same application process, or overdyed and coated with them.

Whereas some dyestuff families, such as sulphur dyes, are well known and widely used to colour denim warps, owing to their dyeing properties and application conditions (as single shades or as complements of indigo), alternatives with other dyes are relatively unexplored. Although they offer interesting possibilities for new shades and effects, the necessity of adapting current conventional dyeing equipment, cost issues and competition from articles dyed in garment form that give a look similar to that achievable with denim make their introduction on a wide scale more difficult. Pressure from the fashion market could eventually activate interest in ranges such as reactives or pigments for new looks and effects, because denim is in continuous demand for novelties.

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## Weaving technologies for manufacturing denim

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## 6.1 Introduction

The word 'denim' derives from *serge de Nimes*, referring to this French town where the fabric is said to have originated. The fabric has come a long way since then. From being used as jeans to widespread acceptance in the apparel world, the fabric has addressed a lot of fashion desires. Denim is slowly finding a place in the least expected sectors including accessories such as bags and purses, and even in automotive interiors and furniture.

The denim market covers about 3% of the entire textile market and has been growing steadily over the past years. About 24,000 weaving machines were running at the start of the twenty first century (Bamelis, 1998). The number of weaving machines and the metres of fabric have increased by up to three times since the start of the century. This is mainly attributed to an increase in the speed of the weaving machines and automisation of the weaving machines. The increase in production capacities over the past decade has resulted in the reduction in price of a pair of jeans (Colourage, 1998). Results of an interview carried out by the Textilwirtschaft showed that 81% of customers interviewed would have liked to have a pair of denim jeans for less than  $100 \notin$  (Textilwirtschaft, 2014).

Furthermore, the trend in fashion for denim is moving toward fabrics that are stonewashed or sand washed and have a damaged or even faded look (Mittex, 2003). All of these treatments for denim fabrics require the fabric to be robust enough to sustain not only chemical treatments but some harsh mechanical treatments as well. The fabric has to be able to hold its strength even after it has undergone post processing which damages the fabric surface. This is a challenge that the technologist who spins the yarn and weaves the fabric needs to consider.

## 6.2 Historical aspects

Denim is more than just cotton fabric and it inspires strong opinions within the hearts of historians, designers, teenagers, movie stars, reporters and writers (Downey, 2007). The story of denim traces back to California in 1853. A young 24 year old German immigrant, Levi Strauss (1829–1902), left for San Francisco from New York to open a branch of his brother's dry goods business. A prospector asked Levi Strauss what he was selling. Strauss mentioned that he had rough canvas that could be used for tents

and wagon cars. Instead, the prospector was looking for pants that could be strong enough to last for a long time. Filling the prospector's request, Strauss used the rough canvas cloth to make waist overalls. These pants were used by miners; after a certain amount of use, the miners complained about wear and tear. Strauss then used twilled cloth made of cotton sourced from France. This fabric was later termed 'denim' (Paul and Joseph, 2003).

Bellis pointed out that in 1873 (Bellis, 2013), Levi Strauss & Co. started using a pocket stitch design. Levi Straus and a Reno Nevada based Latvian tailor named Jacob Davis developed and patented a process of putting rivets in pants to increase their strength. On May 20, 1873, the team of tailors was conferred with United States (US) Patent 139,121. This was the day when the 'blue jeans' arrived in the world.

As suggested in the varied literature, denim fabric originated from France in the 1800s. In France denim fabric was made from a wool and silk mix and mostly had a twill woven structure. At about the same time similar fabrics were made on the other side of the Atlantic in America. Fabrics produced in America were made of cotton and were designed to imitate the look of the French wool/silk twill fabric.

The denim for the first waist overalls came from the Amoskeag Manufacturing Company in Manchester, New Hampshire, on the east coast of the United States. A twill fabric that used one coloured and one plain thread, it bore only a slight resemblance to its French or English predecessors, which were generally piece dyed. Significantly, the coloured thread was almost invariably dyed with indigo; a chemical quirk means that the indigo molecules were adsorbed onto the surface of the cotton thread it dyed. As the fabric wore off, the indigo dye pigments chipped off. This gave denim the worn off, rugged look for which it is known. In 1915, Levi Strauss & Co. started using denim from North Carolina's Cone Mills.

#### 6.3 Fibres for denim manufacture

Denim is normally manufactured using fibres from naturally available regenerative resources. The most common fibre used for the manufacture of denim is cotton. A brief overview of the fibres conventionally used to manufacture denim, along with their properties, is discussed in this section.

#### 6.3.1 Cotton fibre

Cotton fibre is a plant derived natural seed fibre used extensively in the manufacture of denim fabrics. World cotton production touched a high of 113.8 million bales in 2012 (USDA, 2012). Major producers of cotton fibre are China, India, US, Pakistan and Brazil. These countries produce about 80% of cotton globally. Cotton fibre is a plant seed fibre that needs to be harvested and then separated from the seed. Harvesting is carried out by handpicking the cotton boll from the field or by automatic harvesting using a spindle picker. The process involved in separating cotton fibre from seeds is called ginning. The fibre then undergoes processes such as opening, blending, cleaning, carding, combing and so forth. Furthermore, it is treated in a draw frame and speed frame before the fibres are spun into yarns suitable for denim.

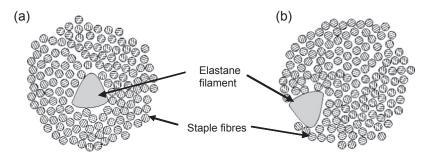
#### 6.3.2 Regenerated cellulosic fibres

In addition to cotton fibre, there is a trend toward using fibres such as regenerated cellulosic fibres. Regenerated cellulosic fibre and its derivatives are available in a fineness of about 1-2 dtex. These fibres are manufactured from wood pulp and use the solvent spinning process. The fibres have a tenacity of about 30-40 cN/tex. However, they have lower tenacity in water. The fibres are normally mixed with cotton fibres with a mixing ratio of up to 25%. Because of the property of high water absorbency, these fibres are suited for use in making denim.

#### 6.3.3 Functional fibres

Denim used for jeans possesses certain functional fibres in very low percentages. These fibres are used to achieve functional properties such as stretch in denim jeans. Stretch is provided by spandex fibres that are used in a filament form. Spandex fibres have an elongation of about 200% and about 5% of these fibres are integrated into the core of yarns that are used for denim production. Although these spandex fibres, which provide the required strech are difficult to process, the fibres have gained firm entry into the highest end fashion labels for aspects such as shape memory and retention (Fein, 2005).

One processing challenge of spandex fibres in denim is to keep fine spandex filament in the core of the yarns. Inappropriate positioning of spandex yarn in cotton spun core yarn could lead to defects in the fabric finishing process. This aspect may be observed in Figure 6.1. Intelligent measuring systems have been designed to detect these kinds of defects, especially for denim fabrics.



**Figure 6.1** Elastane filament in core sheath spun yarn: (a) ideal position, (b) undesirable position.

## 6.4 Yarns for denim manufacture

This section deals with different methods used to manufacture yarns for denim fabrics.

#### 6.4.1 Requirements of denim yarn

Yarns that are used to manufacture denim have to possess certain special characteristics to be considered for the fabric. Yarns for denim manufacture are primarily staple fibre yarns. These are mostly made of cotton staple fibres. The possible structure of a yarn used in denim fabrics is shown in Figure 6.2 (Raina, 2012).

Yarn fineness for bottom weight jeans ranges in size from 50 to 150 tex (Ne 12.5/1-4.0). Finer yarns are used for lighter weight jeans. These yarns may range in count from 20 to 50 tex (Ne 12.5-30.0). The yarn characteristics that need to be engineered to make a yarn for denim are:

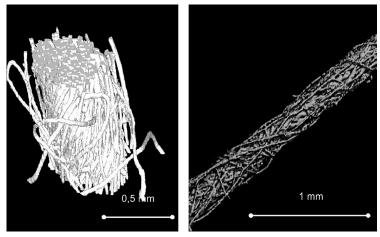
- High yarn strength.
- Pilling resistance.
- · Compactness and less hairiness.
- Evenness/uniformity.

These different characteristics for yarns can be designed using different spinning technologies. Spinning technologies that are widely used to manufacture denim yarns are ring spinning, compact spinning and open end (rotor) spinning.

#### 6.4.2 Spinning technologies

#### 6.4.2.1 Ring spinning

Ring spinning technology is one of the oldest spinning technologies in the world. This spinning technology has a history dating around 200 years ago. According to Plastina,



**Figure 6.2** Three dimensional and longitudinal computed tomographic images of a denim yarn. Raina (2012).

more than two billion spindles are in operation worldwide (Plastina, 2009). Cotton fibre is initially opened, cleansed and evened out and finally converted into fibrous bundles with about 3000 fibres in cross section. These fibrous bundles are called flyer rovings. These flyer rovings are fed into the ring spinning machine to produce yarn. Major operations undertaken with the ring spinning machine include drafting or attenuation of flyer roving and further twisting of the attenuated fibres to form the yarn.

#### 6.4.2.2 Compact spinning

A major challenge observed in ring spinning technology over the years is the hairiness of yarn, which results from loose fibres that are not integrated into the yarn body. This is indeed a deterrent to the quality of denim fabric because the yarns have to be dyed before they are woven. The attribute of hairiness results in problems such as pilling and subsequent loss of yarn and fabric strength. A development in the field of compact spinning provides an answer to the attribute of hairiness. The hairiness of ring yarns is significantly reduced by using different condensers that curb the outward movement of individual fibres in the spinning triangle.

#### 6.4.2.3 Open end spinning

Open end (OE) spinning technology, also known as rotor spinning, belongs to the unconventional range of spinning principles. Yarn formation according to the rotor spinning principle dominates unconventional spinning methods. According to Plastina, more than 7.9 million spindles are in operation worldwide (Plastina, 2009). Denim products are mainly made of OE rotor cotton yarns because production is less expensive and a special yarn quality is obtained. Rotor yarns with a delivery speed of up to 160 m/min have been realised with machines with around 240 spindles (Biermann and Schmidt, 2002). Jansen showed that newer rotor spinning technologies such as Fancynation from Schlafhorst, Germany, have been able to improve the properties of the rotor yarn used for denim with mechanical properties comparable to ring yarn and saving up to 10% on the costs of manufacturing yarn (Jansen and Evren, 2006).

#### 6.4.2.4 Engineering yarn structures

Some of the essential processes during denim manufacture that a yarn undergoes after spinning are determined by the requirements of the yarn structure. The yarn structure needs to survive treatments such as the winding, dyeing, rewinding, fabric manufacture and finishing. The yarn structure can be engineered to retain a high degree of strength even in the final fabric. Some aspects that need to be investigated while engineering yarn structures are:

- Engineering fibrous structures in a yarn with the help of twist, to enhance dyeing performance. The compactness of the yarn and the capillary channels generated within the yarn cross section determine the energy required for dyeing and the dye uptake of the yarns.
- Application of modern spinning technologies such as air jet spinning provides high productivity during yarn manufacture along with enhanced yarn properties that are offered owing to the novel structure of the yarn.

- In the case of OE spun yarns, there is an influence of wrapper fibres on dye uptake and energy consumption during the dyeing and finishing of yarns and denim fabrics.
- Yarn structures need to be designed that enable zero emission of effluents during the fabric manufacturing process.
- Yarn structures need to be engineered to provide self induced elasticity without using external spandex filament yarns, thus resulting in a mono-material fabric.

These investigations would leverage the potential of denim fabric by reducing energy consumption and ensuring efficient recycling in the presence of mono-material systems.

## 6.5 Preparation of denim yarns

Staple fibre yarns are treated in different ways before they are used to manufacture denim fabrics. Warp yarns used for denim fabrics undergo multiple processes, as do the weft yarns.

#### 6.5.1 Production principles

#### 6.5.1.1 Weft preparation

The weft preparation is mainly winding, in which the yarns are wound from the feed onto a bobbin, which is usually a conical or cylindrical tube made of cardboard, plastic or (seldom) metal. Reasons for winding are to:

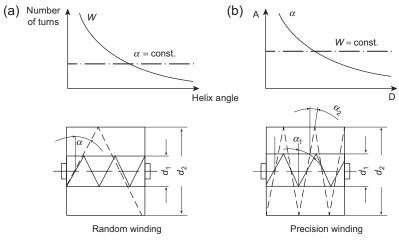
- Enlarge the yarn package for economic reasons and handling (rewinding from the cops of the ring spinning frame onto cross bobbins).
- Improve the draw off properties.
- Improve yarn quality by cleaning out thick and thin places of a yarn.
- Improve cops building for uniform dyeing with package dyeing.
- · Wind after package dyeing and wind off dyed hanks.

Weft yarn can be wound onto a number of bobbin forms and sizes. The most popular weft yarn packages are either random wound or precision wound. Figure 6.3 compares winding principles (Wiesel and Lünenschloß, 1988; Wulfhorst et al., 2006). Random winding is characterised by the:

- Surface drive of the bobbin.
- Constant helix angle  $\alpha$  independent of the bobbin diameter.
- Number of turns, which decreases with increasing bobbin diameter.
- Evolution of 'images', defined as layers, in which the threads lie parallel to each other at an integer ratio.

Precision winding is characterised by the:

- Number of turns W, which is constant with increasing bobbin diameter.
- Helix angle  $\alpha$ , which decreases with increasing bobbin diameter.
- Avoidance of 'image wrappers' with the help of a constant number of turns that is preset accurately at several digits.



**Figure 6.3** Comparison of winding principles. Wulfhorst et al. (2006).

Bobbins with random winding have a more stable construction than bobbins with precision winding. The surface drive of random winding is much less expensive than the spindle drive of precision winding. The essential disadvantage of random winding is the evolution of images. Such bobbins are not suitable for dyeing. Furthermore, layers of threads in the areas of the images may slip off while drawing off the yarns and produce filament breaks. These consequences of image turns can be reduced by methods such as overlapping the basic side traverse frequency with a wobbling frequency, slippage between the bobbin and the surface drive, periodical lifting of the bobbin, stroke displacement and variations in the bobbin speed (step precision).

#### 6.5.1.2 Warp preparation

Basic production principles for manufacturing woven denim fabric from spun yarn are depicted in Figure 6.4. The figure primarily focuses on the processing of warp yarns for weaving. Within the warping process, yarns are transferred from multiple individual yarn packages from spinning machines or winding machines into a single package assembly. Smaller yarn packages are placed in creels that can be arranged depending on the number of yarn bobbins available. The yarns are wound either in the form of a ball or on a dye beam or conventional beam. Once warped, the yarns undergo the dyeing process. The warp beams are warped depending on dyeing principles.

#### Rope dyeing

To manufacture denim, after they have been converted into balls the warp yarns are rope dyed. The ropes are continuously dyed with indigo. Within this process indigo colour is brought to the fabric and fixed, and finally the excess is washed away. It is

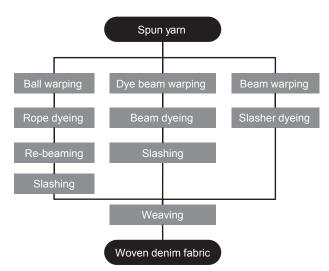


Figure 6.4 Process flow of warp yarns for denim manufacturing. Smekal (2001).

well known that most good ring yarn denim is rope dyed. Normally, 12–36 ropes are dipped in a series of dye boxes along an indigo dye range. Afterward the ropes are dried and sent to the beaming department.

#### Beam dyeing

In this process, warp yarns are wound directly onto a perforated drum. This beam is then dyed in a dye bath under controlled pressure and temperature. The dye liquor undergoes multiple cycles of fluid flow from the inside of the beam to its outside, and the other way round. This is a discontinuous dyeing method because the individual beams are dyed separately. The advantage of this process is that the beam can be directly sized and woven after been dried.

#### Slasher dyeing

Slasher dyeing is also a continuous dyeing process. In this process the entire beam is composed of warp yarns lying parallel to each other. The warp yarns are drawn into the dye baths and then dried. The next process involves directly applying sizing onto the warp yarns. The sized warp yarns are wound onto a beam that then can be directly used for weaving. This process does not require the warp to be re-beamed before it is placed on the weaving loom (Paul et al., 2001).

#### 6.5.2 Quality control

Before the staple fibre yarns are beamed, dyed and woven into fabric, the quality of the yarn needs to be scrutinised. This is especially essential to avoid defective dyeing of the yarns. Some frequent problems that occur are the detection of faulty dyed zones of yarn where the spandex core of the yarn has broken and is emerging from the yarn.

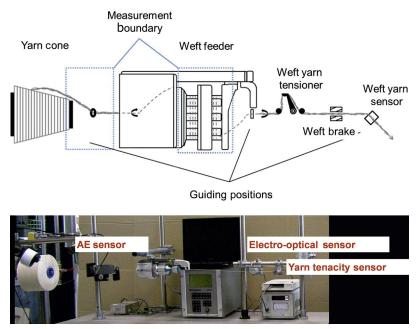


Figure 6.5 Test bench for measuring yarn quality.

In addition, yarn defects such as undesirable slubs cause problems during dyeing and further weaving and finishing of the denim fabric.

At the Institut für Textiltechnik Aachen (ITA), RWTH Aachen University, Germany, a novel test bench (Figure 6.5) was developed with multiple sensors to estimate different yarn faults before dyeing and winding. The test bench was designed for core-sheath yarns with spandex as the core. The test bench involves sensors such as the acoustic emission sensor, electro-optical sensor and yarn tenacity sensor. These three sensors act together to measure significant deviations in yarn properties. The results are further correlated to faults in the yarn. The test bench can also be miniaturised for application in the warp creels or even weft yarn winding machines to estimate yarn flaws before dyeing and winding.

## 6.6 Technologies for denim weaving

Denim weaving is generally carried out using air jet or rapier weft insertion technology. A crucial aspect in weaving denim is the weave design and the cover of the fabric produced. These aspects are discussed in detail in this section.

#### 6.6.1 Weave patterns for denim

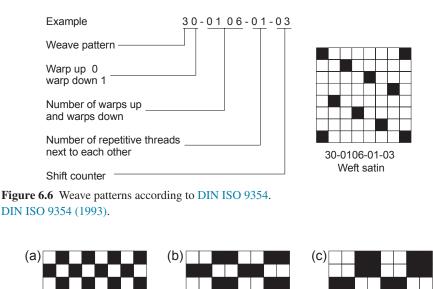
#### 6.6.1.1 Weave symbol

Weave patterns can be conventionally displayed using weave symbols. These are codes composed of repeated patterns of weave, number of warp threads up, number of warp threads down, number of threads and shift counter. The international standard for construction of the weave symbol is defined in DIN ISO 9354 (1993) and Figure 6.6 identifies these weave patterns (DIN ISO 9354, 1993). The first number describes the basic weave pattern, in which 1 stands for plain weave, 2 for twill weave, and 3 for satin weave.

Weaves that are employed for denim manufacture vary depending on the area of application. Fine denim fabrics are normally composed of plain weaves. Denim fabrics that are conventionally used under slightly rougher conditions are made using a twill weave.

#### 6.6.1.2 Plain weave

The plain weave pattern is the most basic as well as the tightest crossing of the warp and weft threads. The plain weave and its variations can be produced with only two shafts, because the threads or groups of threads alternate in tying up. For very tightly woven fabrics with a high density of threads, four, six or more shafts are used. Figure 6.7 shows a diagram of the plain weave and its simplest variations (Wulfhorst et al., 2006).



10-01-01-02-00

Rib weave

10-0202-02-00

Basket weave

**Figure 6.7** Plain weave and simple variations. Wulfhorst et al. (2006).

10-0101-01-00

Plain weave

## 6.6.1.3 Twill weave

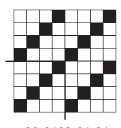
Twill weaves are characterised by a diagonal seam. According to the direction of the seam, Z and S twills are distinguished. The seam is caused by shifting the first warp thread or group of threads to the upper right (or the upper left, respectively). The magnitude of the shift is defined by the shift counter. Figure 6.8 shows basic twill weave patterns (Wulfhorst et al., 2006).

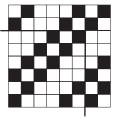
#### 6.6.1.4 Weave for denim jeans

Cotton denim fabric for jeans is woven in a twill weave with a pattern repeat of at least three warp threads and three weft threads. In denim fabrics, the interlacing points are mostly in the Z direction, as shown in Figure 6.9 (Wulfhorst et al., 2006). Twill weave allows tight processing, resulting in a very firm and long-wearing fabric that was originally used for farmer and worker pants in the US.

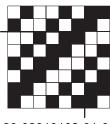
#### 6.6.1.5 Fabric construction

The classical construction of a bottom weight 14.5-ounce denim is 60–64 warp yarns per inch and 38–42 filling yarns per inch. The number of warp yarns per inch is sometimes referred to as the fabric sley. The weight is influenced by the size of the yarn used, the fabric weave design and the fabric tightness. Also influencing the fabric weight is the amount of size left on the finished fabric. Other denim fabrics and denim look-alikes may vary in construction from 52 to 70 warp yarns per inch and from 36 to 52 picks per inch. As a rule,



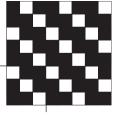


20-01010103-01-01



20-02010102-01-01

20-0103-01-01 20 **Figure 6.8** Basic twill weave patterns. Wulfhorst et al. (2006).



20-02 01-01-01

**Figure 6.9** Twill weave for denim fabric. Wulfhorst et al. (2006).

denim is woven as 3/1 twill, 2/1 twill, 3/1 broken twill or 2/2 broken twill. The weights of these finished fabrics can vary between 3.5 and 16.5 ounces per square yard. The weight of the fabric usually determines what the final garment application will be:

- 3.5–8.0 ounces per square yard: blouses, tops, shirts and top of bed fabrics.
- 8.0–16.5 ounces per square yard: trousers, jeans, jackets and upholstery.

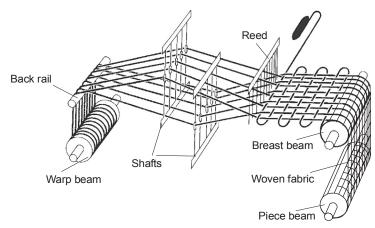
Numerical notations for different denim designs, such as 3/1, denote what each warp yarn is doing relative to the filling yarns with which it is interlaced. In this case, each warp yarn is going over three picks and then under one pick. This would be verbally stated as '3 by 1' twill or '3 by 1' denim. At the next end, moving to the right, the same sequence is repeated but advanced up one pick. This upward advancing sequence continues, giving the characteristic twill line. In this case, the twill line is rising to the right and the fabric is classified as a right-hand twill weave. If the twill line rises to the left, the design is a left-hand twill. Broken twills are designed by breaking up the twill line at different intervals, thus keeping it from being in a straight line (Wulfhorst et al., 2006; Paul et al., 2001).

#### 6.6.2 Basic principles of weaving looms

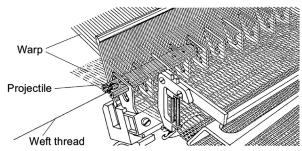
Figure 6.10 (Arbeitgeberkreis Gesamttextil, 1988) shows the basic weaving principle comprising two families of yarns, warp yarn and weft yarn, which are brought together to form a fabric. The warp threads are drawn off the warp beam and redirected into the weaving plane at the back rail. Functions of the back rail are to:

- Redirect the warp threads.
- Compensate for instability in warp tension during shed lifting by an oscillating motion.
- Act as a sensor for the warp let-off motion.

The shafts are equipped with healds through whose eyeholes the warp threads are pulled. The shed is built by the up or down stroke of the shafts. The movement of the shafts



**Figure 6.10** Principle of a weaving loom. Arbeitgeberkreis Gesamttextil (1988).



**Figure 6.11** Principles of projectile weft insertion. Arbeitgeberkreis Gesamttextil (1988).

is generated by cam or shaft machines. The size of the repeat or rapport corresponds to the number of shafts or to a multiple of this number. Wovens with large patterns can be produced with jacquard machines that allow the individual movement of single warp threads.

During weft insertion, the reed (Figure 6.10) is located at the back dead centre while the shed is open. With the change of shed, it moves forward to beat the inserted weft threads at the fell of the cloth. According to the principle of weft insertion, weaving looms can be divided into:

- Shuttle looms.
- Projectile weaving looms.
- Rapier looms.
- · Air jet weaving looms.
- Wave shed weaving machines.

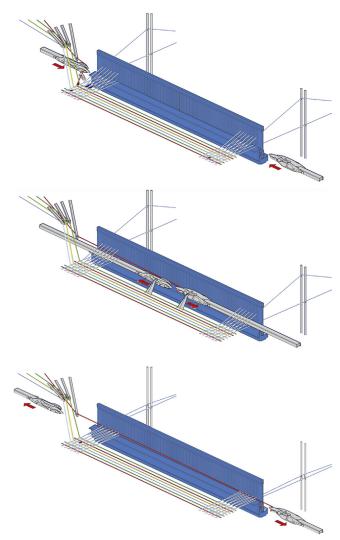
Under industrial conditions, looms that are often used to manufacture denim are the projectile, rapier and air jet looms (Paul et al., 1996).

#### 6.6.2.1 Projectile weaving loom

With the weft insertion principle, the weft thread is pinched in the projectile and then shot through the shed. After insertion, the thread is tensioned tightly and cut off the external weft bobbin. The projectile is transported back outside the shed. Therefore, one weaving loom operates with multiple circulating projectiles. Figure 6.11 shows the principles of projectile weft insertion (Arbeitgeberkreis Gesamttextil, 1988). In some manufacturing facilities, the projectile is also used because of lesser energy consumption compared with other weaving techniques.

#### 6.6.2.2 Rapier loom

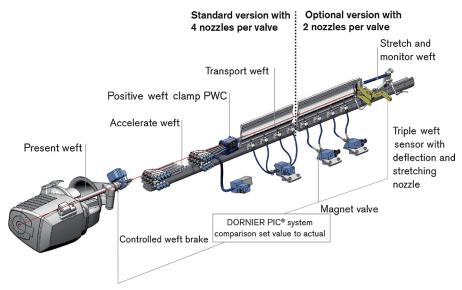
Rapier looms have an interlocking weft insertion system. The gripper head catches the yarn end from the feed bobbin and transports it through the shed. In the middle of the fabric the yarn is transferred to the opposing second gripper. Figure 6.12 shows the principles of rapier weft insertion (Lindauer DORNIER GmbH, 2013). The weft insertion is controlled at every moment of the process. Therefore, this principle is flexible and extremely suitable for delicate materials. Rapiers are available in rigid and flexible forms.



**Figure 6.12** Principles of rapier weft insertion. Lindauer DORNIER GmbH.

#### 6.6.2.3 Air jet weaving

The weft thread is transported through the shed with the help of a jet of air at high pressure (Ballhausen, 1992; Lehnert, 1994). Secondary jets located in the shed assist the main jet in transporting the thread. Air jet looms have the highest weft insertion speeds of all looms but they are limited in their flexibility with regard to suitable materials. Figure 6.13 shows the principles of air jet weft insertion (Lindauer DORNIER GmbH, 2013).



**Figure 6.13** Principles of air jet weft insertion. Lindauer DORNIER GmbH.

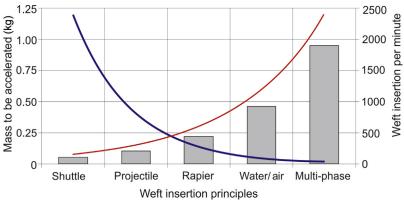


Figure 6.14 Comparison of weft insertion speeds.

#### 6.6.2.4 Weft insertion speed

The average weft insertion capacity of weaving looms is measured in metres per minute and can be calculated by multiplying the machine speed by the fabric width. Weft insertion is intermittent; therefore, actual weft insertion speeds are much higher. The acceleration of weft insertion is up to 1400 g or 14,000 m/s<sup>2</sup>. The evolution of the weft insertion speed is shown in Figure 6.14. The insertion speed may be increased by reducing masses. The most popular machine technologies used to manufacture denims are rapier and air jet weaving. These technologies are competent because of their ability to provide high productivity as well as to process denim fabrics with different yarn fineness.

## 6.7 Denim weaving machines

As described earlier, the denim fabric can be made using either rapier technology or air jet weaving. Multiple commercial companies offer machines that can be used to manufacture denim fabrics. Each major machine manufacturer is mentioned in this section along with its innovative solutions. This section provides also an overview of the technologies and machines available on the market.

#### 6.7.1 Machine manufacturers

#### 6.7.1.1 Lindauer DORNIER GmbH

The company Lindauer DORNIER GmbH, in Lindau, Germany, offers both the technologies: rapier and air jet weaving for the manufacture of denim fabrics. The company offers the P1 rapier weaving machine and the A1 air jet weaving machine for the manufacture of woven fabrics. Figures 6.15 and 6.16 show the rapier and air jet weaving machines (Lindauer DORNIER GmbH, 2013).

Innovations of the rapier machine include aspects such as the following:

- The filling insertion system of the weaving machine with positive control of filling yarn transfer in the fabric centre, combined with the open shed filling insertion feature, provides highest flexibility and quality reliability. The reliable filling insertion of lycra core yarns prevents the loss of elasticity on the exit side of the weft yarn.
- The newly developed QuickSet Tuck-in device, especially for narrow selvedges only 8 mm wide, allows the economic production of label selvedges on a rapier weaving machine.



**Figure 6.15** Rapier weaving machine for high quality denim. Lindauer DORNIER GmbH.

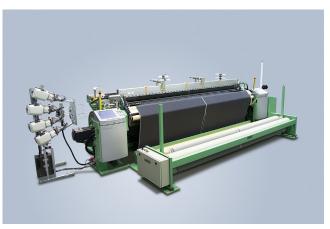


Figure 6.16 Air jet weaving machine for double width denim. Lindauer DORNIER GmbH.

The double width (400 cm) air jet weaving machine shown in Figure 6.16 also has special advantages:

- New TandemPlus main nozzles handle filling yarns gently during acceleration by spreading the point load along a larger thread length with less air pressure in the main nozzles. A hairy cloth appearance familiar using conventional single width air jet weaving machines is thus reliably avoided.
- The patented, new DORNIER PWC (Positive Weft Clamp) holds the filling thread mechanically in the main nozzle tube. Thus, it will not be damaged and colour deviations, i.e. sideto-side-shading in the fabric widths, can be ruled out. Energy is also saved because holding pressure is not necessary.
- The patented two thread full leno device, DORNIER MotoEco, is positioned between the two fabric widths. It prevents so-called 'first-pick-insertion bumps' because it is fully reversible. This is an imperative criterion for using automatic filling stop repair and guarantees freedom from start marks while improving the weaver's efficiency significantly.
- A two thread leno creates the catch selvedge on the filling exit side. This eliminates the expensive manufacture of selvedge yarn spools and their time consuming replacement. Furthermore, the reduced catch selvedge waste can be recycled without problems.
- The fabric quality is also not influenced by the often deficient warp preparation caused by the use of indigo dyes. The air jet weaving machine stops immediately and safely on every sticking warp end, therefore preventing weaving defects caused by a faulty warp.
- With its reliable automatic start mark prevention feature, ASP, and its stable machine frame, the air jet weaving machine produces better fabric quality than projectile and rapier weaving machines without controlled yarn exchange between the rapier heads and with up to 60% higher productivity.
- Maintenance requirements are much lower because of sturdy machine elements, fewer moving parts and therefore lower energy consumption.
- The double width air jet weaving machine handles warp yarns and shedding motion elements extremely gently, with much less strain than that of single width air jet weaving machines. Because of fast shed movements, the latter places extreme loads on yarn materials, and

especially on shafts, heddles and shedding motions. Because filling waste is halved, the double width machine is always more economical than any single width air jet weaving machine (Lindauer DORNIER GmbH, 2007).

#### 6.7.1.2 Picanol NV

Picanol NV, in Ieper, Belgium, is known for machines that are used to manufacture denim fabrics. Picanol offers the OptiMax rapier weaving machine, as shown in Figure 6.17 (Picanol NV, 2013b), for the manufacture of denim fabrics. Some outstanding features of the rapier weaving machine include the capture of the weft before beat-up by the Elsy selvedge device, which results in consistent weft tension in the fabric for stable quality output over the whole length of the beam. To reduce the weft waste to a minimum, and especially to control the release of elasticated wefts in the fabric, the Ergo option is highly recommended because it allows the precise moment of release for each individual weft type to be set independently.

Figure 6.18 depicts the OMNIplus 800 air jet weaving machine (Picanol NV, 2013a). Among special features, productivity is enhanced by the Pick Repair Automation



**Figure 6.17** OptiMax rapier weaving machine. Picanol NV.



Figure 6.18 OMNIplus 800 air jet weaving machine. Picanol NV.

system, which enables incompletely inserted wefts to be removed automatically and the loom to be restarted in less than 30 s. This not only reduces the weaver's workload, it gives a consistent look to the fabric on restarting the loom.

#### 6.7.1.3 Tsudakoma Corp.

Tsudakoma, in Japan, also manufactures air jet weaving machines used to manufacture denim. The ZAX-N is the latest air jet weaving machine offered by the company for the manufacture of denim, as shown in Figure 6.19 (Tsudakoma Corp., 2013). Highlighted features of this machine include the following (Tsudakoma Corp., 2013):

- For tuck selvage formation, fillings are tucked in the edge by force of air instead of conventional tuck in needle movement.
- Combining the positive yarn catcher, the main nozzle clamper and the WBS weft brake system, depending on the type of yarn kind, facilitates weaving of high quality stretch fabrics.
- The stretch nozzle effectively prevents filling looseness. It holds the filling by air to eliminate any slack pick.
- In the case of mis-insertion of the filling, the APR-C automatically reverses the loom, removes the defective pick and restarts the loom by computer control.

Up to eight kinds of loom revolutions per minute (rpm) can be set independently. Formerly, the loom rpm was restricted by some kinds of weft yarns. When using multiple kinds of wefts, including difficult yarn, the programmable speed control automatically increases the loom rpm, except for the section using the difficult yarn. It changes the rpm within one pick, which increases productivity.

#### 6.7.1.4 Itema S.p.A.

Itema S.p.A. is a Swiss–Italian weaving machine manufacturer that provides air jet weaving machines for denim production. The most well known machine offered is the A9500, which is depicted in Figure 6.20 (Itema America Inc., 2013). In addition to the weaving machines mentioned in this section, smaller rapier and air jet machine manufacturers produce machines for local applications. The machinery manufacturers and



**Figure 6.19** ZAX-N air jet weaving machine. Tsudakoma Corp. (2013).



**Figure 6.20** A9500 air jet weaving machine. Itema America Inc. (2013).

the machines mentioned encompass a large market volume and produce high quality denim fabrics.

#### 6.8 Weaving with intelligent machines

Denim fabric has a number of applications. However, further market penetration of the fabric can be achieved by producing the fabric at high quality and at low cost. Automation offers an avenue to reduce costs as well as to produce at a high quality. This section takes into account the major processing parameters that have been automated to have an intelligent machine.

Warp tension is the major process parameter for weaving. It influences process stability and product quality. Too high a value for the tension leads to warp breaks and interruption of the weaving process. Too low a value leads to clamping of the threads, which also results in warp breaks.

New approaches to simulate warp tension and predict fabric quality using radial basis functions are presented. Recently, new simulation tools were developed at RWTH Aachen University to realise a cognitive weaving process. Using DesParO software developed by Fraunhofer-SCAI, Germany, researchers investigated the ability to predict process parameters and product quality on a loom. The main components of DesParO software are radial basis functions (Clees, 2004).

#### 6.8.1 Simulation of warp tension

The database for the simulation comes from an OMNIPlus800-4-P 190 air jet loom from Picanol NV, Belgium (warp: CO 740 dtex, 4044 threads; weft: 100 tex; pattern: twill weave). In the design of experiments, the following parameters were used, as shown in Table 6.1:

- *X*/*Y* position and slope of warp stop motion.
- Number of picks per centimetre.
- Loom speed.

Warp tension and heald frame movement were recorded using a measurement system developed at ITA, Germany (Gloy et al., 2009).

| Machine parameter                     | Unit       | Level A | Level B |
|---------------------------------------|------------|---------|---------|
| X position of warp stop motion        | (°)        | 0       | 13      |
| <i>Y</i> position of warp stop motion | (mm)       | -20     | +20     |
| Slope of warp stop motion             | (mm)       | 0       | 100     |
| Number of picks per centimetre        | (picks/cm) | 8       | 17      |
| Loom speed                            | (rpm)      | 400     | 800     |

Table 6.1 Varied loom parameters

 Table 6.2 Varied loom parameters

| Warp tension | Unit      | Measured | Simulated |
|--------------|-----------|----------|-----------|
| Minimal      | (cN/yarn) | 00.5     | 00.2      |
| Maximal      | (cN/yarn) | 28.8     | 29.6      |
| Medium       | (cN/yarn) | 10.6     | 10.8      |

#### 6.8.2 Verification of simulated results

Simulation with DesParO was able to predict warp tension and product quality based on loom parameters. For example, the leave-one-out cross-validation of the simulation shows that the simulation predicts nearly the same values as the warp tension measurement with a tolerance of  $\pm 0.02$  N, as shown in Table 6.2.

Furthermore, DesParO gives a weighted presentation for the correlation between input and output parameters. This correlation matrix shows that the Y position of warp stop motion has the biggest impact on the warp tension. Figure 6.21 shows the simulated characteristics of warp tension depending on (left) the loom speed and Y position of the warp stop motion and (right) the correlation matrix of machine parameters regarding warp tension. These initial endeavours have been successful in producing woven denim fabric of high quality at comparatively lower costs using intelligent weaving machines and algorithms.

#### 6.9 Manufacture of high quality denim

The quality of the denim has a crucial role. To enhance the quality and make it measurable, some technological developments in terms of the use of sensors have been undertaken. Fabric weight is a fundamental quality criterion for a woven fabric. It is determined according to DIN EN 128,181 by weighing. The setting of the weaving machine with regard to the fabric weight can be calculated using the following formula:

$$m_{\rm G} = T_{\rm Warp} \cdot F_{\rm d_{Warp}} \cdot \left(1 + \frac{C_{\rm Warp}\%}{100}\right) + T_{\rm Weft} \cdot F_{\rm d_{Weft}} \cdot \left(1 + \frac{C_{\rm Weft}\%}{100}\right)$$

with  $m_{\rm G}$ =fabric weight [g/m<sup>2</sup>], *T*=yarn count [tex],  $F_{\rm d}$ =thread count [picks/cm] and *C*=crimp (Schmitt et al., 2011).

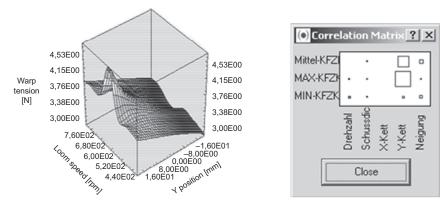


Figure 6.21 Simulated characteristics of warp tension.

Hence, for a given thread material and fabric weight, the required thread count can be calculated and the weaving machine accordingly set up. In general, a sample fabric is woven and the fabric weight is measured. If the measured fabric weight differs from the reference fabric weight, the weft count is further adjusted until the reference fabric weight is matched. Adjustment of the warp count involves time and effort. A possibility for controlling fabric weight during the weaving process is presented in the following sections.

#### 6.9.1 Principles for measuring fabric basis weight

Looking at the weaving process, it is clearly apparent that transport of the fabric between the breast beam and cloth roll is a mass transport. Following the construction catalogue (Ramakers et al., 2006), there are various methods for weighing a mass transport:

- Photodiode/quantum detector.
- Capacitive.
- Mass flow measurement with static charge/charge separation.
- · Mass flow particle measurement.

Furthermore, the heavy mass of a line load can be determined by:

- · Integrated or additional belt weighing machines.
- · Gravimetric basis weight measurement.

In addition, the following mass detection systems may be considered (Kochsiek, 1989):

- · Mass spectrometer.
- Measurement of the absorption of radiation.
- Measurement of the reflection of radiation.

| Measuring methods   | Fitness | Ability to integrate | Cost | Sum |
|---|---------|----------------------|------|-----|
| Photodiode/quantum detector                                   | 1       | 1                    | 1    | 3   |
| Capacitive  | 1       | 2                    | 2    | 5   |
| Mass flow measurement with static<br>charge/charge separation | 0       | 1                    | 1    | 2   |
| Mass flow particle measurement                                | 0       | 1                    | 1    | 2   |
| Integrated or additional belt weighing machines               | 0       | 0                    | 1    | 1   |
| Gravimetric basis weight<br>measurement                       | 2       | 0                    | 0    | 2   |
| Mass spectrometer   | 2       | 0                    | 0    | 2   |
| Measurement of absorption of radiation                        | 2       | 2                    | 1    | 5   |
| Measurement of reflection of radiation                        | 2       | 2                    | 0    | 4   |

#### Table 6.3 Evaluation of methods for measuring mass flow

0=not suitable, 1=suitable, 2=perfectly suitable.

The different measuring methods were evaluated and key factors for the evaluation were fitness, ability to integrate in the weaving process and cost. The results of the evaluation are shown in Table 6.3.

#### 6.9.2 Online measurement of fabric weight

The highest performance is achieved by the capacitive sensing and capacitive absorption measuring methods. Pre-examination has proven that the capacitive measurement is not suitable and therefore measurement of absorption of radiation was investigated (Gloy et al., 2012). The X-ray measuring system used was offered by BST ProControl GmbH, in Freudenberg, Germany. The system consists of an X-ray emitter and a receiver, as shown in Figure 6.22 (Spies and Moder, 2006). The X-ray emitter operates at an accelerating voltage of 5kV. The sensor has a measurement range of 500–1000 g/m<sup>2</sup>, a resolution of  $0.1 \text{ g/m}^2$  and an accuracy of  $0.3 \text{ g/m}^2$ . The sensor needs a pressurised air supply with 3 bar.

Mounts were manufactured to integrate the measuring system into the weaving machine. Thus, the measuring system can be installed between the breast beam and cloth roll. Figure 6.23 shows the exact measuring arrangement. The measuring system was tested on an OmniPlus 800 weaving machine manufactured by Picanol NV in Belgium, in the technical centre of the ITA, RWTH Aachen University, Germany. The weaving machine is equipped with polyester 730 dtex f2 in weft and warp yarn. The warp density is 20 picks/cm. The operating speed is 700 rpm and a twill 3/1 fabric is woven. The sensor signal is recorded while running the

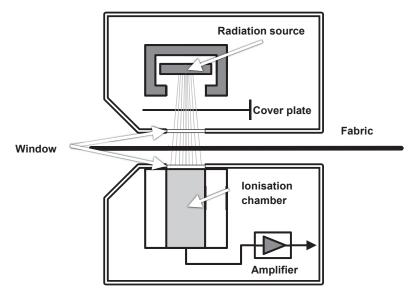


Figure 6.22 Principle of X-ray system.

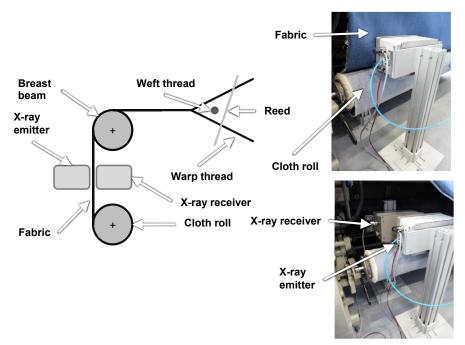
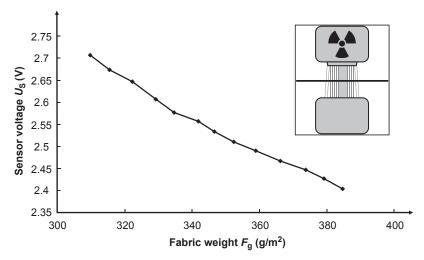


Figure 6.23 Installation of X-ray system in a weaving machine.



**Figure 6.24** Correlation between sensor signal  $U_s$  and fabric weight  $F_g$ .

machine on different weft densities. Afterward, the fabric weight for each variation of the weft density is measured according to DIN EN 128,181. A linear correlation between the fabric weight and sensor signal was found after test results were evaluated (Figure 6.24).

#### 6.9.3 Control of fabric weight

Integration of a suitable sensor in the weaving process is an essential milestone for the realisation of fabric weight control. The following section describes the design and realisation of fabric weight control. Because of the arrangement of the measuring system, a high dead time affects the control. This means that variations in the weft density or fabric weight can be detected only after a certain time. The time depends on both the weft density and the rotation speed of the machine.

A possible way to control processes with high dead time is to use the Smith predictor. The Smith predictor uses a parallel dead time free model of the process. The control loop was implemented in the software ibaLogic, from iba AG, Fürth, Germany. The connection to the weaving machine was established using an Ethernet interface. A proportional and integral controller with the weft density used as the manipulating variable was designed. Figure 6.25 shows the control loop using the Smith predictor to control the fabric weight, where  $G_F$ =transfer element to scale the actuating variable,  $G_R$ =transfer element of the controller,  $G_S$ =transfer element of the sensor,  $G_S$ =transfer element of the sensor model,  $G_W$ =transfer element of the weaving machine model,  $G_T$ =transfer element of the dead time and  $G_W$ =transfer element of the weaving machine.

First, the system needs to be adjusted with regard to the yarn material. For this, two different weft densities are woven. The corresponding X-ray signal is recorded and the fabric weight of the two weft densities is weighed in the laboratory. For the

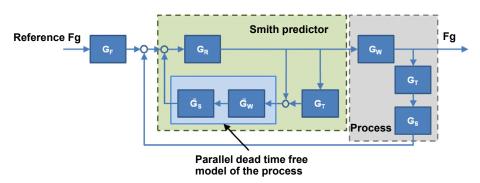


Figure 6.25 Use of the Smith predictor to control fabric weight.

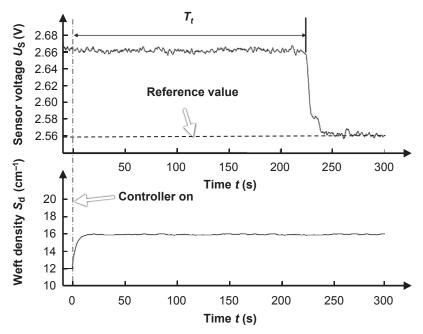


Figure 6.26 Dynamic behaviour of sensor voltage and weft density.

following system check, the reference fabric weight was set to  $300 \text{ g/m}^2$ , which was equivalent to a 2.55 V sensor signal. The controller was started at time t=0. Within 25 s the weft density reached a value of 15.7 picks/cm, which satisfied the reference fabric weight. Thus, the control system was successfully implemented. Figure 6.26 shows the dynamic behaviour of the sensor signal and the weft density during the system check.

In a final step, the control was verified in a field test at the Weyermann Technical Textiles GmbH & Co. KG, in Wegberg, Germany. For this purpose the system was installed in a weaving machine OmniPlus 800 manufactured by Picanol NV, in Belgium. The machine was equipped with polyester 167 dtex f64 for weft and polyester 76 dtex f74 for warp. The machine ran at 675 rpm and a twill fabric was produced. At first the weft density was preset to 26.5 picks/cm. A fabric with 80 g/m<sup>2</sup> should have been produced. During the operation, the control set the weft density to 27.1 picks/cm in less than 30 s. The produced fabric at this weft density had an average fabric weight of 79.8 g/m<sup>2</sup>. Thus, the functionality of the control was shown in this field test.

In this way, it is possible to monitor and control the fabric weight on a weaving machine with an X-ray sensor. The positioning of the sensor creates a high dead time. Therefore, a Smith predictor was used in those investigations. Validation of the control showed good results. A fabric weight with an accuracy of 3% was obtained in less than 30 s. These properties are advantageous for the manufacture of high quality denim fabrics with automated technologies.

#### 6.10 Future trends

The denim market is highly competitive and is driven by volume and not necessarily by niches. Thus, success for companies in the denim market needs to be driven by aspects such as process optimisation and marketing profile (Österreichische Textil Zeitung, 2004). Future trends also signal the use of different kinds of finishing technologies to differentiate among fabrics. Fabric finishing in the form of stone washing, damaged looks and so forth call for fabrics with even, high strength and robust properties. Engineering the denim fabrics and producing them at lower prices will be the trend in the future. Because a basic need is to make fabrics cheaper, automation will have a significant role in the manufacture of denim fabrics. Self optimised manufacturing processes that are also self learning are the path into the future. This will involve aspects such as quality monitoring and regulating in real time on machines.

Another future trend will be the self configuring of denim fabrics by end use customers. The ideas and concepts of mass customisation will be the drivers here. Using customer requirements and realising one piece flow manufacturing at lower rates is also the future of the denim manufacturing industry.

Denim is currently used to a significant amount in the apparel and accessories industry. A trend is slowly building to use denim for certain other applications. Denim as a fabric is expanding its horizon of application in other fields. There is an interesting trend for using denim fabrics as surface layers in fibre reinforced composites in applications such as automotives, suitcases, bags, furniture and such. The principal driving factor is the denim look, which has been appreciated over the centuries.

#### 6.11 Conclusion

This chapter provides an overview of different aspects associated with denim fabric manufacture. After a brief introduction of the beginnings of denim fabric, different fibres and yarns used for the fabric manufacture were described. The potentials of designing a yarn for denim applications have been discussed in detail. These avenues for engineering yarn structures should be explored to be able to address issues such as a reduction in energy consumption and material efficiency in denim manufacture. A detailed overview of the different weaving technologies and weave designs and machines was elaborated upon. The future lies in automation of the denim weaving process. Avenues have been revealed for automation of the weaving process using different simulation tools.

Quality also has a decisive role in the denim industry. New quality control systems have been introduced to measure fabric quality online. Implementation of these technologies for commercial use will be the future of quality control in denim manufacture. The future of denim manufacture also depends on aspects such as the production of denim on self optimised cognitive machines. These machines will also regulate themselves to provide the highest possible quality, but also will reduce energy consumption in the manufacture and will optimise material and resource efficiency.

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Part Two

# Manufacture and finishing of jeans

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## Role of denim and jeans in the fashion industry

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## 7.1 Introduction

One response to a question regarding an understanding of the role of denim jeans could be 'jeans is an attitude, not a pair of pants' (Plenzdorf et al., 1997). Denim jeans, which have historically been considered a universal symbol of freedom, rebellion and expression of individualism, are slowly becoming a status symbol. Nowadays, fit, style and comfort are becoming increasingly important for consumers. In this context, it is interesting that the global production of denim jeans is over 1.7 billion jeans each year. Although it is consumed globally, 70% of global denim textile production occurs in Asian countries (Textiles Intelligence, 2012). Once thought of solely as work wear, jeans are now accepted in almost all situations (Wajda, 1992). Quantitative data and intrinsic consumer value are equally important when analysing the importance of denim. This section focuses on resources to determine the economic importance of denim, and this is followed by the intrinsic value provided when consumers wear jeans. The intrinsic value of denim drives their economics because it is a way of life for consumers.

The jeans market is composed of a full range of retail price points from 25 to over 800 USD. Jeanswear typically refers to jeans that sell in mass merchandisers and mid-tier retail stores for under 100, whereas premium denim jeans typically sell in contemporary department and specialty stores for over 130 USD. Industry analysts predict the global jeans market to reach 56 billion USD by 2018 (Salfino, 2013). The largest jeans manufacturers are located in the United States. Levi's, Wrangler<sup>TM</sup> and Lee, owned by Levi Strauss & Co. and VF Corporation, respectively, annually sell approximately 7.9 billion USD.<sup>1</sup> VF expects its jeanswear division to grow to 3.3 billion USD by 2017 with a focus on continuous product innovation and to expand its jeanswear portfolio of brands (Security and Exchange Commission, 2014a,b). Europeans consume more premium jeans than do American consumers and its market is approximately double the US market (Kellogg, 2013). Large European firms Hugo Boss and Armani, who have premium jeans in their product lines, sell over 3.8 billion EUR,<sup>2</sup> with the Armani's Jeans segment accounting for annual sales of over 300 million EUR (Giorgio Armani, 2012; Hugo Boss AG, 2012).

<sup>1</sup> Sales of VF Jeanswear, VF Contemporary Brands Coalitions and Levi Straus & Co. Revenue.

 $<sup>^2</sup>$  Hugo Boss AG and Giorgio Armani are corporate sales, not solely jeans. These figures exclude licensing sales.

Although it is small relative to jeanswear, the premium denim jeans sector is a considerable market segment. Kellogg (2013) noted that although the apparel business is never a straight line, she expected premium denim jeans market segment to grow over the next 10 years. For instance, current 7 for All Mankind sales at 415 million is anticipated to grow to 645 million USD within 5 years (Security and Exchange Commission, 2012; VF Corporation, 2013). Denim jeans are increasingly important to consumers: Women account for 50% of the market share, followed by men (27%) and children (23%) (Newbery, 2009). For some companies such as Levi Strauss & Co., men account for a substantially larger market segment than women (Security and Exchange Commission, 2014a).

Globally, denim consumers differ among Europe, the US, and Asia. European consumers desire high priced fashion denim, whereas American consumers generally pay less than international consumers (Security and Exchange Commission, 2014b). American men typically spend an average of 50 to over 75 USD for denim jeans whereas Australian men are willing to pay 50–800 (USD) for jeans and European consumers typically buy premium denim jeans retailing for more than 130 USD (Cohen, 2013; Kellogg, 2013; Jegethesan et al., 2012). In the US, female consumers are fragmented and generally pay less than 50 USD or over 75 USD, whereas female Australian consumers pay between 150 and 400 USD (Cohen, 2013; Jegethesan et al., 2012). Asian consumers prefer mid-tier American branded jeanswear that are of high quality. Chinese consumers are cognizant of the price of denim jeans, which makes it the most important purchase decision, whereas Indian consumers view fit and country of origin before considering price (Jin et al., 2010).

# 7.2 Denim fabric and apparel business

Denim fabric and finished garments are globally imported and exported. As top tier developed countries, the US and European Union (EU) are indicators of the economic importance of denim. As with most apparel products, the US and EU import most of their denim<sup>3</sup> textiles and apparel. In 2012, the US imported 30.5 million m<sup>2</sup> of denim fabric valued at 79.7 million USD and 4.1 billion USD of men's and women's blue denim trousers (United States Department of Census, 2012). Mexico is the leading supplier of raw denim pants (before finishing), followed by China and Bangladesh. These three countries account for over 66% of raw denim imported into the US. Most of the imported blue denim was considered low or mid-tier price points. The raw denim (before finishing) import price ranged from 6 to 14 USD for men's and boys' jeanswear and 6 to 11 USD for women's and girls' jeanswear (Textiles Intelligence, 2013). Denim finishing, which gives a considerable value added price to denim products, is located in Los Angeles (Security and Exchange Commission, 2012). Imported denim jeans typically sell for mid-tier price points in which the average consumer spends 35 USD (Salfino, 2013). The US is a major exporter of textiles

<sup>&</sup>lt;sup>3</sup> The specific categories are 347-D and 348-D for blue denim, referring to the fabric structure used in apparel.

and finished denim jeans. In 2009, the US exported 108.4 m<sup>2</sup> of blue denim valued at 215.2 million USD and slightly over 4.7 million units of men's and women's jeanswear (United States Department of Census, 2012). Levi Strauss & Co., the largest denim jeans manufacturer, exports approximately 50% of its products, and Europe and Asia Pacific consumers buy approximately 1.8 billion articles of Levi jeanswear (39% of company revenue) (Security and Exchange Commission, 2014a).

The EU varies slightly from the US with imports: Denim accounts for 34% of men's and 23% of women's pants imported into the EU, with the raw denim value (before finishing) accounting for 2.6 billion USD. Asian countries including China, Turkey and Bangladesh are the major denim export countries to the EU (Textiles Intelligence, 2011, 2013). European denim apparel companies including Armani Jeans export denim jeans throughout the world (Giorgio Armani, 2012).

## 7.3 Soft value of denim jeans

The importance of denim is not simply numeric valuation; rather, it is valuable to consumers. Many consumers value denim jeans because of their practicality in numerous social settings. The president of VF Contemporary Brands provides an analogy:

Wearing premium denim jeans is a very emotional proposition and it's an indulgence; it's like why would you buy a BMW versus a Volkswagen or why would you treat yourself to Häagen-Dazs<sup>®</sup> versus Dryers ice cream? A 200 USD pair of jeans is a splurge. Compared to a 50K BMW, it's an affordable splurge. Compared to a 20 USD Chanel lipstick it is not. I think that the psychology behind it is that premium denim jeans are an indulgence. Wearing your favorite denim jeans brand makes you feel better, you think you look better, and it gives you confidence. Kellogg (2013)

Not long ago, there were strict dress codes. People wore jeans only for work and never in social situations such as going to church or school (Wajda, 1992). This contemporary scenario at a country club is an anomaly because societal norms changed and wearing denim jeans is the norm rather than the exception: 'Jeans are not allowed at the country club. They would not let me get up for the buffet line; they had to bring me my food and they asked me not to leave my table or go to the bathroom, but they would allow me to finish my meal (Kellogg, 2013)'. Despite some formalities, the casualisation of America and the world is here to stay, and denim jeans are acceptable for wear most everywhere from church to a wedding, which once was taboo.

## 7.4 History of denim and jeans

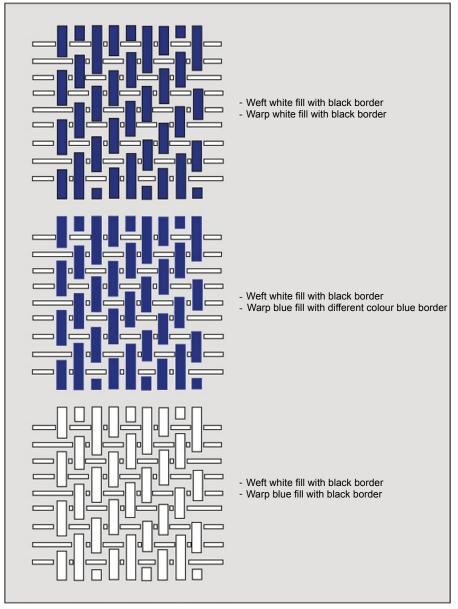
The history of denim spans over 400 years. Denim, an old fabric, originated in Europe and remains current, is seen and manufactured all over the world. Looking at the history of denim allows us to see the transition of denim from its association with peasants and the working class to one of cultural acceptance in all social classes (Paul and Joseph, 2003a). One can sum up the history of denim with the keywords 'twill', 'invention' and 'rivets'.

#### 7.4.1 Twill fabric

By the thirteenth century, England and the European Continent had an established textile industry (Miller, 1965). During the Middle Ages, cotton fabrics were available throughout Europe and Britain (Gallo, 2010). The first recorded denim textile manufacture is from Nimes, France, however, some historians contest this locale, stating that jeans fabric originated in Genoa, Italy (Charlton, 2010). The history of denim, although nebulous, begins in the seventeenth century with an anonymous painter nicknamed the 'Master of Blue Jeans' (Charlton, 2010). Curators from Galerie Canesso in Italy provide excellent documentation of the Master of Blue Jeans (Gallo, 2010). The Master of Blue Jeans, believed to be from Northern Italy, painted in the Lombard style. The Lombard style is associated with Italian painters who composed simple themes with exquisite detail. The Master of Blue Jeans appears to be the first recorded document that shows all of the elements of denim with indigo dye, white cotton warp and twill fustian weave (Charlton, 2010). The fabric represented in the paintings was not referred to as denim during the 1600s, but close examination of the fabric shows distinctive blue and white yarns representative of toile de Génes or Genoese fabric manufactured in the Northwest region of Italy (Gruber, 2010). One may ask why a seventeenth century painter chose to paint working class people in a blue cloth that resembled denim and painting with indigo dye.

Historians trace denim structure to fustian, a fabric with a cotton weft and linen warp that has it roots in antiquity. During the Middle Ages, fustian became increasingly important to Italian entrepreneurs as they manufactured varying weft and warp structures composed of cotton, wool and linen in tabby and diagonal weaves. During the Middle Ages and the Renaissance, textile mills named fabrications after the city of manufacture (Paul and Joseph, 2003b; Gallo, 2010). Denim is a type of fustian in which an indigo dyed warp is combined with an undyed weft into a 3/1 twill fabric (Textiles Intelligence, 2011). Figure 7.1 (illustration by Jennifer Cello) shows the twill structure of denim fabric. Fustian cloth was popular among the working class for its attributes of reasonable price, strength and soft drape.

While Italy gained a reputation for manufacturing low cost sturdy fabrics, competition, always prevalent in the textile industry, was in nearby Nimes, France. Fustian cloth and *serge de Nimes*, or cloth of Nimes, coexisted simultaneously (Gallo, 2010). Denim's nomenclature starts to gel as historians found linkages to the origin of the denim nomenclature with France's *de Nim* and Genoa textile entrepreneurs who nicknamed its inexpensive fustian fabric as *jean* (Downey, 2007; Paul and Joseph, 2003a). As a port city, Genoa, Italy, had an important role in the export of fustian cloth because this inexpensive cloth rapidly spread to the continent, to Britain, and eventually to America. Britain textile manufacturers offered an extensive



**Figure 7.1** Denim twill structure. Jennifer Cello.

selection of cheap and mid-range fabrics; historians believe British mills exported *serge de Nimes* in the late 1600s (Miller, 1965). The American colonies imported fustian cloth, and by the late 1700s American mills began to manufacture denim. The distinction of American denim is that warp and fill was made from cotton yarns;

*serge de Nimes*, made at the same time on the European continent, was made of silk and wool (Downey, 2007). Textile mills also produced *jean* for work clothes (Gallo, 2010), however, the waist overalls associated with blue denim jeans had not yet been developed.

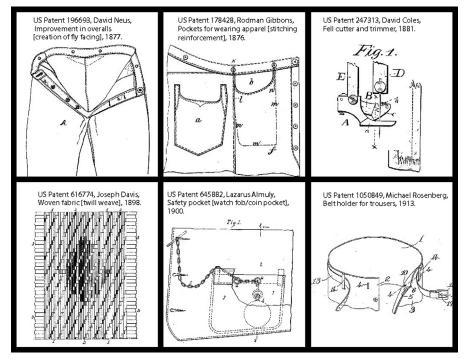
## 7.4.2 Invention of waist overalls

The general population associates Levi Strauss with being the originator of jeans. Downey (2007) noted that Levi Strauss did not create the cut or fit of the first waist overalls; rather, his company patented the use of rivets to strengthen work overalls (Davis, 1893). Historians who studied original artwork, garments, military records and reports during the eighteenth and nineteenth centuries use these as indicators of the invention of classic jeans. France was the leader in men's styled pants, introducing breeches, pantaloons and trousers (Moore and Haynes, 2003). These men's clothing styles eventually came to the US. Historians trace waist overalls, an American invention, as the origin of denim jeans (Karr, 2012). First recorded by the Continental Congress in 1776, waist overalls appeared in the US as part of the military uniform. Waist overalls were a variation of pantaloons that had a looser fit, sat higher at the waist and fit snugly over shoes (Moore and Haynes, 2003). Waist overalls were common and practical for early American military explorers in the 1800s, such as Lewis and Clark, and subsequently were adopted by the general public. Like other pants styles, waist overalls had a front fall (flap) tie in the back and tight waistband, and were worn with suspenders. Waist overalls primarily consisted of wool and linen fibres dyed blue or bleached white during the early 1800s. Some early settlers preferred leather, however, kersey was the primary fabrication for waist overalls. Kersey was a twill fabrication made from inferior wool fibres. Other fabrication included duck cloth and sheeting. Generally, military explorers wore cloth overalls until they wore out. Men replaced the kersey or duck cloth overalls with animal skins and leather hides because they were available in the wilderness (Moore and Haynes, 2003).

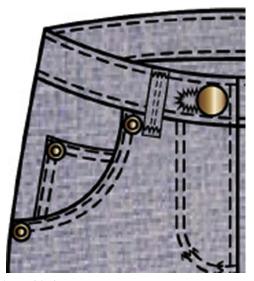
Design components associated with elements of the classic denim jeans style evolved during the 1800s. Early American explorers noted the use of a small pocket on the front of overalls to hold a watch fob (Moore and Haynes, 2003). By the mid to late 1800s, many entrepreneurs invented design components relative to classic jeans styling. Waist overalls were not a single invention; rather, many entrepreneurs should be given credit for their silhouette and design details. Clothing patents were prolific in the US during the mid to late 1800s. Related to waist overalls design were the button fly for trousers (Neustadter, 1877), a pattern for the bifurcated garment with side pockets by Clyde (1881) and a scoop inseam pocket variation by Rodman (1876). Buttons date back to antiquity, however, molded buttons and rivets, commonly found on classic jeans, are associated with military style buttons. Two piece buttons, found in rivets, were invented in England in 1813, later known as the Scoville button. They were commonly used by US soldiers in the 1800s (Moore and Haynes, 2003). Michael Rosenberg invented a belt holder for trousers that today we commonly call belt loops (Rosenberg, 1913). Among many

sewing machine inventors, David Coles invented a fell cutting attachment that we associate with inseams or outseams of classic jeans (Coles, 1881). The early explorers commonly sewed patches on their waist overalls (Moore and Haynes, 2003); patches resurged as a fashion trend in the 1960s (Gordon, 1991). Even the skinny jeans style is not new because skintight pantaloons, emulating this style, were worn as early as 1803 in the US (Moore and Haynes, 2003). Figure 7.2 (compiled by author) shows the historical evolution of jeans based on various inventions in US patents.

Nonetheless, Levi Strauss is a principal figure in the history of denim; apparel entrepreneurs dream of his achievements. A visionary who cohesively combined separate design elements to develop a historically successful clothing style, Strauss, born Loeb Strauss, aged 18, immigrated to New York City from Bavaria with his mother, following his eldest siblings. Strauss worked at Strauss & Brother, his brother's dry goods store, in New York City. Following his married sisters, he moved to San Francisco in 1853. He partnered with and received merchandise from Strauss & Brother in New York and his in-laws helped build the San Francisco business (Michael, 2013; Paul and Joseph, 2003b). Strauss became a successful retail merchant; his dry goods establishment sold clothing and dry goods, and imported items as well as wholesaling



**Figure 7.2** Evolution of jeans from US patents. Collage created by author.



**Figure 7.3** Jeans pockets with rivet support. Jennifer Cello.

dry goods and fabrics for merchants and tailors (Tamony, 1973). From its inception, Levi Strauss & Co., formally established in 1860, was a close-knit family business (Michael, 2013).

Jacob Davis, a customer of Levi Strauss & Co., was a struggling tailor who sewed horse blankets, tents and wagon covers (Sullivan, 2006). A customer asked Jacob Davis to make sturdy work pants that would not rip at the seams, thought of because the miners who put rocks in their pockets complained because they ripped (Downey, 2007; Robinson, 2013). This inspired Davis to apply copper rivets at stress points, the same technique he used to reinforce horse blanket straps. Figure 7.3 (illustration by Jennifer Cello) shows jeans pockets with a rivet support.

Davis' idea was popular, but without the money to pay for a US patent to protect his idea, he wrote to Levi Strauss. Jacob Davis knew Levi Strauss because he bought denim fabric from his dry goods store (Downey, 2007; Downey, 2013). In his letter, Jacob described the novelty of his rivet fastenings and explained that he could not keep up with the demand. He appealed to Strauss to file a joint patent (Tamony, 1973). After three tries, Strauss and Davis received US Patent 139,121 for improvements in fastening pocket openings (Figure 7.4). The patent was to place metal rivets or eyelets at pocket openings to prevent ripping of seams from strain or pressure (Davis, 1893; Sullivan, 2006). The original Levi Strauss & Co. waist overalls were made from Amoskeag Manufacturing Company cotton duck and denim fabrics. By 1915, Strauss formed an exclusivity arrangement with Cone Mills (known as the Proximity Manufacturing Company) (Anon., 2009–2013). Levi Strauss continued to improve his original design and by 1890 he trademarked the XX (Levi's 501) waist overalls (Downey, 2007, 2008; Levi Strauss & Co., 2010b).

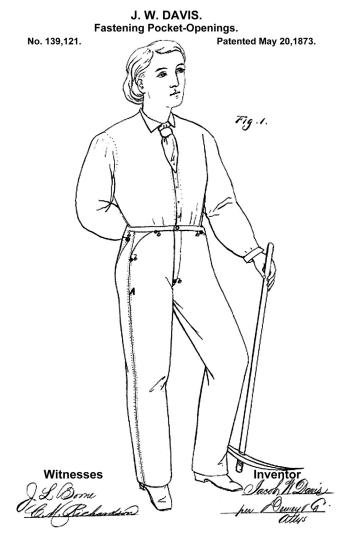


Figure 7.4 Illustration of US Patent 139,121.

# 7.5 Social influence of jeanswear

At the beginning of the twentieth century, jeans became a commodity aesthetic associated with selected groups. Commodity aesthetics are those in which its purchase promises a certain value in its use (Kramer, 2006). Wearing denim jeans allows an individual to stand out from the crowd, whether worn by a labourer, a cowboy, a rebellious teen or an individual desirous of prestige. As with most apparel, denim apparel companies sell to specific target markets, however, many apparel segments cannot say they that have a set social culture the way denim has. 'Sociocultural' refers to an associated language and value structure of a set group of people. Throughout its history, denim jeans have been considered a symbol of opposition or protest, or an attitude toward life (Kramer, 2006).

## 7.6 Cultural influence of denim work wear

The first denim culture was a work wear culture. The first documented evidence shows denim associated with working class people and beggars. The anonymous painter's subjects in the 1600s wore denim clothes exhibiting tears and mending, typical of working class people (Gruber, 2010). In the 1800s, waist overalls were worn by the US military and made from canvas; the fabric changed in 1909 to blue denim (Emerson, 2006). By the 1900s, historians concur that jeans became an American icon as a typical garment of the working class (Kramer, 2006). Levi Strauss and Jacob Davis intentionally made their pants for labour workers including miners, cowboys, ranchers and lumbermen (Downey, 2008). These rugged dungarees and waist overalls were a muddy brown colour and were made for labourers, miners and farmers who appreciated their utilitarian durability, and not those who lived in cities (Robinson, 2013). By 1902, Leopold Guiterman patented bib overalls (Guiterman, 1902), which began a new denim clothing style that the Lee Mercantile Company, started in 1889, popularised with its Union-All work jumpsuit in 1911. The denim bib overalls had a loyal following of farmers, labourers and railroad workers and this style is still worn today (Lee, 2012). Gideon Sunback patented his zipper invention in 1917 and in 1920 Lee Mercantile was the first denim apparel company to use a zipper in waist overalls (Sunback, 1917; Lee, 2012). Today, Lee focuses on providing authentic, no frills, value-driven work wear pants for the average consumer (Klara, 2012).

Caesar Cone recognised the importance of the work clothes segment. Creating denim, this founder of Cone Mills in 1896 believed that using cheap shoddy fabrics was a deterrent for work clothes and that durable, dependable, long lasting fabric for work clothes was a necessity (Balliett, 1925). This ideology is still true today. Cone Mills, a subsidiary of International Textile Group, is one of the world's largest denim producers and takes pride in producing innovative and long lasting denim for apparel companies wishing to differentiate themselves in consumer lifestyles, fashion or branding (Security and Exchange Commission, 2014c). During the early 1900s, denim jeans were most associated with the hard work of agriculture workers and ranchers. A dramatic change occurred in the 1930s with the Great Depression. Because of the instability of banking and financing, followed by a severe drought, many people throughout the developed world were unemployed. During the Great Depression, the US government hired contract photographers who documented unemployed and migrant workers. These visual images created a stereotype in which wearing denim jeans indicated being an impoverished farmer or unemployed industrial worker (Kramer, 2006). It was not until entertainers such as Buffalo Bill and Wild Bill Hickok introduced blue jeans onstage that city dwellers began to accept jeans as a wardrobe item (Downey, 2007). Denim jeans had a different name, depending on where you lived: On the East Coast jeans were known as dungarees and on the West Coast they were waist overalls. Only later, when dungarees became popular, were they called jeans (Robinson, 2013). In the 1930s, jeans started to transcend from ranches to urban dwellers.

## 7.6.1 Image of denim as Western clothing

Jeans spread from solely work wear to a subculture of Western attire, and by the 1940s Western regions became a formal apparel market, with clothing targeted specifically to cowboys, ranchers and farmers (Deweese, 2012). Western culture adopted a certain clothing style that is in concert with the Cowboy Code. Cowboys, associated with an affinity for violence and anti-intellectualism, had a Cowboy Code that they passed on from one generation to the next. The Cowboy Code is to have the qualities of loving nature, courage (bravery), individualism, loyalty and independence (Allen, 2005). Western clothing epitomises the cowboy culture, as noted by a former Wrangler design consultant:

The Western market is very specific both territorially and its taste level. There's a certain vanity level to cowboys and they dress up more than the average male does. Cowboys wear their boots, the big license plate size belt buckles, and they even starch their jeans. They like to show off a bit, so for their garments, they wear their jeans tighter and the shirts more fitted in bolder patterns and colors. A true cowboy is loyal to country music, drives an American pickup, and wears authentic Western brands. The non-Western market for the last number of years has been hammering home finish, finish, so they are mixing silicones with enzymes, and overdyes and finishing fabrics with sanding and grinding. The Western market doesn't even acknowledge that because as consumers they like things crisp, sharp, and starched. *Kumiega* (1995)

During the early twentieth century, denim was closely associated with the Western lifestyle. It was synonymous with a life of independence and rugged individualism, rodeos, country music and myths about the American frontier (Moos, 2000). A Wrangler merchandiser describes a cowboy's lifestyle:

Western lifestyle we call it. They live west of the Mississippi. They may or may not have horses in their life, most of the time not these days. But they do use rodeo as entertainment. They've had horses, cattle, and agriculture in their family background. They live in the West, they wear jeans to work most of the time, and most of them wear Wrangler<sup>TM</sup> jeans. Wrangler<sup>TM</sup> jeans denote Western; you do not wear Levi or any other brand. But you are Western if you wear Wrangler<sup>TM</sup>.

Cox, 1995

Designing for specific consumer markets is as relevant today as it was when CC Hudson hired Bernard 'Rodeo Ben' Lichtenstein to design Wrangler<sup>TM</sup> jeans made specifically for a cowboy. Rodeo Ben, a Philadelphia tailor, designed with

the cowboy in mind: Belt loops were wider and spaced to accommodate heavier belts and large buckles, a slim fitted pant leg and a boot cut to accommodate Western boots, with a zipper closure (Wrangler, 2013). Within the apparel industry, Wrangler<sup>(TM)</sup>'s 11-ounce men's Western zipper (11 MWZ) jeans established the technical design of garments for a specific activity (Deweese, 2012; Moos, 2000). At the turn of the twentieth century, various inventors including Jacob Davis and William Scott filed US patents for 2/1 twill and opposite left/right twills, respectively (Davis, 1898; Scott, 1914). Blue Bell recognised the denim twist problem and collaborated with mills to create a broken twill fabrication (weave that alternates left and right in no consistent direction) for its Wrangler<sup>TM</sup> pants.

Although it is difficult for apparel companies to stay specific to a cultural lifestyle, Wrangler<sup>TM</sup> succeeded, because its core consumer today is Western and garments sold at Western specialty stores (Security and Exchange Commission, 2014b). Levi's marketed to cowboys until the 1960s, however, the company changed to urban chic as a new consumer market adopted its brand. Lee introduced Lee Riders in 1924 but later moved to mainstream consumers and selling product in mid-tier department stores (Little and Bond, 1996; Security and Exchange Commission, 2014b).

#### 7.6.2 Women and jeans

During the early twentieth century, social norms required women to wear constricting dress and have set roles. Social and leisure time activities changed women's dress during the early 1900s. During World War I, US denim companies capitalised on promoting freedom. Levi Strauss & Co. promoted 'freedom' from constricting garments with their Freedom-Alls and Togs made in 1918 and 1921 respectively. These loose fitting garments were designed for housework and outdoor leisure (Moore and Downey, 1996). Although these garments were not made of denim, they became the lineage to develop jeans specifically fit for women. People needed a relief during the vast unemployment of the Depression, and movie themes focused on relieving the stress of people's living conditions. Hollywood promoted comedy movies emphasising the differences and gaps in men's and women's roles. One marketing strategy was to portray a glamorous Western image with movie stars such as Katherine Hepburn and Carole Lombard wearing dungarees (Comstock, 2011). In response, Levi Strauss & Co. introduced Lady Levi in 1935 and Lee introduced Lady Lee Riders in 1949 (Lee, 2012; Moore and Downey, 1996).

Dude ranches, located in the middle of nowhere, attracted East Coast tourists during the 1920s and 1940s who wanted to romance the Wild West. Upper class women did not wear pants during this time and the introduction to denim jeans symbolised fashion freedom from conventional norms of East Coast society in the US. To the 'dudines' (women), dude ranches symbolically represented freedom, independence and courage as they enjoyed many physical activities including horseback riding and hunting (Johnson, 2012; Tamony, 1973). Historians note that the first lifestyle clothing market segment was the glamourised Western culture of dude ranches and wearing jeans (Gordon, 1991). Advertisers promoted denim with dudines wearing denim skirts and Lee Jeans were especially popular with 'old girl' women who worked on ranches (Little and Bond, 1996; Robinson, 2013). World War II was a time of tremendous social change. Large denim companies switched production to produce (non-denim) military clothing (Little and Bond, 1996). In addition, the shortage of men prompted companies to hire women. Wartime promotions portrayed denim overalls as glamorous, and companies such as Blue Bell created a dungaree style called 'the Jeanie' (Gordon, 1991). Although denim work clothes gave women a feeling of pride and status that they were contributing to the war effort, they often felt dungarees and overalls were a necessity for work only, and wore feminine dresses for leisure and social activities. Dungarees influenced employee regulations because company executives felt women wearing tight pants would distract male employees in industrial settings. If a woman expressed her feminism in an industrial setting, a manager reprimanded her. However, by the mid-1940s employee safety was the impetus to make it acceptable for women to wear pants in industrial settings (Boris, 2006).

Many Americans prospered after World War II and denim apparel companies switched from producing work to play clothes as leisure time activities became prominent (Little and Bond, 1996). Teenagers had lived through rationing during World War II and youth starting asserting their rights. Unisex looks of denim jeans became associated with youth, freedom and rebellion (Gordon, 1991). Hollywood produced movies for youth that had a rebellious theme. *The Wild One* staring Marlon Brando, featuring motorcycle gangs, and *Rebel Without a Cause* starring James Dean became symbolic movies of rebellious youth. The symbolism of the roles Dean and Brando played promoted rebellion and breaking away from previous generational ideologies. This influence started in the US and later spread throughout western Europe (Heiduschke, 2013). Dean and Brando wore blue jeans and leather jackets in those films and this clothing style became a symbol of a defiant teen desiring freedom (Gordon, 1991). Levi's capitalised on these rebellious movies because jeans spread from being identified solely as work wear to a social lifestyle (Robinson, 2013).

## 7.6.3 Expression of American youth independence

The 1960 and 1970s, nicknamed the 'Jeaning of America', abruptly changed the direction of the denim apparel industry (Gordon, 1991). One could describe the activist movement as a deviation of the Cowboy Code. The youth culture embraced an individual search for personal expression, religion and communal living, along with alcohol and drugs (Allen, 2005). Figure 7.5 shows jeans as a symbol of youths' expression of independence.

Levi's<sup>®</sup> became a visual symbol of social change (Tamony, 1973). The rebellious uniform spread to European countries and became a symbol of disenfranchised youth, hippies and opponents of the Vietnam War. During this time jeans became a symbol of individualism and venue for personal statements. Many youth wanting to show off their physiques would to put on their Levi's<sup>®</sup>, get them wet and let them dry on the body (Tamony, 1973) or show individualism by having holes, patches, embellishments, paint and embroidery associated with memorable experiences on their jeans (Gordon, 1991). Along with personal freedom, jeans were a symbol of violence and anti-establishment. It did not hurt Levi Strauss & Co. when an article



Figure 7.5 Jeans as a symbol of youth expression.



**Figure 7.6** Illustration of cutoff jeans. Brandi Reed.

about a riot would state a young man or woman was arrested wearing Levi's<sup>®</sup> and a T-shirt and carrying a smoke bomb. Within a 10-year period, from 1965 to 1975, youth had embraced Levi's<sup>®</sup> and it became an icon and a uniform (Robinson, 2013). An illustration of cutoff jeans by Brandi Reed is shown in Figure 7.6.

During the 1960s, public and private schools had strict dress codes and teenagers would have sit-ins rebelling against dress codes. Schools would publish dress regulations stating that students could not wear 'Levi's<sup>®</sup> or T-shirts' to school. Levi Strauss & Co. had to counteract the generic use of its name and created a promotional program to visually communicate appropriate dress to students using generic images and names. Schools eventually relaxed their dress codes around 1965–1966 (Robinson, 2013). Surpassing all such restrictions, this 'blue magic material' has become an evergreen favourite for all and a fabric for today and tomorrow. Denim garments and jeans are now widely worn by people of all ages and their popularity among children and teenagers is ever increasing. Figure 7.7 depicts denim garments as favourite clothing among children.



Figure 7.7 Denim popularity among children.

## 7.6.4 International appeal of jeans

Since the 1960s, international youth aged 16-20 are the primary target market for jeanswear (Vrontis and Vronti, 2004). Most Europeans associated blue jeans with the working class, however, starting in the 1960s the US troops who wore jeans enthralled young European soldiers (Robinson, 2013). In Eastern Europe, blue jeans, blue shirt and glasses became a symbolic uniform of intellectual Europeans promoting social equality. This movement spread to young liberal Americans (Kramer, 2006). During this time, jeans started to become popular with western and eastern Europeans (Techorn, 2005). By the 1980 and 1990s, there was an imbalance of denim supply, creating high demand and high prices of jeans in some Eastern Bloc countries and in the Soviet Union. This phenomena positioned jeans to be a prestige rather than jeanswear (Vrontis and Vronti, 2004). Military unlisted men permitted to travel to Eastern Bloc countries would smuggle Levi's<sup>®</sup> by wearing them under their clothes. These jeans would sell for as much as one month's salary (Robinson, 2013; Kramer, 2006). Although Levi Strauss & Co. liked the publicity of the 100 USD pair of jeans sold in Eastern Bloc countries, the company was not connected with smuggling Levi's<sup>®</sup> because all of their products were sold through international distributors (Robinson, 2013).

# 7.7 Denim as luxury attire

The 1970s saw a radical change in denim from work wear, rebellion or individualism to one of prestige. The status denim market matured and developed into premium denim jeans. European entrepreneurs such as François Girbaud created new denim finishing techniques, such as stonewashing (Herbst, 2008). This juncture is the first time denim became segregated into a status symbol and the industry starting separating

jeanswear from premium denim jeans (Little and Bond, 1996). Denim mills started to create a wide variety of finishing techniques. They developed bleaching techniques marketed as snow wash or granite wash, and double dip dyeing techniques such as midnight blues or ink wash (Paul et al., 1996). Garment finishing, such as jeans washing techniques, created a new apparel sector for commercial laundry contractors that specialised in denim (Paul and Malanker, 1997).

Premium denim jeans are often defined as a price point (e.g. jeans above 130.00 USD) with superior fit and styling (Security and Exchange Commission, 2014b). Premium denim jeans, however, are not simply a price point. Susan Kellogg, President of VF Contemporary Brands (2013), defines premium denim jeans as jeans that are not designed for the average consumer because they have a high point of entry, however, price is just the starting point. Of primary importance, Kellogg notes, is a denim apparel company's DNA (or brand personality). Brand DNA means to create classic branding strategies, clearly define its target customer, identify its market position, describe what the brand means and synthesise the experience desired by consumers wearing the product. Jegethesan et al. (2012) agreed, noting that premium denim jean companies use marketing strategies that appeal to young adults. Authentic US premium denim jean companies are a part of the contemporary apparel market segment. Specifically, these companies produce denim apparel made in Los Angeles from the finest global fabrics. The designers carefully develop their fit specifications and products using quality finishing such as handwashing and hand sanding. Kellogg states that the recent departure of premium denim companies to manufacture in Mexico abolishes them as being authentic premium denim jean brands.

The European premium denim jeans market is larger than in the US, especially in the men's sector. Hugo Boss and Armani Jeans are two prominent European denim brands (Kellogg, 2013). Giorgio Armani, a leader in the global fashion industry, steadfastly developing innovative, unique designs with a meticulous attention to product quality. Armani Jeans are targeted to a consumer with fashion sensibility who has a young independent and casual lifestyle (Giorgio Armani, 2012). Hugo Boss aims for feminine styling using the finest fabric and sophisticated design details (Hugo Boss AG, 2013).

#### 7.7.1 History of premium denim jeans

High profile designers such as Calvin Klein and Gloria Vanderbilt expanded denim apparel to designer status. Designer jeans (c.1970s) distinguished itself from jeanswear by creating new styling and super tight jeans. Decades later, consumers still remember teenager Brooke Shields proclaiming, 'Nothing comes between me and my Calvins'. Numerous new status denim apparel brands started in the 1970 and 1980s, including US brands Guess, Jordash, Sassoon and DKNY. European couture designers such as John Galliano, Giorgio Armani and Versace quickly got into the designer jeans market. The onset of designer jeans created the new fabrication of stretch denim as women from all over the world tried to squeeze into their designer jeans by lying on the floor.

Designer denim differs from premium denim jeans. As the designer jeans market leveled off, the premium denim jeans market began. The industry distinguishes designer denim as an established designer putting a name on jeans compared with that of premium denim, which is a jeans brand. Guess, True Religion and 7 for All Mankind were among the first US premium denim jeans companies (Kellogg, 2013). At the same time, Adriano Goldschmied was instrumental in forming premium European jeans brands such as Diesel and Replay. With creative designers, Italian laundries became instrumental in changing the look of finishing for jeans (Techorn, 2005).

#### 7.7.2 Premium jeans as status indicator

Designer jeans and the subsequent premium denim jeans brands created class distinction rather than a sociocultural movement. With premium denim jeans, consumers associate select premium jeans brands as a symbol of high quality. Denim jeans alone do not indicate whether a person is middle class or upper class; rather, recognition of the style, denim quality or designer label is a clue to a person's social standing (Wajda, 1992). United States consumers will state that important attributes for premium denim jeans are brand name recognition, belief about the quality of denim products and brand loyalty (Wade, 2011). The president of VF Contemporary Brands supports this stance:

Premium denim jeans are a status symbol because most people cannot afford it. Some people may not be able to afford premium denim jeans, but they will give the image that they can. We interviewed some UCLA (University of California Los Angeles) students. There were four of them that lived in a one-bedroom apartment. I remember telling the market research leader that I didn't think they had done their proper screening because why would we be visiting this crummy apartment that had four guys who shared one bedroom? Were we sure that we had the right address? Were we sure these were 7 for All Mankind customers? The answer was they really were. So what the guys would do, is go out on dates wearing 7 for All Mankind and get the pretty girls. Their living accommodations were not great at all: They had one room that had a plasma TV, a leather couch, a really nice stereo and they would alternate when someone could bring someone home. They would never bring them to the bedroom, because the bedroom had two bunk beds in it with all these designer jeans. And by the way, they were eating Campbell's<sup>TM</sup> soup because that's what they could afford, but they would spend 200 USD on a pair of jeans to get the girls!

## 7.7.3 Premium denim jeans versus jeanswear

Today a multitude of jeanswear and premium denim jeans brands are vying for consumer discretionary income. Premium denim companies approach pants design differently from the traditional jeanswear company. The president of VF Contemporary Brands distinguishes premium jeans from jeanswear: 'We fit our jeans like couture. The jeans can have up to seven fittings just to get it right so there is nothing mass about it. So it has to do with the quality of fabric you use, quality of thread and trim, and that wash techniques and finishing are by hand. Our view is that we are an atelier for the denim business'. Italian denim apparel companies embraced the Italian couture work ethic by taking time to design product and not focus on production speed or output. Italian firms focus on minute details such as the quality of the cotton fibre and achieving a handcrafted appearance to fabrications. Some high end Italian premium denim apparel brands include Candiani, Italdenim and ITV (Techorn, 2005).

#### 7.7.4 Premium denim jeans silhouettes

Consumers evaluate jeans based on style, brand, country of origin and company ethics. Style considerations are fit (classic, comfortable) fashion innovation and colour (Wade, 2011). Consumers attribute fashion innovation by evaluating style and measurement specifications, and whether the garment is at the early adoption stage of the fashion cycle. The 7 for All Mankind Vice President of Product comments, 'Premium denim jeans brand may have similarities in the basic silhouettes and these evolve over time; for example a skinny versus boot cut or a low rise versus a high rise. A boot cut can be important one year and not the next. The difference is on the premium side, the consumer wants to be at the beginning of the fashion cycle not when the trend peaks or declines in popularity' (Jewell, 2013).

Consumers evaluate the aesthetics of premium denim jeans, but fit is a higher evaluative criterion (Jegethesan et al., 2012). Each denim company has its own measurement specifications: 'It comes into subtle nuances of the jeans. If you bought skinnys from 10 different brands, the leg opening, the front rise, and the back rise would be different measurements. These are all attributes that go into making the best fit for your consumer' (Jewell, 2013). The VP of Product notes that denim fibre and fabrication attributes are closely related to the final fit appearance desired. Thus, designers choose the highest quality denim fabrics:

We evaluate denim jeans as if they were a science experiment. The fit integrity has to be maintained. It's not like a sweater where it looks really good and you toss it on and you can get away with it not fitting quite right and no one is going to notice. On denim jeans, it is the first thing that you notice whether it looks right because it is on your body. We evaluate denim fabrications for fit appearance, fabric recovery and number of washes. This is not an easy selection because if you wash certain fabrics you lose the recovery of the fabric. Our designers aim to have a snug jeans fit that does not get baggy. After a few hours, one premium denim fabric may have excellent recovery and feel like a second skin whereas another will be baggy and feel like being at the supermarket.

*Jewell* (2013)

#### 7.7.5 Fabric quality

If consumers have a high perception of value, they will be loyal to and continue to buy that brand of premium denim jeans (Wade, 2011). Denim fabrication is a contributor to a consumer's value perception and designers create value by globally sourcing fabrics. While textile mills from each country have their own specialty, Japan and Italy textile mills produce some of the best premium denim fabrications (Friede, 2012; Kellogg, 2013). Some mills are better in innovations with special qualities that make them uniquely different. Depending on the desired aesthetic effect, designers will buy

fabric from Italy, Turkey, Japan or the US (Jewell, 2013). The VP of Product for 7 for All Mankind notes, 'With denim it's very subtle, but with people who love premium denim jeans they notice the subtle differences right away' (Jewell, 2013). Premium denim jeans designers use a more diverse range of denim fabrications and finishes than are applied to normal jeanswear. In addition to common types of denim such as classic denim, heavy denim, ring denim or mercerised denim, unique denim finishes include soft, soda-pop, reused, worn-out, bullet hole, shot gun, vintage, crushed or hairy (Paul and Pardeshi, 2003). Having a diverse range of premium denim fabrications and finishes allow designers to experiment. 'The effect is like being a scientist almost, between the fabric that you choose, what you choose to do with it, in terms of processing, whether its grinding or rinsing will have different end results' (Jewell, 2013). Premium denim jeans designers learn to look for nuances in denim fabrication of similar weights, such as applying a range of colours. Finishing techniques used to distinguish brands include tinted jeans, overdyed denim, reverse denim, kiss roll techniques, printed denim and two-colour techniques. For each season, premium denim jeans companies adopt new denim finishes and change existing finishes to create a competitive design advantage (Adivarekar et al., 2001). Reverse denim is currently popular in premium denim jeans to create many different finishing effects. For example, one denim fabrication that has white weft will have white come through after washing; whereas a fabrication with a black weft, even if it were ground, would never have the white coming through (Jewell, 2013).

The VP of Product for 7 for All Mankind notes that careful consideration needs to be made for finishing techniques as well as fibre content selected for premium denim jeans:

After our designers have determined the washing effect, (denim finishing) we look at our garments from the consumer point of view. With washing, 100 percent cotton denim behaves differently than denim with stretch and coated denim. We have to figure out how long the consumer will wash and dry an entire load, what other items will go into the dry cycle with the denim, whether the jeans can get stuck in the middle of the dryer or be an outlier that doesn't get the same amount of heat or whether they dry the garments longer than they're supposed to. All of these contribute to the shrink percentage or whether washing causes the denim to lose all of its recovery and desired jeans fit. Stretch denim may get smaller, but some of the coating processes can break down fibres so garments actually become bigger.

Jewell (2013)

### 7.7.6 Embellishment

Embellishment is not new or unique to the premium denim jeans industry. Levi Strauss & Co., Lee and Wrangler trademarked easily recognisable embellished labels and back pocket embellishments from their inception. The new indicator was that an embellished back pocket indicated status and brand loyalty rather than simply branding. Consumers wanted observers to recognise that they were wearing 100–200 USD pair of jeans. The VP of Product for 7 for All Mankind comments, 'I call it the 50 foot rule. If you see whose jeans you are wearing from 50 feet, then it is probably an

aggressive back pocket or embellishment'. The adoption theory holds true with regard to embellishment. Because jeanswear companies emulated elaborate back pocket embellishments, premium denim consumers – as early adopters – did not want aggressive designs. Responsive to consumer needs, the premium denim industry cleaned up embellishment as jeanswear companies became overly embellished (Jewell, 2013).

## 7.8 Future trends

## 7.8.1 Trends in jeans design

It might appear that denim has come full circle and the jeans world has gone from work wear to creating a cultural statement about prestige, and the future cannot not bring anything new. But now, as individuals are globally and instantaneously connected, the highly competitive fashion industry moves at lightening speed. This speed is changing the business model for all apparel companies. Future silhouettes, finishes, and colour trends traditionally have come from fashion trend forecasters. While their services are still relevant, denim jeans companies often find they do not have time to wait for the seasonal trend forecasts (Jewell, 2013). Rather, daily and weekly point of sale information from major retailers enable large denim jeans companies to quickly analyse product assortments and new offerings from a demographic and geographic point of view (Security and Exchange Commission, 2014b). Many apparel companies use trend forecasters to validate a company's merchandise mix, such as determining the number of styles needed for a specific leg variation – for instance, flare legs – in the product line rather than viewing trend services as predictors of trends (Jewell, 2013).

The future is nebulous because online access gives consumers tremendous power to compare prices and quality attributes of branded apparel products. Differentiating products is challenging among competing brands as jeanswear and premium denim jeans companies state priorities of developing unique styles, new finishing techniques, innovative design details, superior fit, fine fabrics, unique finishes and high quality (Hugo Boss AG, 2013; Security and Exchange Commission, 2013, 2014a).

Analysing denim's rich cultural history can provide clues for predicting future trends. Some past trends noted in this chapter include:

- · The appearance of denim for the working class and peasants.
- · Patents by many individuals to develop the waist overalls silhouette.
- · Jeans viewed as a utilitarian for military explorers, labourers and agriculture workers.
- Acceptance as a uniform for selected sociocultural groups from cowboys to a work uniform for working women and youth expressing individuality.
- Elevating denim jeans to a luxury status.
- Acceptance for all consumers in all social situations.

Next, professionals need to correlate historical trends of denim with market growth. Growth markets influencing denim are:

- Niche markets.
- · Technological application to consumer goods apparel.
- Mass customisation.

## 7.8.2 Niche denim markets

Throughout the history of jeans, subcultures have embraced it as a symbol. Niche markets are the subculture of tomorrow. As with the past, niche marketing meets the needs of a specific sociocultural lifestyle. The president of VF Contemporary Brands responded to concerns that premium denim jeans were only 1% of the total denim market. 'The question arose, would our business be big enough? I said yes because if that target consumer bought our brand, then we could have scale and that one percent has money' (Kellogg, 2013). Niche marketing can take many forms from heritage construction to meeting a small market segment. Denim jeans micro brands are predicted to lead niche marketing. Meeting niche market needs means denim apparel companies need to reach out to consumers before designing product to create apparel products that meet specific target groups. Interesting niche market ideas may include creating denim jeans with back padding to create a fuller derriere for women who desire more curves, having denim jeans with longer leg lengths for tweens and having flattering denim styles for short stature, full figured young women.

## 7.8.3 Technological trends in denim

Sustainability is another future trend for denim manufacturers. With regard to product design, sustainable practices fall into categories of cotton fibre substitution, safer finishing practices and reuse of denim products. Cotton supply is volatile and denim textile and apparel companies hinge on its availability at a reasonable price. Whether under a guise of sustainability, reducing the amount of water to grow cotton or lowering raw material costs, textile mills are developing new fibre blends to reduce the amount of cotton in denim. A current trend is substituting cotton for other fibres such as bamboo, viscose and Tencel<sup>TM</sup>. For instance, G-Star is using a cotton/viscose/Tencel<sup>TM</sup> blend to improve fabric hand and Nankatan, a Norwegian apparel company, uses 100% Monocel to develop stretch denim (2012) (Szmydke, 2013). A question arises whether fabrication is authentically denim if it is only at or close to a 100% cotton fibre or whether denim can be a mixture of fibre contents. True sustainability is the use of fibre(s) that has a smaller carbon footprint through the reduction of water or chemicals used to grow cotton. Some unique approaches are the reuse of fibres rather than the substitution of cotton. Nudie Jeans Company has reduced its carbon footprint with the introduction of dry jeans. ISKO and Nudie Jeans Company collaborated to grind post consumer denim into a pulp (Nudie Jeans Co., 2013). Grinding post consumer denim into a pulp for reuse is not new and companies such as Wrangler<sup>TM</sup> have done this to make pencils and paper. ISKO's innovation is that post consumer denim is spun into a new yarn and is strong enough to be woven into a new denim fabrication (Nudie Jeans Co., 2013). Levi Strauss & Co. is a pioneer in having strong ethical values and social responsibility to reduce its carbon footprint in the manufacture of denim products. The company has numerous ongoing initiatives to meet sustainability goals (see details on its Web page) (Levi Strauss & Co., 2010a). Among some of the initiatives are Waste < Less<sup>TM</sup> and ITV denim. Waste < Less<sup>TM</sup> uses post consumer polyethylene

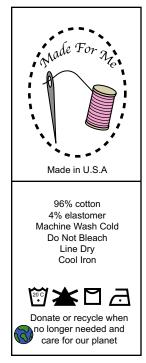
terephthalate products collected from recycling programs that are manufactured into yarn and then woven by Cone Mills into a denim fabrication. ITV Denim Italy collaborated with Levi Strauss & Co. to develop a natural dye from red wine. The dye is free from chemicals, is colourfast, and uses less water than conventional indigo dyeing (Textiles Intelligence, 2012).

A trend for denim fabric and apparel companies, as well as all companies, is to be diligent with social responsibility. Social responsibility can affect denim apparel product design. Mechanised sandblasting, once commonplace for a multitude of denim jeans companies, is detrimental to employee health and it is not ethically acceptable to place workers in this kind of danger. Hugo Boss and 7 for All Mankind, as well as other denim apparel brands, no longer use mechanised sandblasting and have replaced this process with hand sanding, a more expensive finishing process (Hugo Boss AG, 2012).

A trend for apparel companies is to extend the usefulness of denim products (Szmydke, 2013). Encouraging reuse replaces consumers' conspicuous consumption attitude with that of reuse. Levi Strauss & Co. suggests that sustainability is also the responsibility of consumers, with the Care Tag for Our Planet campaign. Consumers trash 23.8 billion pounds of clothing that end up in landfills. (Goodwill Industries, 2013). Young consumers today feel positive about donation and reuse and want to be socially responsible in disposing clothing items (Lee et al., 2013). In partnership with Goodwill, Levi's® launched Care Tag for Our Planet along with care instructions; the care label states, 'Donate to Goodwill when no longer needed' (Goodwill Industries, 2013). A novel care label idea by Stephanie Kuhn is shown in Figure 7.8. Many consumers feel that they need more education about how to dispose, repurpose or reuse clothing items. If made aware, many young consumers think they would put forth an effort to donate, reuse or repurpose clothing (Lee et al., 2013). Mud Jeans is a denim apparel company with an innovative apparel rental program. Through their lease jeans program, consumers pay a monthly fee to rent their product for 1 year. After 12 months, a consumer can return the jeans, exchange them for a new model or keep them. The company deconstructs returned jeans to create new products (Mud Jeans, 2013).

## 7.8.4 Mass customisation applied to denim

Although it has been in existence for three decades, mass customisation is reaching a pivotal point owing to increased online purchasing. Apparel manufacturers typically standardise sizing and cater to a similar global target market; yet consumers find it difficult to fit into form fitting jeans (Security and Exchange Commission, 2014a; Vrontis and Vronti, 2004). Denim apparel brands are recognising consumers' concerns about fit and are offering a plethora of fits from classic to curvy, relaxed and tight. However, consumers are frustrated by the time and energy required to try on clothes to find the correct fit. Many denim jeans companies recognise that fit is a primary concern for consumers. Levi Strauss & Co. is moving forward to meet the needs of female consumers. The company recognises that the waist and hip curvature is a challenging area to fit jeans and shorts. In response, they developed a low-tech portable shape



**Figure 7.8** Novel care label idea. Stephanie Kuhn.

measuring tool that measures seat and hip fullness and helps identify the curvature of a person's body (Smith-Habelow, 2013). G-Star International adopted an approach used in the performance apparel market to create a new innovative construction that fits the three-dimensional body. Using seam stretch and shrink technologies and resin treatments, they bake in a three-dimensional shape (2012).

One future trend is to assist consumers at the point of purchase to match a consumer's body shape to denim apparel brands. Raj Sareen, a physicist, developed the Smart Fitting Room, an innovative approach that uses body scanning technology to assist consumers with purchasing ready-to-wear apparel (Jha, 2012). Raj Sareen, Styku CEO, comments:

Traditional brick and mortar is changing to meet the needs of the Omni-channel shopper. Apparel brands must become more technologically advanced and efficient to compete in an increasingly competitive market where shoppers have many more choices and can purchase anywhere. With online returns sometimes as high as 30–40%, online retailers can leverage brick and mortar stores and smart fitting rooms to build consumer insight, improve product development, size distribution, and consumer confidence when buying online, all of which results in lower returns. Sareen (2013) The Smart Fitting Room uses Microsoft's Kinect platform to develop an affordable body scanner for retailers to install in fitting rooms or for a consumer to use at home. Once the consumer scans himself or herself, the Smart Fitting Room program matches a consumer's body scan measurements with specifications provided by apparel brands for the best fit (Jha, 2012).

## 7.9 Conclusion

Denim and jeans have made a major impact on the lives of the consumers. Once thought of as utilitarian work wear, denim and jeans have socially influenced lives since their inception and have become symbols for cowboys, women and youth, and for economic status. Historians trace denim back to the 1600s in France and Italy. As explorers traveled and traded throughout the continent and Britain, the denim textile industry quickly spread. Although it originated in Europe, it became an American icon, with Levi Strauss commonly indicated as the originator of jeans. However, denim jeans did not start with Levi Strauss as noted in many folktales; rather, denim has a mysterious beginning with the Anonymous Painter of Blue Jeans.

Whereas many inventors patented elements that eventually became the silhouette of classic denim, Levi Strauss & Co. has been the longest standing denim apparel company. Premium denim jeans first influenced a small group of luxury goods consumers and now current consumers from all levels of social economic status embrace them. Denim apparel manufacturers face challenges in developing products for niche markets, having technological innovations and meeting consumer demands for better apparel sizing.

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# Joining techniques for denim jeans

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# 8.1 Introduction

Denim, the hard wearing material that first became popular when it was used to make trousers for American gold prospectors, is now arguably the most popular piece of clothing in the world and one of the most iconic and individual. Millions of pairs of jeans are now sold throughout the world. Currently, hardly anything exists for which there is not a version in denim. Denim is not just denim these days, but a material available in a vast range of qualities.

As tough and hard wearing as the material is when worn, it can be a problem for processing. Problems can arise, including broken needles, sewing thread breakage and skipped stitches. This results in repeated interruption of the sewing process and a reduction in the quality of the end product. Timely consideration of all manufacturing processes that go into the production of these garments is needed to ensure a quality product each time.

However, before this assembly sequence begins, the denim fabric has to be laid up and cut out into its constituent parts. As with any industrial garment cutting process, the efficient use of fabric is paramount. All aspects of the lay planning process are focused on maximising fabric use and reducing fabric waste. Computerised lay planning and marker making (this may be a virtual marker for computer controlled cutting) usually achieves an efficiency of around 80%, which can often be increased by human intervention by placing large pieces initially in the lay and back filling with smaller components. The marker is also driven by the sizing mix and, consequently, the stepped lay plan. The making of denim jeans also involves various other steps such as design, pattern making and so forth before the different pieces are stitched together (Paul et al., 1996). A process flow sequence for making five pocket jeans from denim fabric is shown in Table 8.1.

# 8.2 Seams in the construction of jeans

A seam joins more than one piece of material together, and the type of seam used depends on the product to be sewn. Seams in denim have different levels of complexity depending on the design of the product. The different seams used in the production of denim jeans are discussed in this section. Considering the requirements of a seam on the outside leg of a pair of jeans and, by contrast, the type of seams that go into attaching belt loops and pockets:

- There may be an uneven pressure on jeans owing to leg movements.
- There is a gradual build up of stress loading on the seam of the jeans.
- Strong seams are required throughout the garment to ensure the product performs as intended and does not fall apart.

| Operation number | Operation  |
|------------------|--|
| 1                | Pocket hemming   |
| 2                | Pocket overlock  |
| 3                | Pocket creasing  |
| 4                | Pocket attaching   |
| 5                | Second stitch back pocket                                  |
| 6                | Back yoke attach   |
| 7                | Back rise join   |
| 8                | Size label attach  |
| 9                | Coin pocket hemming  |
| 10               | Coin pocket attach jet piece (right)                       |
| 11               | Pocket bag attach with jet piece                           |
| 12               | Overlock pocket bag  |
| 13               | Top stitch pocket bag                                      |
| 14               | Overlock zipper fly  |
| 15               | Overlock front panels, crotch                              |
| 16               | Zipper attach left fly                                     |
| 17               | Left fly attach front panel (inseam and top stitch)        |
| 18               | J-stitch left fly  |
| 19               | Front pocket mouth hemming                                 |
| 20               | Pocket bag stitch to front panel side and top              |
| 21               | Right fly attach with zipper and crotch join               |
| 22               | Loop preparation   |
| 23               | Main label attach waistband and waistband joining in chain |
| 24               | Top stitch inseam  |
| 25               | Side seam join (attach front and back panels)              |
| 26               | Top stitch side seam                                       |
| 27               | Waist band stitch  |
| 28               | Waist band corners finish                                  |
| 29               | Loop attach  |
| 30               | Bottom hemming   |

Table 8.1 Work sequence for five pocket denim jeans

One factor that these and other seams have in common is that the seams must combine the required standards of appearance and performance while ensuring economy of production. The aesthetic characteristics of a seam are usually influenced by the accuracy of the stitching, the visibility of threads of differing colour from each other and the surface of the fabric. Seam performance relates to the strength, extensibility, durability, security and comfort as well as maintenance of specialist fabric properties.

Generally, the seam must exhibit properties similar to those of the fabric into which it is being introduced. Also, depending upon the physical properties of the area within a product, the seams occasionally modify that product area. The strength of a stitch line is assessed both longitudinally in the direction of the seam and transversely



Figure 8.1 Seam grinning on jeans outside leg seam.

perpendicular to the seam, and is assessed in terms of peak tensile load at breaking. Seam extensibility can be quantified simultaneously while applying the load longitudinally and the seam grin can be measured while a seam is under transverse load. Seam grinning, as shown in Figure 8.1, is when the fabric is under stress at the seam area and the stitches are exposed on the face side of the fabric.

Factors influencing the strength and extensibility of a stitch line within a seam include:

- Stitch density (stitches per centimetre).
- Thread tension (static thread tension setting on the sewing machine).
- Thread properties (strength and elasticity determined by fibre type).
- · Fabric integrity (cover or tightness factor).

The seam performance relates to:

- Strength.
- · Aesthetic appeal.
- Extensibility.
- Durability.
- · Ease of assembly.
- Security.
- Comfort in wear.

The only British Standard test in existence is the BS 3320: 1998 – Determination of slippage resistance of yarns in woven fabrics: Seam method often referred to as the

grab test. Seam strength is often referred to as seam efficiency, which is an expression of seam strength as a function of fabric strength.

Seam efficiency =  $\frac{\text{Unseamed fabric strength}}{\text{Seamed fabric strength}} \times 100\%$ 

The requirements of seam extension can vary dramatically with the product application, that is, comfort stretch (up to 30%) for casual garments (including most denim jeans), and performance wear and support garments can exhibit extensions of over 100% power stretch.

The durability and security of the seam are directly related to these properties and the integrity of the sewing thread under normal use and laundering conditions. Many types of seams can be constructed in ways involving different raw materials, stitch types and machinery. An optimum combination of these along with minimised thread consumption will provide an economical approach to manufacturing. There are hundreds of different seam types but they are basically categorised into six simple categories, described as follows.

## 8.2.1 Superimposed seams

Generally, two or more plies of fabric are laid on top of each other superimposed in the same orientation. They are stitched near the edge with one or more rows of

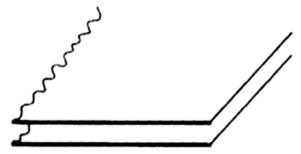


Figure 8.2 Superimposed seam ply alignment.

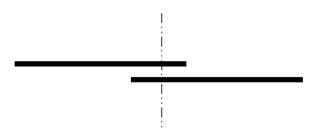


Figure 8.3 Overlapped superimposed seam ply alignment.



Figure 8.4 Combination stitched superimposed side seam.



Figure 8.5 Double lapped seam ply alignment.

stitching, as shown in Figures 8.2, 8.3 and 8.4. The rows of stitching may be sewn simultaneously or consecutively. An example of a suitable machine is given later in this chapter.

## 8.2.2 Double lapped seams

These are:

- Two or more plies are lapped together, overlaid, plain or folded.
- Secured with one or more rows of stitching.
- One of the most common is the double lap felled seam with two or more rows of stitching.
- This provides a strong seam with fabric edge protection.
- Often used on the side seam of jeans, other denim products and tents.

This seam type exhibits very high strength and is used extensively where durability and flexibility is needed in the garment, as shown in Figures 8.5 and 8.6. An example of a machine used in producing this seam type is given later in this chapter.



Figure 8.6 Double lapped seam.



Figure 8.7 Schematic view of bound seam.

## 8.2.3 Bound seams

These are formed by:

- Folding a binding strip around the raw fabric edge(s) and securing with one or more rows of stitching.
- This produces a secured neat seam on an edge often exposed to view or wear.
- It is also often used in other areas of manufacture such as luggage.

This type of seam is normally found on the waistband of the garment, as shown in Figures 8.7 and 8.8. An example of the machine and the operation is given later in this chapter.

## 8.2.4 Hems

There are two main areas of the garment where hems are used: on the bottom hem of the jeans, namely the leg, and on areas such as pockets and zippers. The leg hems as shown in Figures 8.9 and 8.10 are double folded in one operation on a leg hemming machine. The pocket hems as shown in Figure 8.11 are folded once onto the fabric and top stitched with either one or two rows of stitching.

# 8.2.5 Zippers and belt loops

The zippers and belt loops are similarly attached using a combination of superimposed seams, as discussed later. The most common stitching of a zipper on denim jeans is



Figure 8.8 Bound seam of waistband.



Figure 8.9 Schematic view of hem.



Figure 8.10 Hem of denim jeans leg.

called the J-stitch, shown in Figure 8.12. It looks like a letter "J" because of the stitch on the front of the garment.

Belt loops are created through a folder that butts the two edges of the fabric together and the sewing head stitches them together using a flat seam (type 402), as shown in Figures 8.13, 8.14 and 8.15. An example of the machine is given later in this chapter.



Figure 8.11 Hemmed top of patch pocket.



Figure 8.12 J-stitched fly zipper surround.

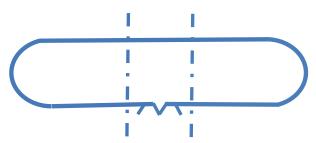


Figure 8.13 Schematic view of belt loop fold.



Figure 8.14 Belt loop attached to waistband and jeans body.



Figure 8.15 Belt loop showing 402 stitches in the underside.

## 8.3 Stitch types in jeans manufacture

Stitch types used in the manufacture of denim jeans are both interesting and varied. These stitches provide not only strength to hold the garment together, but also – by using different combinations of thicknesses of sewing threads – they give the garment an aesthetic appeal, setting it above other garments of its type. All stitches used on a garment have a number. This number is specific to that stitch. In other words, a different stitch cannot possess the same number. This enables technical teams to identify stitch types, which is particularly useful when planning a product in pre-production. An account of these stitch types and formations is given below.

#### 8.3.1 Stitch categorisation

Before the stitch types used on denim are discussed, it is important to understand the different categories and classifications into which all stitches fall. These are classified as:

- Class 100 single thread chain stitches.
- Class 200 hand stitches.
- Class 300 lock stitches.
- Class 400 multi-thread chain stitches.
- Class 500 over edge chain stitches.
- Class 600 covering chain stitches.

Each number denotes a sequence of stitches within that class. For example, all lock stitch formations are contained within the class of 300. Therefore, stitch types 301, 302 and 303, and so forth are all single needle lock stitches. The primary stitches for sewing denim fabrics are described further.

#### 8.3.2 Single needle lock stitch – 301

The lock stitch (stitch number 301) is the most common of all stitch types of all machines used in the clothing industry. It is often referred to as a double lock stitch owing to the way it locks together inside the material. This stitch type is formed by interlacing a needle thread supply with the spool thread supply underneath the machine bed. These stitches are secure, because a break in one stitch will not cause the seam to completely unravel although it will compromise the overall seam performance.

This stitch can provide up to 30% extension for comfort stretch garments and it is unique because it is the only stitch formation that looks the same on both sides. It is also the only stitch formation to reliably sew around a 90° angle. This makes it an ideal stitch for sewing pockets and zippers. Figures 8.16–8.21 demonstrate the formation of the single needle lock stitch; an example of this stitch on a back pocket is given in Figure 8.22. The sewing machine that produces this stitch is given in Figure 8.23. Other examples of where this stitch is used are on pocket hems and the leg hems at the bottom of the jeans.

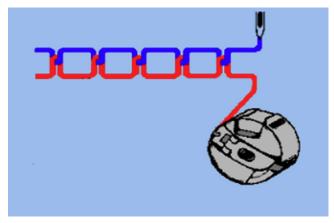


Figure 8.16 Descending needle bar.

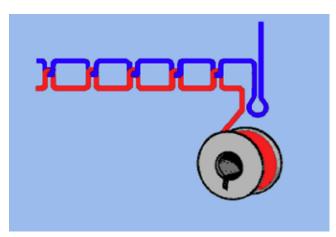


Figure 8.17 Needle thread loop formation as needle bar rises.

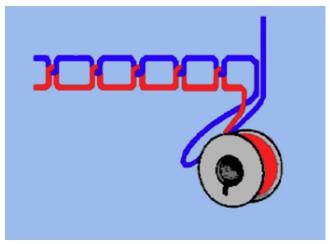


Figure 8.18 Needle thread loop collected by rotary hook and expanded.

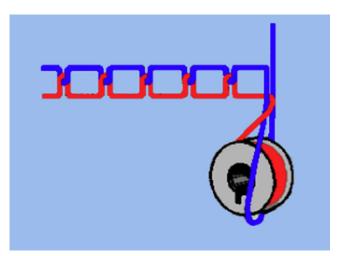


Figure 8.19 Needle thread loop fully expanded and taken around spool.

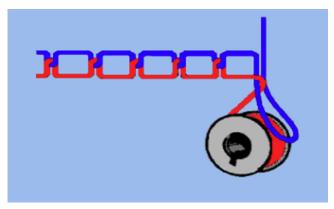


Figure 8.20 Needle thread loop released after passing 6 o'clock position.

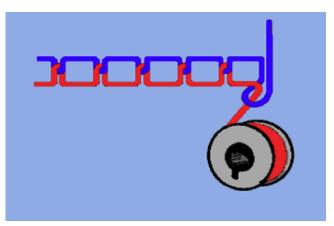


Figure 8.21 Needle thread loop drawn up by take up leaver and check spring.



Figure 8.22 Back pocket of denim jeans showing 301 lock stitch.



Figure 8.23 Four motion drop feed lock stitch sewing machine.

### 8.3.3 Two thread chain stitch – 401

Stitch number 401 is commonly used in denim products, particularly jeans, and is indeed one of the most important stitches used on this garment. It has great extensibility, durability and strength, which are important properties for a material and product of this kind. The chain stitch is produced by the machine passing one or more needle thread loops through the material and inter-looping it on the underside with a looper

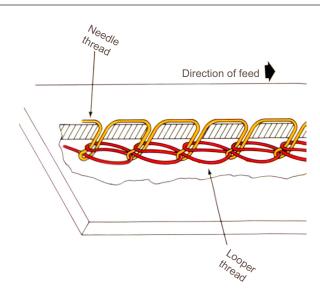


Figure 8.24 Schematic view of the 401 chain stitch.

thread. Unlike the lock stitch, constant thread supplies from cones of sewing thread enable continuous stitching without the need to change the cone, because one cone contains approximately 5000 m of thread. Lock stitch spools need to be changed regularly because they only carry a small amount of thread and therefore run out of thread quickly. Figures 8.24 and 8.25 show the 401 chain stitch, in which the upper thread is the needle thread and the lower one is the looper thread.

The stitch forming mechanism is completely different from that employed in the creation of the lock stitch. This stitch is commonly used on the side seams of the jeans, providing extra extensibility to the seam. It is also used on the waistbands. This stitch has approximately 60% extension (double the lock stitch) because of the extra needle thread loop length, the lower static tension required to form the stitch and the extendable looper thread geometry, which gives the garment good extensibility. This stitch has the appearance of a lock stitch on the face of the fabric but it has loops on the underneath of the material that make it a chain stitch, as shown in Figure 8.26. The machine that produces this stitch will be discussed later in this chapter.

#### 8.3.4 Two thread chain stitch – 402

This stitch formation is also called bottom cover and is made with two needle threads and one looper thread, with the looper thread passing across the underside of the seam to give cover. Each needle thread passes initially through the loop made in the looper thread, which subsequently passes through the needle thread loop. This stitch gives good extensibility while capturing and covering the folded raw edges on the underside.

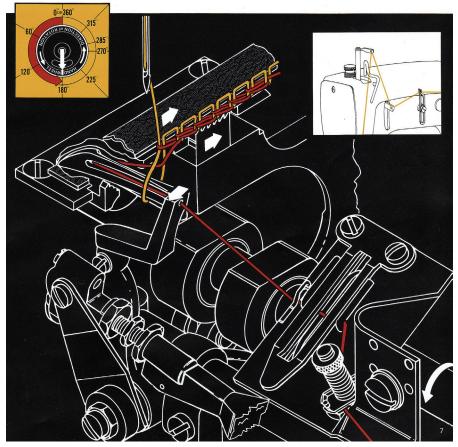


Figure 8.25 Looper mechanism creating the 401 chain stitch.

### 8.3.5 Three thread over edge – 504

This stitch formation consists of one needle thread and two looper threads, with the looper threads forming a purl on the edge of the fabric, as shown in Figure 8.27. The needle thread provides the seam strength and the looper threads provide cover on the edge of the fabric that prevents frayed edges, creating a neat appearance on the seam.

### 8.3.6 Five thread over edge – 516

This stitch formation has a row of stitch type 504 plus and an extra row of stitch type 401, as described above. This stitch is produced on one machine and has the dual role of providing neatness on the edge with the 504 stitch while time providing great



Figure 8.26 Underside of 401 chain stitch on outside leg seam.

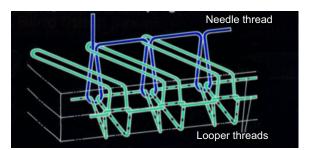


Figure 8.27 Schematic view of three thread over edge stitch.

strength to the seam with two thread chain stitch 401. An example of the stitch and its appearance on the seam is given in Figures 8.28 and 8.29. The machine producing this stitch will be presented later in this chapter.

#### 8.3.7 Bar tack stitches – 304

Bar tack stitches (special case) are often used to reinforce pockets and zippers, and particularly to attach belt loops to the waistband. These stitches have a zigzag formation and are lock stitches, as described previously. Bar tacking stitches are given in Figures 8.30 and 8.31; the machine that produces this stitch, as shown in Figures 8.32 and 8.33, is described later in this chapter.

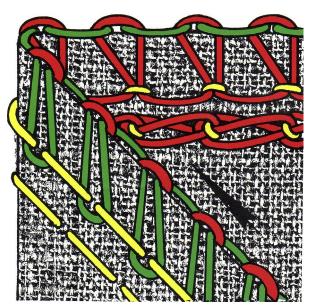


Figure 8.28 Schematic view of five thread over edge stitch.



Figure 8.29 516 stitch used in the inside leg of jeans.

### 8.3.8 Selection of correct stitch density

As part of the stitching process, it is important to have the correct stitch density in the garment because it directly influences the seam strength, seam appearance and seam extensibility. Factors affecting stitch density are:

- Type and weight of the fabric.
- Stitch and seam construction.
- Thread type and size.
- Stitch balance (thread tensioning).



Figure 8.30 Bar tack stitch reinforcing a back pocket.



Figure 8.31 Bar tack stitch on a belt loop.

A normal consistent stitch density for denim jeans is approximately eight to ten stitches per 2.54 cm, equivalent to approximately three stitches per cm.

# 8.4 Sewing threads for jeans

Sewing threads are an integral part of many things used daily. Most apparel is joined by a sewing thread. Choosing the right sewing thread is essential if the garment is to be fit for a purpose and not fall apart during general wear.



Figure 8.32 Bar tack stitching machine.



Figure 8.33 Bar tack machine reinforcing a zipper.

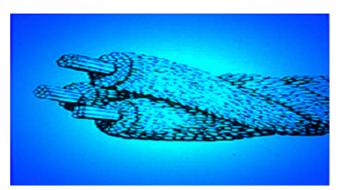


Figure 8.34 Core spun yarn.

### 8.4.1 Factors in choosing a thread

The main factors to consider when choosing the correct thread are:

- Sewability of the garment.
- Strength.
- Durability.
- Elongation.
- Shrinkage.
- Abrasion resistance.
- Colour fastness.
- · Resistance to chemicals, light, heat, etc.

Product factors include:

- · Required seam strength.
- Type of seam.
- Stitch type.
- Stitch density (stitches per centimetre).
- Type of material being sewn.
- Type of machine and related equipment.
- Conditions under which the product should perform.
- · Normal life of product.
- Cost effectiveness.

The most common sewing thread used to sew denim is a cotton/polyester core spun yarn. This yarn serves two purposes. Polyester provides strength to the yarn when stitched into the garment. The cotton outer core is core spun – in other words, wrapped around the polyester – and provides protection against heat during washing. An example of a core spun yarn is given in Figure 8.34.

### 8.4.2 Sewing with heavy thread sizes

As mentioned at the beginning of this chapter, denim has a place in history as being a diverse material with a vast range of qualities. From a designer's perspective, this

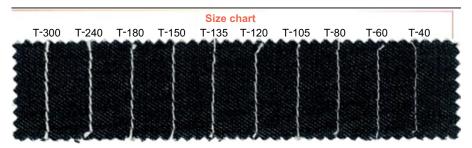


Figure 8.35 Sewing thread sizes on a selection card.

enables the opportunity to make products unique by using different combinations of sewing threads. From a thread outlook, this can include:

- · Using contrast colour threads:
  - · For all topstitching operations.
  - For different operations.
  - · For different needles of the same operation.
- Using threads that will maintain their colour regardless of the wash process:
  - Using a 100% polyester thread dyed with disperse dyes.
  - Using a cotton wrapped core thread.
  - · Using a true indigo dyed cotton wrapped core thread.
  - Using different thread sizes that give a bolder stitch appearance.

An example of a thread sizing chart for denim is given in Figure 8.35.

# 8.5 Sewing needles for jeans

The sewing machine needle is the most important component of the sewing machine because it carries and delivers the sewing thread to the sewing mechanism. If it is not changed regularly it can be responsible for major quality problems. It is also subject to the most abuse of all machine parts because it penetrates the material at speeds of 5-6000 times per minute for lock stitches and 8-10,000 times per minute in chain stitches. Friction caused by penetration of the needle into the fabric causes extreme needle heating, with temperatures in excess of 250 °C, which can lead to premature needle distortion, thread breakage and thread charring.

Before the practicalities of changing the needle are discussed, it is important to have some knowledge about what the needle does and its component parts. Sewing needles come in a wide range of point types that are used to sew many different types of material with different properties. The needle is a slender pointed instrument usually made of tempered steel, containing an eye to carry a thread through a fabric for sewing. The main function is to part the yarns in the material so that the thread can form a stitch in the fabric. The factors to consider when choosing a needle are:

- Fabric type.
- Fabric density.

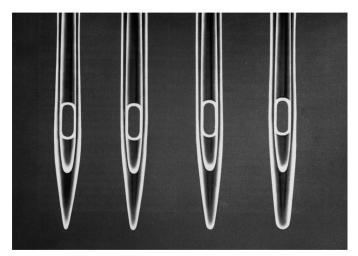


Figure 8.36 Examples of needle point types.

- · Fabric composition.
- Type of machine.
- Type of sewing thread.
- · Fabric thickness.

The most important aspect of needle design is the needle point because it has to penetrate the fabric without causing damage to the material. It is also the most diverse part of the needle because of the many different types of points used. These needle points are designed to sew many different fabric types and create various seams. An example of needle point designs and the component parts of the needle can be seen in Figure 8.36.

When fabrics are stitched together, the impact from the needle as it penetrates the fabric can cause buckling and distortion of the yarns and fibres. The mechanical strain on the yarns increases if the needle is damaged, as shown in Figure 8.37. This causes the fibres to rupture, thus reducing seam strength significantly. The following factors need to be taken into account to avoid this problem:

- Use a needle with a smaller diameter for the fabric and seam being sewn.
- Adapt the opening of the sewing plate to fit the needle size.
- Use a sewing thread with the correct diameter for the needle eye.
- Use the correct needle point for the type of fabric being sewn.
- Consider whether the type of seam that is being used to construct the garment could be changed or use multiple seaming to divide the strain.

A smaller diameter needle reduces the mechanical forces exerted on the yarns. Needle diameters can range from size 50s (0.50 mm) to in excess of 150s (1.50 mm). When sewing industrial fabrics, for example, needles can be 100–120 mm long with a diameter of 3–4 mm.

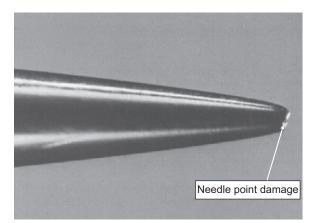


Figure 8.37 Damaged needle point.

#### 8.5.1 Component parts of needles

Component parts of the needles are the:

- Butt.
- Shank.
- Shoulder.
- Blade.
- Long groove.
- Short groove.
- Needle eye.
- Scarf.
- Needle point.
- Needle tip.

The shank fits into the needle bar of the machine. The grooves that are channelled into the blade are designed as a protective channel for the sewing thread. Some needle types have a short groove that runs from the scarf of the needle up to the shoulder. The needle eye is threaded with the sewing thread. The scarf is the flattened part of the needle, designed to enable the sewing mechanism (in the case of a lock stitch, the sewing hook) to pick up a loop of the sewing thread and thus form a stitch. The point and the tip are the first point of contact with the fabric. Diagrams for needle component parts are given in Figure 8.38(a) and 8.38(b). Threading of the needle for a lock stitch machine can be seen in Figure 8.39.

#### 8.5.2 Problems caused by needles

A major cause of seam failure in denim products is needle damage, as shown in Figure 8.40; Figure 8.41 shows a special needle profile for damage reduction. During manufacturing, the needle point can become damaged either by deflection of the needle onto the sewing mechanism or just by general wear and tear. The

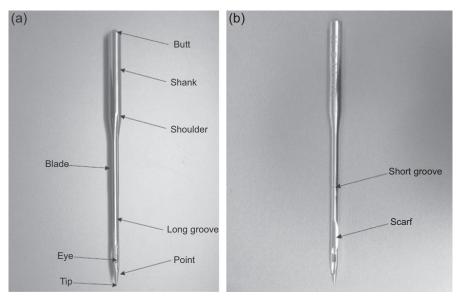


Figure 8.38 Needle component parts (a) front, (b) back.

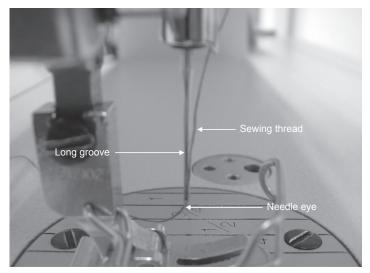


Figure 8.39 Typical needle threading path.

needle then has a hook rather like a fishhook, or a sharp edge on the tip of the needle commonly known as a burr. This burr on the needle damages and cuts the fibres in the material upon entry into the fabric, and even more so on its return stroke when the needle rises from the fabric. The weave threads burst, causing

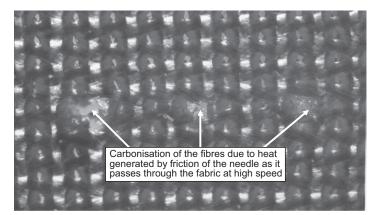


Figure 8.40 Needle heat induced fabric damage.

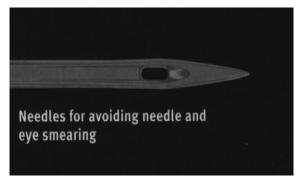


Figure 8.41 Special needle profile for damage reduction.

major weakening of the seam. The garment is more likely to rupture at the seams during washing owing to forces exerted from the mechanical action of the washing process.

### 8.5.3 Bent needles

A bent needle causes the sewing mechanism to miss the loop of thread from the needle, therefore causing the machine to miss stitches. This is common in denim, so the needle should be changed regularly to prevent such damage from occurring. As a guide, the needle should be changed at least once a day, possibly twice depending on the thickness and density of the material being sewn. The needle is threaded with the sewing thread. Note that on this machine, the sewing thread is threaded from left to right, with the long groove acting as the protective channel with the scarf on the opposite side of the needle.

### 8.5.4 Needle heating

Needle heating is caused by needle to fabric friction as it penetrates and withdraws from the material. The level of damage caused is directly related to the sewing. On medium thickness and average density materials and with a sewing speed of approximately 4000 stitches per minute (SPM), an average sewing needle reaches a temperature of 250 °C. At speeds of 8000–10,000 (SPM) on modern sewing machines, the needle temperature rises quickly to more than 350 °C unless special precautions are taken to prevent this. This can affect the needle hardness (temper) and will almost certainly cause problems to the sewing thread as well as the material in the region of needle penetration.

Although natural fibres can sustain needle temperatures of 350 °C for a short time, the dressings with which many weaves are treated do not withstand such high temperatures. They melt and smear over the surface of the needle, thereby increasing friction even more. Where the fabrics consist of synthetic material, high temperatures are harmful to an even greater extent. The needle temperature can be reduced by:

- · Reducing needle friction by using special needle shapes and surfaces.
- · Reducing friction by fluids.
- Cooling by fluids.
- Cooling by compressed air.

Preventive measures can be taken, as previously stated, such as:

- Changing the needle regularly.
- Using the correct needle for the application: point, type and size.
- Using a sewing thread of the correct diameter for the sewing needle.
- · Only authorised personnel to distribute needles.

#### 8.5.5 Applications of needle points

Some needle points (Figure 8.36) have been specifically developed for sewing different types and structures of material. When the needle passes through the fabric, the fabric yarns are pushed aside as well as downward, according to the angle of the point. The angle of the sharper needle point is more acute than that of the blunter point. The surface area of contact between the needle point and the fabric is less than that of the rounder or ball point. The most common needle used to sew denim is the normal round point needle (Figure 8.38(a) and 8.38(b)).

#### 8.5.6 Broken needles and contamination

Broken needle procedures and metal contamination policies are becoming increasingly common in clothing production factories. Broken needles left in garments can cause serious injury to the wearer of the garment. Therefore, more and more retailing organisations are demanding these procedures from their suppliers. An example of such a policy is given below. The capital letters are as how they would appear on a sheet, laminated and fixed to a factory wall, sometimes even fixed to the sewing machine bench.

# NOTE: THIS IS NON-NEGOTIABLE. IT WILL BE ENFORCED RIGOROUSLY.

#### **OPERATOR RESPONSIBILITIES**

- 1. <u>NO</u> PINS, STAPLES OR OTHER SMALL PIECES OF METAL ARE ALLOWED IN THE SECTIONS OF SEWING MACHINES AND <u>NO</u> NEEDLES EXCEPT THOSE IN USE.
- 2. CLEAN MACHINES DAILY. KEEP WORKPLACE CLEAN AND TIDY.
- 3. PLACE CLOTH UNDER FOOT WHEN NOT IN USE.
- **4.** BE AWARE OF QUALITY AT ALL TIMES. CHECK STANDARD DAILY AND PRO-DUCE WORK OF EQUAL QUALITY TO IT.

#### **BROKEN NEEDLE PROCEDURE**

- 1. INFORM SUPERVISOR. TOGETHER, TRY TO FIND ALL PIECES. THE SUPERVISOR IS TO TAPE ALL PIECES TO THE BROKEN NEEDLE SHEET BEFORE ISSUING ANOTHER NEEDLE.
- 2. IF UNABLE TO FIND ALL OF THE PIECES, THE SUPERVISOR WILL ATTACH PIECES THAT ARE FOUND TO THE SHEET. THEN THE SUPERVISOR WILL ISOLATE ALL WORK AROUND THE SEWING MACHINE AND CHECK WITH A METAL DETECTOR. WHILE THE SUPERVISOR IS DOING THIS, CHECK ANY LIT-TER BINS AND EMPTY THE CONTENTS INTO A PLASTIC BAG, WHICH MUST BE PUT INTO THE DUSTBIN. IF ALL OF THE NEEDLE PIECES CANNOT BE FOUND, THE SUPERVISOR MUST TAKE THE WORK FROM THE SECTION AND INFORM THE FACTORY MANAGER.

#### USED NEEDLE REPLACEMENT PROCEDURE

WHEN ROUTINELY CHANGING USED NEEDLES, THE OLD NEEDLE <u>MUST</u> BE HANDED BACK TO THE <u>SUPERVISOR</u> BEFORE A NEW NEEDLE IS ISSUED.

ON NO ACCOUNT MUST AN OPERATOR APPROACH A MECHANIC FOR NEEDLES.

#### NEEDLE STORAGE

NEW NEEDLES ARE STORED IN A SECURE LOCKED BOX AND ARE KEPT IN THE PRODUCTION OFFICE.

#### DOCUMENTATION

ALL DOCUMENTATION IS LOGGED ON THE BROKEN NEEDLE PROCEDURE SHEET.

A LAMINATED CARD IS ATTACHED TO EVERY RELEVANT PIECE OF MACHINERY OUTLINING THIS PROCEDURE TO THE OPERATIVES.

# 8.6 Machines for making jeans

Sewing machines are classified according to three distinct factors that differentiate between the types of machines for various seaming operations. These three factors are:

- · Machine bed type.
- The feed system they use.
- The stitch type they produce.

For example, it is possible to have a machine with a flat bed and a top and bottom feed system producing a 301 lock stitch. Alternatively, the machine could have a raised bed and a drop feed system creating a 401 chain stitch. The descriptive configuration would be:

Machine 1:

- Flat bed.
- Top and bottom feed.
- Lock stitch.

Machine 2:

- · Raised bed.
- Drop feed.
- Chain stitch.

The machine (sewing head) usually offers only one stitch type; the exception is a combination stitch machine in which more than one stitch type is produced on the same machine. An example of this would be a five thread over edge machine producing over locking stitch number 504 and one row of chain stitch number 401 to give stitch 516, as described previously.

The machine bed is also determined by the volume of fabric that passes beneath and around the needle and the amount of manipulation required for this fabric. The machines and machine bed types used for manufacturing denim products are discussed further.

#### 8.6.1 Flat bed

A flat bed is primarily used where large open parts are to be joined when more than just the seam allowance must pass to the right of the needle, as shown in Figure 8.42. It is easy to mount guides and markers on this type of bed.

### 8.6.2 Cylinder bed

The cylinder bed is used when parts are small or curved and when the operation is being performed on partially closed components such as hemming a jeans leg, as shown in Figure 8.43.

#### 8.6.3 Feed off the arm

The feed off the arm machine head is used when the product part is being closed into a tube and the final seam is introduced by the feed off the arm machine, as shown in Figure 8.44. Typical use is on the outside leg of a pair of jeans.

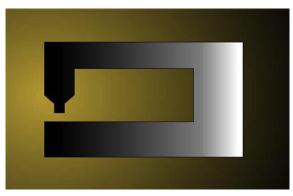


Figure 8.42 Schematic view of flat bed machine head.

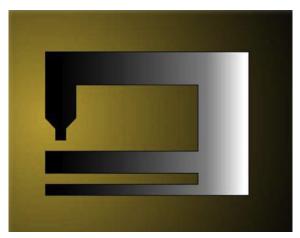


Figure 8.43 Schematic view of cylinder bed machine head.

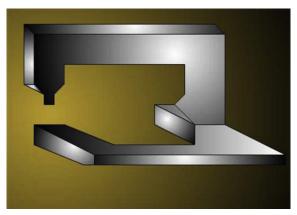


Figure 8.44 Schematic view of feed off the arm machine head.

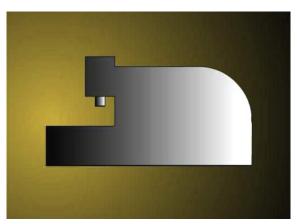


Figure 8.45 Schematic view of over edge bed machine head.



Figure 8.46 Integrated sewing unit showing control panel.

### 8.6.4 Over edge machine

By its very nature, the over edge machine requires clearance to the right of the needle because excess fabric is trimmed by reciprocating blades as stitching takes place, as shown in Figure 8.45. The bed may be raised from the work top to allow better handling around the work area for sewing smaller pieces such as pockets and underwear. Further details about machine beds are discussed later in this chapter.

# 8.6.5 Integrated sewing unit

The integrated stitching/sewing unit (ISU) is so called because it provides many useful functions that help reduce operator fatigue while improving the efficiency of production. These machines, as shown in Figure 8.46, may be referred to as basic units, but there is nothing basic about them. Most have built in computers that provide a variety

of time saving, cost effective functions. Various components that the electronics in the machine can control include:

- Automatic foot lift: Pressing back with the heel on the treadle causes the presser foot to rise, or at the end of a seam of a prescribed number of stitches the presser foot will rise automatically.
- Automatic back tack: The machine can be set so that when the foot treadle is pressed to start sewing, the machine will feed forward a set number of stitches and then reverse a set number of stitches to reinforce the stitch area at the beginning of sewing. By pressing back on the treadle with the heel, a similar function is performed that reinforces the stitch at the end of sewing.
- Automatic under bed thread trimmer (UBT): This device cuts sewing threads without the need to use scissors. Again, this function is usually performed at the end of the sewing operation on the seam that has just been sewn. Pressing back firmly on the treadle activates the UBTs.
- Needle positioning motors: None of these could take place without these special motors that
  make the machine move and perform its operations. These machines use what is called a
  synchroniser, which positions the needle in the same position each time the machine stops. It
  would not be possible to control accurate trimming of the sewing thread or automated back
  tacking without these types of motors.

The ISU machine is often called the workhorse of the sewn product industry. It is the most widely used machine in high volume production.

## 8.7 Fabric feed systems

The principle of the feeding mechanism is to move the material from one stitch position to the next over the prescribed distance given by the length of the stitch. In doing so, the fabric must be controlled precisely under minimum pressure. As shown in Figure 8.47, the feed system is made of the following components:

- Throat plate.
- Feed dog (feeder).
- Presser foot.

These are often described as the fittings because they fit together.

#### 8.7.1 Throat plate

These are designed to support the material being stitched and allow easy passage of the material over its surface. The throat plate is manufactured with a needle hole to allow the needle to penetrate the fabric.

- The needle hole must be large enough for the needle and sewing thread to pass through.
- Slots in the throat plate allow the feed dog to rise and engage the underside of the fabric.
- The slots should match the width of the rows of teeth on the feed dog without allowing contact.

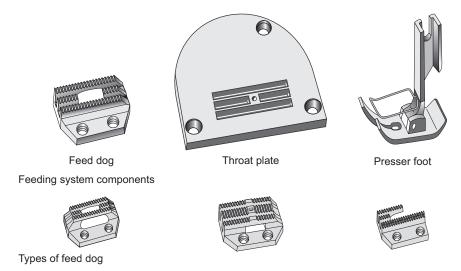


Figure 8.47 Elements of the fabric feed system.

### 8.7.2 Presser foot

The primary functions of the presser foot are to:

- · Hold the fabric with the required minimum pressure against the throat plate.
- Enable the feeder to advance the material through the machine during feeding.
- Provide stability around the needle point for correct loop formation of the sewing stitch.

There are many types of presser foot, which are selected for specific applications including:

- · Hinged presser foot.
- · Compensating foot.
- · Piping foot.
- Narrow hemming foot.

## 8.7.3 Feed dog

- Feed dog or a feeder is a solid mass of hardened steel that takes the form of multiple rows of teeth.
- The number of rows affects the level of support offered to the fabric during feeding.
- The number of teeth per centimetre on the feed dog is determined by the fabric, weave/knit and its thickness.
- A feeder with fine teeth (high tooth density) is used to feed delicate lightweight fabrics.
- A feeder with coarse teeth is used to feed heavier fabrics (such as denim).

## 8.7.4 Feed settings

It is usual to allow the full depth of one tooth to be above the throat plate at the point of maximum lift, as shown in Figure 8.48.

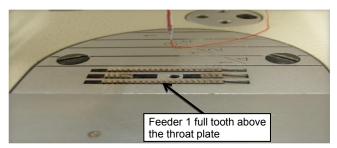


Figure 8.48 Depth/rise setting of the feed dog.

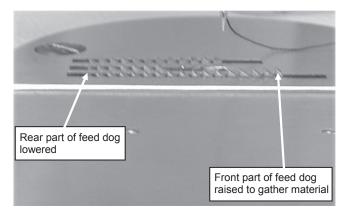


Figure 8.49 Raised front feeder to gather material.

The feed dog can be tilted to the front or the back, which can help prevent fabric overfeed, as shown in Figures 8.49 and 8.50, or underfeed.

- Tilted at the back helps reduce structural jamming pucker by stretching the needle penetration hole.
- Tilted up at the front helps to reduce extension on the fabric by feeding more fabric into the stitching area.

## 8.7.5 Feed systems

To feed the material correctly for denim materials, as is required for effective stitch formation, several different feed systems have been developed. These are given as follows:

- Four motion drop feed.
- · Differential drop feed.
- Compound feed.
- Variable top and bottom feed.
- Puller feed.

Many feed systems are used in specialist areas of production; therefore, only the most common ones are illustrated here and those specific to denim jeans manufacture.

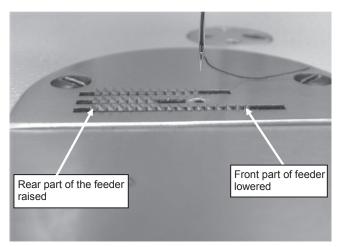


Figure 8.50 Raised rear feeder to stretch material.

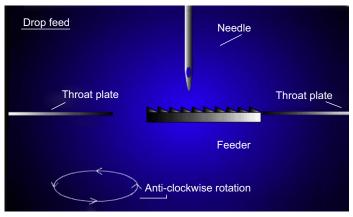


Figure 8.51 Four motion drop feed action.

# 8.7.5.1 Four motion drop feed

- It is the most common of all the feed systems, as shown in Figure 8.51. The feed dog engages the underside of the bottom fabric ply intermittently.
- Set up (timed) to engage the fabric as late as possible after the needle has raised clear of the top ply.
- Ensuring the fabric movement has finished before the needle re-descends into the fabric.

# 8.7.5.2 Differential feed

- By feeding more with the back feed dog than the front feed dog (in the same stitch cycle), it is possible to stretch the bottom fabric ply.
- Conversely, by feeding more with the front feed dog than the back feed dog, it is possible to introduce fullness into the bottom ply, as shown in Figure 8.52.

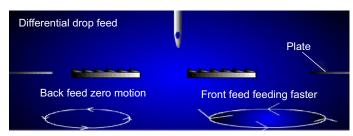


Figure 8.52 Differential feed action.

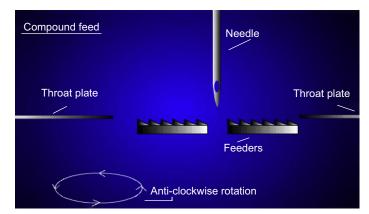


Figure 8.53 Compound feed action.

## 8.7.5.3 Compound feed

- This combines needle feed with the four motion drop feed system.
- The feed timing is such that the feed dog rises and engages the bottom fabric ply at the same time as the needle descends into the fabric.
- Both the feed dog and needle move the fabric through the prescribed stitch length.
- This can help reduce feeding pucker and ply slippage during stitching because the fabric plies are pinned together during stitching (often used on jeans waistband attach operations), as shown in Figure 8.53.

## 8.7.5.4 Variable top and bottom feed

- · A combination of the feeding foot synchronised with a four motion drop feed system
- Often used to sew high friction materials such as denim and composites in which the use of a static presser foot is unsuitable, as shown in Figure 8.54.

### 8.7.5.5 Puller feed

• This is an auxiliary feed (in addition to the main feed system) that takes the form of a continuously or intermittently turning weighted roller positioned at the rear of the needle

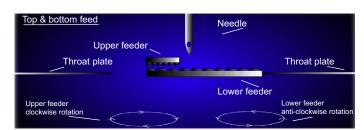


Figure 8.54 Variable top and bottom feed action.

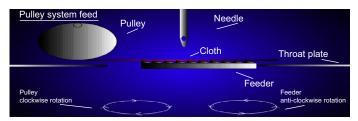


Figure 8.55 Puller feed action.

• Mainly used to seam heavy fabrics or maintain tension in lightweight materials. Sewing waistbands onto denim fabrics is an example of this, as shown in Figure 8.55.

# 8.8 Stitching of denim jeans

The stitching of denim jeans is a labour intensive and complex process. Sewing machines used to process denim are both interesting and complex; an account is given here of the most commonly used machines.

### 8.8.1 Stitching of inside seams

This machine uses an over edge bed with a 516 stitch and a differential feed mechanism to stitch the inside seam. An example of this is given in Figure 8.56.

### 8.8.2 Twin stitching pocket hem

This operation shows a machine with two needles that has a compound feed and uses two rows of lock stitch, stitch type 301. An example is given in Figure 8.57.

## 8.8.3 Twin stitching zipper with J-stitch

A machine similar to that of the pocket hem is used, but this time top stitching a zipper using a J-stitch as discussed earlier. An example is given in Figure 8.58. This operation is often semi-automated and uses a programmable lock stitch sewing machine to give a consistent shape because it is a highly visible section of the garment.



Figure 8.56 Inside leg seam with 516 stitch on over edge machine.



Figure 8.57 Twin needle lock stitch with folder making pocket hem.

### 8.8.4 Stitching of back rise

This operation shows a feed off the arm machine stitching a back rise and back yoke to the main body of the garment. This machine uses a 401 two thread chain stitch and a drop feed. A puller feed is also used at the back of the machine as an extra force to feed the fabric through the machine. The fabric is fed through a double lap seam folder to form an accurate and strong seam, as shown in Figure 8.59.

### 8.8.5 Stitching of side seams

This operation shows a feed off the arm machine stitching the side seams of the jeans together. The configuration of the machine is similar to that described above. However, this machine also uses a tractor foot, as can be seen in Figure 8.60. This enables the machine to climb excessive seam thicknesses where all the fabrics come together in one join. It provides great stability when clamping down on the fabric and reduces the possibility of missed stitches.



Figure 8.58 Twin needle lock stitch J-stitching the fly profile.



Figure 8.59 Attaching hip yoke with a twin needle chain stitch.



Figure 8.60 Twin needle chain stitch with lap felled seam folder.



Figure 8.61 301 lock stitch on a cylinder bed making a leg hem.



Figure 8.62 Attaching of waistband.

### 8.8.6 Bottom leg hems

This machine uses a cylinder arm, as described above with a 301 lock stitch, and a puller feed, as shown in Figure 8.61. The fabric is fed through a double hem folder also described before in this chapter.

## 8.8.7 Attaching waistband

Another important machine operation is attaching the waistband to the main body of the jeans. In this example, the machine has two needles and the waistband is fed through a continuous folder, thus reducing operator handling. The stitch formation is a two thread chain stitch 401 and the feed system is a combination of a drop feed and a puller feed. An example of the machine is given in Figure 8.62.



Figure 8.63 Making of belt loop.

## 8.8.8 Making belt loop

The fabric is folded through a dedicated belt loop folder. The belt loops are fed through the folder, producing a seam as described previously. The stitch produced is stitch type 402 and a drop feed is used to feed this material. An example is given in Figure 8.63.

# 8.8.9 Attaching belt loop

Belt loops on this garment are attached using a semi-automatic belt looping machine. A continuous roll of finished belt loop, as described above, is cut to length and a clamp holds the belt loop and presents it to the machine. Two needles are employed on this machine to sew both ends of the belt loop in one operation. Again, operator handling is reduced where only the body of the garment is held, making operation faster, more accurate and more efficient. The machine uses a 304 lock stitch and the feed mechanism used clamps the fabric using x and y stepper motors. An example is given in Figure 8.64.

## 8.8.10 Bar tacking for reinforcing

Exactly as for stitching the belt loop, this is a similar machine but uses only one needle and is classified as a mechanised (fixed cycle) unit because when the treadle is pressed, the machine cycle cannot be interrupted until the operation is finished. An example of this machine is given in Figure 8.65.

# 8.8.11 Eyelet buttonholes

This machine produces the buttonhole commonly used on denim apparel. These machines are one of the most complex and have to be used with great care. This fixed cycle machine can be either a cut-before or cut-after type. An example is given in Figure 8.66.



Figure 8.64 Attaching of belt loop.



Figure 8.65 Bar tack machine for reinforcement.

## 8.8.12 Pockets and labels

Semi-automatic machines require less human involvement and do more of the work autonomously. Such machines are used to attach pockets, as shown in Figure 8.67, and to attach labels to the jeans, as shown in Figure 8.68.

# 8.9 Sewing faults and troubleshooting

Faults may result from numerous causes. In all cases, however, it is necessary to check the machine for correct settings. In most cases this will eliminate the fault.



Figure 8.66 Electronic buttonhole machine.

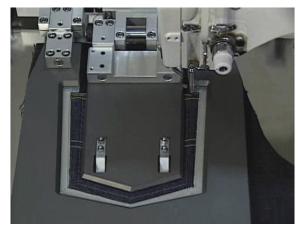


Figure 8.67 Patch pocket attaching machine.

### 8.9.1 Thread breakage

- Thread channels jagged: Check and polish all thread guiding parts. Check for correct thread run according to operating instructions.
- Faulty threading: Check thread run according to operating instructions.
- Blunt, crooked or wrong needle: Insert new needle.
- Needle too high: Adjust needle height.
- · Needle too low: Insert needle as far as it will go. Observe operating instructions.
- Wrong relationship between needle and thread: Observe specifications. Only use good quality thread in the specified thickness and twist. Do not use thread that has been stored for too long in dry conditions.
- Needle threaded from wrong side: Always thread needle from the long groove side. Observe operating instructions.
- Needle hole nicked by needle: Lightly trim edges and polish needle hole. If necessary, fit new throat plate.



#### Figure 8.68 Label attaching machine.

- Needle hole too small or excessively thick needle thread: Fit throat plate with larger diameter hole or re-machine the needle hole. Use needle thread according to specifications. Observe relationship between needle and yarn.
- Hook badly worn. Sharp edges: Fit new hook and adjust.
- Bobbin case tension spring screws too high and thread catches: Tighten screws sufficiently. If this creates excessive tension, slightly bend the tension spring.
- Thread clearance between bobbin case support and hook inadequate: Adjust according to instructions. The clearance should be sufficient to ensure that the thickest thread gauge to be used passes through smoothly.
- Hook catches needle thread loop too late or late early: Adjust hook or loop life.
- Excessive tension: Adjust tension according to the material to be sewn. Observe operating instructions.
- Knotty or brittle thread: Only use good quality threads in the specified thickness and twist.
- Hook, bobbin case top and bottom sections nicked by needle, rusty or broken: Use new parts. Re-polish existing parts.
- Too much loose thread as the needle enters. Needle pierces loose threads: Adjust take up spring.
- Thread clearance insufficient between hook bottom and bobbin case bottom section, needle thread loop catches (dirt and fluff): Clean hook; if necessary, fit new hook.
- Excessive bobbin thread tension: Adjust tension according to operating instructions.

#### 8.9.2 Needle breakage

- · Wrong hook setting: Adjust hook according to specifications.
- The needle is bent and clears the hook point: Fit new needle.
- Needle too thin for needle hole or material: Use correct needle system and gauge. When using thick needles, fit throat plate with a larger needle hole. For thick or hard material use thicker needle or a needle with a cutter point.
- Needle protection: The needle should enter in such a way that it does not allow the presser foot to be lowered onto the throat plate even with the needle pressed off, and so that the throat plate allows the needle to enter in such a manner that the specified clearance between the needle and hook point is obtained.

- Wrong needle/thread ratio: Observe specifications.
- Knotty or even thread: Only use good quality threads in the specified thickness and twist. Do not use thread that has been stored for too long under dry conditions.
- Needle breaks upon entering into the material or feed incorrectly relative to needle position: Adjust according to instructions.
- Bobbin case incorrectly fitted: Press in bobbin case until it engages with an audible click. See operating instructions.
- Hook point too close to needle: Adjust needle/hook point clearance.
- Throat plate incorrectly fitted: Lightly tighten throat plate set screws in a diagonal sequence and then tighten firmly. Check countersunk screw holes and screw heads. These must be uniform.
- The material is pushed or pulled during sewing from needle seats: Guide material more lightly. See operating instructions. Check feed follow up movement. Increase presser pressure according to operating instructions.
- Feed dog too high, moving along material during its forward movement: Adjust feed dog height.
- · Feed dog feeds too early or too late: Adjust according to instructions.
- Hook worn: Fit new hook.
- Needle drops out during sewing. Fixing screw fails to clamp needle satisfactorily: Check fixing screw and replace if necessary.
- Needle bar excessively worn: Fit new needle bar or bush.
- Excessive thread tension; needle bends and is caught by the hook point: Set correct tension to suit sewing material. See operating instructions.

### 8.9.3 Skipped stitches

- Needle wrong, bent or incorrectly fitted: Fit new needle. For correct fitting see operating instructions.
- Faulty threading: Observe thread run according to operating instructions.
- Faulty take up: Adjust take up spring.
- Wrong hook setting: Observe correct setting.
- Needle/thread ratio incorrect: Use appropriate needle system, size and gauge according to instructions.
- Hook point damaged: Machine hook point, polish or fit new hook.
- Needle hole is too large and material is drawn in: Use throat plate with a smaller needle hole. Observe purpose of machine (material thickness).
- Needle too low: Fit needle as specified in operating instructions.
- Needle too high: Adjust needle bar height.
- Poor needle quality: Only use good quality needles at the specified gauge.
- Insufficient presser pressure and with thick materials the needle raises the material: Adjust presser pressure according to operating instructions.
- The thread twirls; irregular loop formation; thread too sharply twisted: Only use good quality thread at the indicated gauge and twist.
- Thread unevenly thick and brittle: Do not use thread that has been stored too long under dry conditions. Only use good quality thread at the indicated gauge and thickness.
- · Right hand twisted thread: Only left hand twisted thread should be used in most machines.
- · Hook catches thread loop too early or too late: Adjust loop lift according to instructions.
- Insufficient or excessive tension: Adjust the tension to suit the material to be sewn, in accordance with operating instructions.
- Needle too far from hook point: Adjust clearance between needle and hook point.

#### 8.9.4 Uneven seams

- Here, faults may be caused in the same manner as indicated under 'thread breakage' and 'skipped stitches'.
- Looping of threads above or below the material: Adjust needle and bobbin thread tension according to operating instructions.
- Poor and knotty thread: Only use good quality thread. For gauge and twist, see instructions.
- Forward and reverse stitch of different length: Observe adjustment instructions.
- Hook has run out of oil. Guide groove rough, bobbin case on edge: Observe oiling details in operating instructions. Fit new hook and adjust.
- Faulty threading: Observe thread run according to operating instructions.
- · Tensioning discs dirty, fouled or sticky: Clean components and, if necessary, re-polish.
- · Thread guiding components rusty or rough: Remove rust and re-polish.
- Thread take up incorrect: Adjust take up spring. (Adjust resilience of material thickness accordingly.)
- Needle too high or too low: Fit needle according to operating instructions or adjust needle bar height.
- Thread fails to pass smoothly over hook: Re-polish all thread contact points. Observe settings.
- Feed dog setting incorrect: Set to feed dog figures given in instructions.
- · Fouled hook. Hook prevented from rotating evenly: Clean hook. Observe setting.
- Machine sews in curve: Check feed dog position. Check contact of presser foot on feed dog.
- Bobbin irregularly wound, wrongly inserted or threaded: Rewind, insert and thread according to operating instructions.
- Machine fails to sew over seams and folds: Incorrectly set presser foot pressure. Adjust feed dog height. Set presser foot pressure to suit material's thickness according to operating instructions.
- Coarse feed dog teeth ruffling the material: Use correct feed dog teeth as provided by the works. For thin, lightweight materials, use fine toothed feed dog. Coarse and saw tooth type feed dogs should be used only for the material for which they have been intended. (Observe the setting.) (Feed dog follow up movement.)
- Irregularly wound bobbin thread: When winding up, make sure that the threads lie adjacent to each other.

# 8.10 Attaching fastenings on jeans

A variety of machines are used to attach press fasteners to denim materials. These include the manual foot ratchet machine, in which components are manually fed and activated using a foot ratchet press, as shown in Figure 8.69. Alternatively, electric machines can be manually or hopper fed. Their selection usually depends on the speed and volume of throughput required, but also on access to equipment. For sample making or low volume requirements, the manual foot ratchet machine will normally suffice.

Most suppliers of press fasteners offer a machine rental scheme, particularly when automatic equipment is required. All machines, whether manual or automatic, will require a corresponding set of dies used to hold and attach the press stud components.



Figure 8.69 Rivet and stud attaching machine.

Figure 8.70 shows a set of dies used to attach a particular configuration of press fastening components. Such dies are not universal and should be specified and supplied by the relevant press fastener company, which should recommend the most appropriate press fastener as well as the correct application including the correct pinch setting, which will be dealt with further.

#### 8.10.1 Non-snap components

There are several other components that are not press fasteners but require the same safety procedures and machinery when being attached. These include buttons on denim garments, as shown in Figure 8.71, also called tack buttons, and eyelets. Both are made from metal, usually brass that has been electroplated, to offer a variety of finishes or a metal–plastic combination. Buttons for denim products are composed of two components: namely, the button, which can have a fixed or swivel top; and the prong, which allows the button to be fixed to the garment.

Eyelets are also composed of two components: namely, the eyelet and the washer, as shown in Figure 8.72. Careful testing and control of application using a safety data sheet are highly recommended for these components.

In terms of rivets, many different designs and finishes are available but they are likewise composed of two components, as shown in Figure 8.73: namely, the rivet,



Figure 8.70 Die set for attaching press studs.



Figure 8.71 Stud button components.

which is the part that can be seen when attached; and the tack, which is similar to the prong used to attach a jeans button.

## 8.10.2 Safety of press fasteners

The correct selection and application of press fasteners are of paramount importance not only to ensure a high quality product but also to ensure the safety of the end user. This is of particular relevance when proposing to use a press fastener on children's

| Eyelet | Washer |
|--------|--------|
| 0      | 0      |

Figure 8.72 Eyelet components.



Figure 8.73 Rivet components.

or baby wear, but the same standards should be applied across the whole spectrum of product sectors.

The supplier of the press fastener components should recommend the most appropriate press fastener for the specified item of apparel. They are also responsible for specifying dies, appropriate machinery and the pinch setting, which is composed of two measurements as follows:

- The basic pinch setting refers to the measurement between the two surfaces of the components when attached to each other with no fabric.
- The fabric to which the components are to be attached should be measured by a torque micrometre; this will measure the thickness to which the fabric will be compressed by an attaching machine.
- The combined effect of these two measurements will give the machine pinch setting to which the attaching machine should be adjusted for all applications of these relevant components on the appropriate fabric (ASBCI, 2011).

The pinch setting and the press fastener components should be formally documented by the component supplier in the form of a press fastener product data safety chart, and these data should be carefully followed by the manufacturer. This includes setting up a quality control procedure in which the machine settings and pinch settings are checked and recorded periodically throughout the workday. Regular daily visual inspection also forms an important part of ensuring high levels of safety and quality. Below are recommended general procedures to ensure the quality and performance of attached fastenings:

- In relation to press fastener components containing metal, where prolonged contact with the skin is anticipated there must be compliance with the statutory nickel safety requirement within EC Regulation No. 1907/2006.
- Fasteners should not be applied to a single ply of fabric; when required, a secondary fabric or interlining patch to stabilise the base material should be incorporated.
- Post fasteners should not be used for knitwear; when applied, they punch a hole in the fabric and can easily result in laddering. Prong fasteners are more appropriate for most knitted materials.
- Garments designed to undergo wet processing such as enzyme or chemical finishing should have press fasteners applied afterwards to prevent detrimental effects on the fastening.
- There should be no gaps or movement between the fabric and component. For example, if a fingernail can be placed under the attached component, the pinch setting is too loose. Always refer back to the manufacturer's pinch setting.
- The component should not be applied too tightly because this can cause the fabric to be cut or damaged. Evidence of a tight application will cause the outer perimeter of the fabric to pucker. Likewise, there should be no distortion of the component. Always refer back to the manufacturer's approved pinch setting.
- Fasteners should only be applied to a flat base and should not be applied over seams or uneven surfaces because loose components can be extremely sharp and therefore dangerous to the wearer.
- Where prong type fastenings are applied, there should be no visible prongs sticking out around the prong ring; always ensure the correct die has been used and refer back to the press fastener data sheet for the correct dies and settings.
- When possible, for the purpose of metal detection in children's wear, press fasteners from high quality brass should be selected, as opposed to those containing ferrous metals. Metal detectors should be calibrated at least every 4h and records should be archived for at least 1 year.

In addition to these general concerns, it is necessary to comply with the following statutory requirements and standards.

#### 8.10.2.1 Statutory requirements

- EC Regulation No. 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals.
- Statutory Instruments 2005 No. 1803 Consumer Protection General Product Safety Regulations 2005.

## 8.10.2.2 British standards

- British Standards BS EN 71-3:1995 Safety of Toys Part 3: Migration of certain elements.
- British Standards BS 7907:2007 Code of Practice for the design and manufacture of children's clothing to promote mechanical safety.

- British Standards BS EN 12472:2005 + A1:2009 Method for the simulation of wear and corrosion for the detection of nickel release from coated items.
- British Standards BS EN 1811:1998 + A1:2008 Reference test method for release of nickel from products intended to come into direct and prolonged contact with the skin.

#### 8.11 Future trends

Future trends in the joining of denim will be dictated by developments in the material itself, environmental drivers and, of course, economic factors. More extensible denim materials are being developed, emulating the characteristics of knitted fabrics rather than woven materials. These materials may be impossible to match in performance with traditional sewn seams and could pave the way for increased use of bonded non-sewn technology to provide a softer feel and more extensible seam – but durability is still an issue to be met. The recent development of soluble sewing threads that can be easily 'removed' from a garment, allowing for easier re-manufacture of the material into a second life product, will undoubtedly have some impact on sewing operations for the product's first and second incarnations.

Because of their consistency in design and the relatively stiff nature of the denim material, standard denim garments lend themselves perfectly to semi-automatic operations. Combined with a drive for onshore (or near onshore) production, this could lead to further developments in this manufacturing technology as a way to minimise direct labour costs in the manufacture of denim garments. As the open design wave propagates, it is possible that individuals could build their own denim garments and jeans, perhaps even at home. Because the very nature of the material and the construction techniques are lending themselves to personalisation, they would lead to further developments in joining techniques and technologies.

## 8.12 Conclusion

The growth of denim products has been phenomenal, from work wear to business attire, and its gradual rise does not seem to have reached a peak. It has become more popular over the decades and has far reaching influence in a global market as designers have created new and innovative merchandise for the apparel consumer. Manufacture of the material into garments requires machines that are able to cope with the density of the fabric and the thickness of the seams. Therefore, heavy duty machines need to be used and specialist components have been developed, such as tractor presser feet and feeders to feed the material effectively through the machine.

Other components such as heavy duty needles, sewing threads that have high strength for securing the seams and buttons and studs for securing the pockets have been specially developed for this fabric. The production of this material into garments has other challenges associated with it, as well. There is greater stress on operators when stitching the material owing to its heavy weight and dense construction. This can create greater operator fatigue; therefore, sophisticated equipment to automate certain processes has been developed to reduce some of this fatigue while increasing productivity. The future of denim seems secure and its popularity is growing throughout the world. This seems likely to continue for the foreseeable future.

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## Dyeing technologies for denim garments

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## 9.1 Introduction

Garment dyeing refers to the process of adding colour to garments that may be either in the form of cut and sewn or fully fashioned woven and knitted (Bone et al., 1988). The process was first adopted by the textile and apparel industry in the early eighties and tremendous strides have been made since that time (Fulmer, 1995). Garment dyeing was advocated because of its advantages over other stages at which colour can be added to textiles, such as fibre, yarn and fabric.

The principal advantage of garment dyeing is the flexibility to respond to quick and ever changing colour demands of retailers and the fashion world (Bone et al., 1988; Turner, 1987). Integral to this rapid response is efficient inventory management and the use of instrumental colour control and information technology enabled services. Lead times in garment dyeing are 2-5 days compared with 2-3 weeks with other methods of dyeing (Bone et al., 1988; Cotton Incorporated, 2001; Houser, 1991). Garment dyeing can also incorporate nick of time fabric styling and surface design changes. As well, the popularity of leisure wear, casual wear, exercise apparel and other segments of the market that are acutely sensitive to colour and fashion has contributed to the allure of garment dyeing (Gore, 1995). The aesthetics of garment dyed denim clothing is also a significant charm and contributes to the popularity of the garment dyeing process. Other advantages include minimal variation in colour between multiple parts of the same garment and the ability to dye small batches of a particular garment line in different colour ways (Scotney, 1988). In addition, if some colours are rejected by the consumer they can be dropped from the line and the quantity of better selling colours can be quickly increased to meet the demand (Gore, 1995; Turner, 1987).

Moreover, the rapid turnaround and short lead times facilitate better planning and production control, leading to fewer discounts, markdowns and nominal wasted inventory at the end of a season (Bone et al., 1988). Garment dyeing is also sustainable because only the fabric used to construct the garment is dyed and therefore there is no wastage of fabric or dyes. Indeed, the ability of the garment dyeing process to seamlessly integrate with modern supply chain systems and thereby keep abreast with the latest fashion trends is without doubt its major benefit over other dyeing processes.

Without detracting from these numerous advantages of garment dyeing, there are, however, a few disadvantages and dyeing concerns. Fabric or piece dyeing is less expensive than garment dyeing although the difference in costs depends

on the batch size and productivity of the garment dyeing operation (Bone et al., 1988). It is also critical that garments be well prepared for the garment dyeing process, more so than for piece dyeing, because once a garment has been dyed it is extremely difficult to correct (Houser, 1991). In particular, desizing, bleaching and other preparatory treatments need to be accomplished at the highest quality standards to minimise shade uniformity problems resulting from differences in dye uptake (Houser, 1991). Garment assembly must also be consistent with attention to fabricating the garment not only from the same source but preferably from the same prepared fabric roll (Turner, 1987). During cutting and making-up, allowances in size need to be accounted for to compensate for puckering and shrinkage during dyeing (Bone et al., 1988; Cotton Inc., 2001). Finally, denim intended for garment dyeing should include designers from the conception stage because sewing threads, buttons, studs, zippers, other accessories and trim materials have to be taken into consideration for successful garment dyeing (Bone et al., 1988).

## 9.2 Garment dyeing processes

Denim jeans as well as any other type of woven or knitted denim garments are well suited for garment dyeing. Figure 9.1 depicts a typical flow path for denim garment dyeing and finishing (Bone et al., 1988; Swicegood et al., 1994). Moreover, particularly in the case of denim, in addition to regular garment dyeing, wet processing via washing, desizing and decolourisation resulting in stonewashing, snow washing and overdyeing or highlighting effects may be considered a separate category of garment dyeing.

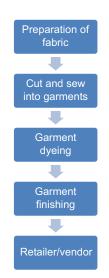


Figure 9.1 Typical garment dyeing and finishing flow path.

#### 9.2.1 Preparation for garment dyeing

The first procedure in garment wet processing is to prepare the fabric to be used for garment dyeing. Approximately 95% of garments to be dyed are cut from previously prepared fabric (Turner, 1987). Good preparation results in fabric with a white back-ground and good absorbency that allows for uniform dyeing and excellent reproducibility. In addition, fabric preparation relaxes the fabric, enabling consistent sizing of manufactured garments (Cotton Incorporated, 2001). Knowledge of fabric history is important to aid in judicious selection of pretreatment methods for the best preparation for dyeing. Such history may include information about the quality of the cotton fibre and the nature of impurities on the fabric, specifically fats, oils and waxes and the chemical nature of the sizing agents used. For woven fabric to be used in garment dyeing, preparatory steps include singeing, desizing, scouring and bleaching. For knit fabrics, the desizing step is omitted (Turner, 1987).

Desizing can be done by either using a biological amylase enzyme or oxidative desizing by using hydrogen peroxide, persulphate or bromite. If a polyrenthane fibre has been added to the denim fabric for stretch and fit purposes, bleaching with hydrogen peroxide is better to maintain the strength of the polyurethane fibre. Alkali scouring is the next step and is accomplished using sodium hydroxide or other alkalis such as sodium carbonate. Scouring removes hydrophobic materials such as fats, oils and waxes. Bleaching with the help of hydrogen peroxide or sodium hypochlorite removes the intrinsic colour of cotton, making the fabric whiter in appearance. During the preparation process water soluble lubricants, anti-curls and softeners may be applied to assist in the garment manufacturing process (Gore, 1995; Jenkins et al., 1994; Swicegood et al., 1994). At the conclusion of preparation treatments, tests are done for absorbency, whiteness, percent extractables, pH, percent alkali/acid and fluidity to judge the effectiveness of the treatments. The fabric is then delivered to garment manufacturers for cutting and sewing operations. For the small percentage of garments made with greige fabric, a complete desizing, scouring and bleach procedure is done before dyeing (Bone et al., 1988; Gore, 1995; Jenkins et al., 1994).

#### 9.2.2 Selection of colourants for garment dyeing

Before dyeing a thorough check for absorbency of the garment, whiteness index, residual chemicals such as hydrogen peroxide and sizing agents and the pH of the garment needs to be conducted (Dixon et al., 1994; Tyagi, 2008). Moreover, garment dyers have to be aware of the sewing thread and metal components used in the manufacture of the garments to avoid any dyeing problems. Cotton denim garments intended for garment dyeing should preferably be fabricated using unmercerised cotton thread to produce a uniformly dyed unnoticeable seam. Use of mercerised cotton thread where the seam appears darker after dyeing or the use of polyester thread that will not be receptive to cellulosic dyes can be used for design effects. With regard to metal components, ferrous materials are corroded by electrolytes used in dyeing and brass components may be sensitive to copper sensitive dyes. Nickel plated brass is reported to be the most satisfactory option for the best outcome in garment dyeing. Use of a sequestering agent such as ethylenediamine tetra acetic acid minimises shade alteration resulting from to chromophore sensitivity (Chakraborty et al., 2005). Addition of a corrosion inhibitor such as alkylsulphoamido carboxylic acid for ferrous metal or tolyltriazole for copper also helps alleviate staining resulting from metals used in denim garments (Gore, 1995). As for zippers, pre-dyed polyester zippers provide the best shrinkage control. If garment labels have been sewn or printed before the dyeing process, care should be taken to ensure their legibility after dyeing (Bone et al., 1988; Jenkins et al., 1994; Turner, 1987).

Cotton denim garments can be dyed using various classes of cellulosic dyes such as direct, reactive, vat and sulphur. Pigments are also used for denim colouration. Each class has its advantages and disadvantages. Selection of a particular class of dye depends on fastness requirements, cost analysis, range of shades required and performance requirements of the denim garments (Houser, 1991).

As a class of dye, direct dyes are the easiest to apply, cover a wide range of shades and are inexpensive but suffer from poor wet fastness in heavy shades (Aspland, 1997; Bone et al., 1988; Perkins, 1996). When a combination of direct dyes is selected it should generally have a narrow range of maximum exhaustion temperature to ensure uniformity and reproducibility (Bone et al., 1988). As a rule, direct dyes with similar migrating power should be selected for maximum levelness and repeatability (Dixon et al., 1994). Analogous to piece dyeing, electrolyte is usually added in installments. To improve seam penetration, an anionic wetting agent may be added. After dyeing, the dye liquor is cooled before draining to reduce creasing problems owing to abrupt cooling. A cationic aftertreatment to improve wet fastness and prevent migration of dye within the garment can be applied (Bone et al., 1988).

Reactive dyes offer a complete range of shades and possess good colour fastness properties, particularly high wet fastness, because they form a covalent dyefibre linkage with cotton fibres under alkaline conditions. Application of reactive dyes, however, requires large quantities of salt (Aspland, 1997; Bone et al., 1988; Perkins, 1996). Of the many reactive dye chemistries, hot dyeing monochlorotriazine reactive dyes are most suited for garment dyeing. Good seam penetration is possible with the monochlorotriazine reactive dyes because of their high migration and diffusion properties and low reactivity. They are also suited for automated processes in garment dyeing (Bone et al., 1988). A typical reactive dyeing process involves addition of sodium sulphate in installments followed by addition of alkali in equal increments. The temperature is then gradually raised by 2-3 °C/min to the required dyeing temperature. After soaping with nonionic detergent, an aftertreatment with a cationic, hydrolysed dye complexing agent is recommended for higher fastness (Gore, 1995). Prior treatment with cationics can be done to obtain special surface effects that can subsequently be enzyme washed for a worn out appearance (Tyndall, 1996).

Vat dyes have limited colour range and moderately higher cost but possess excellent colour fastness. The dyeing method involves dispersing the vat dye as an insoluble pigment under alkaline conditions at a temperature of 60–80 °C. In this form the dye has little or no affinity for the denim fabric. The dye is then reduced to leuco form by using a chemical such as sodium hydrosulphite and penetration into the garment is achieved. The reduced dye is finally oxidised back to its insoluble form. A final hot soaping treatment removes any unfixed dye (Dixon et al., 1994). To enhance the hand of the garment, a cationic softener may be applied (Bone et al., 1988). A process for continuous garment dyeing with indigo has been described in United States Patent 4756037 (McFadyen et al., 1988). The process describes a method for moving garments and immersing each garment at room temperature in an aqueous dyeing solution consisting of indigo dye, sodium hydroxide and sodium hydrosulphite for 1–5 min until each garment is uniformly impregnated with the aqueous dyeing solution. The garments are then transferred to a second bath in which each garment is immersed in an aqueous solution containing hydrogen peroxide and sodium carbonate for 2–10 min until all the indigo dye in the garment is uniformly oxidised. In the next step, the oxidised garments are washed followed by drying (McFadyen et al., 1988). However, the vat dyeing procedure is more demanding and requires technical expertise and at the same time is also less forgiving of dyeing errors than other classes of dye (Dixon et al., 1994).

Sulphur dyes are low cost and are a good choice for earth shades, blacks and navies and are an economic option especially when denim garments are later intended to be acid washed (Houser, 1991). Successful garment dyeing results are achieved by cationic pretreatment followed by dyeing with sulphur dyes (Gore, 1995).

Pigment garment colouration is attractive because it offers good light and chlorine fastness at moderate cost and can be washed down for colour and style effects such as a distressed look. In addition, the application times are shorter with lower energy and water usage (Cotton Incorporated, 2000; Dixon et al., 1994). According to Tyndall (1996), depending on preference and performance requirements, two methods of using pigments are prevalent. The first is a two step procedure in which cationic pretreatment and the binder are applied first and then the garment is pigment coloured. The second method is a three step procedure in which the first step is cationic pretreatment followed by pigment colouration and the third step is treatment with acrylic binder.

Because pigments have no affinity for cotton denim, for both methods of colouration with pigments the crucial step is uniform cationic pretreatment because it ensures affinity and adequate uptake of pigment (Chakraborty et al., 2005). Good results are obtained when pretreatment is performed at a pH of 8–8.5. Similarly, better pigment colouration is obtained when the process is started in an alkaline medium and exhausted in acid media (Gore, 1995). Because pigment garment colouration is a blend of art and science, it is expected that no two garments will look alike, and this is indeed one of the unique selling points of pigment coloured denim garments. Drawbacks with pigments can include inferior wet crocking fastness, and therefore, their use for dark shades is debatable. Increasing the amount of binder, neutral pH of bath, longer fixation times and higher curing temperatures are suggested measures to improve crockfastness (Gore, 1995). Garments that are pigment coloured are good articles for treating with cellulase enzymes for a weathered look (Tyndall, 1996).

A distinctive way of using pigments is for creating novel differential colour effects. For example, denim can be dyed with any of the cellulosic dyes – direct, reactive, vat, sulphur and subsequently acid washed with sodium hypochlorite/potassium permanganate. After further treatment with sodium bisulphite and rinsing, the garment can be

re-coloured with a contrasting pigment colour. A different way of obtaining a two colour effect is by spraying resist paste or a semi viscous solution over the dry garment. After drying, the treated garment can be coloured with pigment. The portions of the denim with the resist paste will be lighter in colour (Gore, 1995; Harper and Lambert, 1992; Tyndall, 1996).

#### 9.2.3 After treatments for garment dyed fabrics

After dyeing, a number of treatments may be done to improve garment handle, drape and texture. A common treatment is application of a softener. Cationic and amino functional silicones and their combinations are often used. Softeners may cause yellowing during drying, so care must be taken to minimise shade changes (Cotton Incorporated, 2001). Other aftertreatments may include application of water repellant and fluorocarbon finishes imparting water resistance (Tyndall, 1996). Garment dyed fabrics can also be made wrinkle resistant via application of a resin such as dimethylol dihydroxy ethylene urea (DMDHEU).

Immediately after garment dyeing, a resin finish can be applied to the wet garments by immersing the garments in a resin formulation to create easy care garments. The final steps, in order, are: centrifugal hydro extraction followed by tumble drying or radiofrequency drying, pressing and curing (Bone et al., 1988; Tyndall, 1996). Acceptable crease durability, Durable Press rating, seam smoothness and residual shrinkage were obtained by following this method (AATCC Northern Piedmont Section, 1987). Application of resin before cut–sew and dyeing operations is also possible although problems can occur, such as panel-to-panel shade variation resulting from uneven finish application, shade differences owing to variation in the degree of curing and differential dye uptake between treated fabric and untreated sewing thread and trim (AATCC Northern Piedmont Section, 1987).

## 9.3 Garment dyeing machinery

Garment dyeing machines are categorised as either paddle dyeing or rotary dyeing (Parr, 1988). In a paddle dyeing machine a stationary box with a rotating paddle circulates garments within the machine. Paddle dyeing machines can either be top-paddle or side-paddle. In a top-paddle machine the garments and dye liquor are contained in a curved beck like lower section. The garments are moved by a rotating paddle that extends across the width of the machine (Saravanan and Ramachandran, 2009). In a side-paddle machine the rotating paddle moves in a lateral direction. An illustration (by Oliver Frias, Madeline Kirshoff and Sherrie Uy) of a paddle dyeing machine is depicted in Figure 9.2. An advantage of paddle dyeing is the gentle dyeing action resulting in minimal damage to garments. However, the low degree of agitation can be problematic for level dyeing of multilayered seams (Bone et al., 1988). Other drawbacks include the amount of liquor required for efficient circulation and uniform dyeing, especially in the case of top-paddle machines (Stewart, 1994).

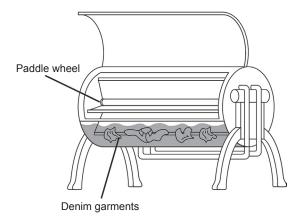


Figure 9.2 Paddle dyeing machine.

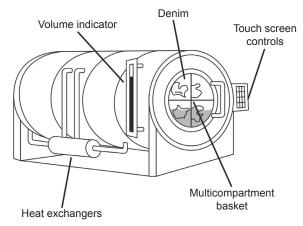


Figure 9.3 Rotary dyeing machine.

The liquor ratios in paddle dyeing machines range from 25:1 to 40:1 (Bone et al., 1988). In a rotary dyeing machine a large perforated cylinder containing the garments rotates in the dye liquor contained in a stainless steel outer closed cylinder (Chakraborty et al., 2005; Dixon et al., 1994). A pictorial representation (by Oliver Frias, Madeline Kirshoff and Sherrie Uy) of a rotary dyeing machine is shown in Figure 9.3. Most technological advances with regard to garment dyeing machinery have been with rotary dyeing equipment. Some significant enhancements that are now standard features incorporated by most rotary garment dyeing machine manufacturers are (Bone et al., 1988; Collishaw et al., 1988; Martin, 1992; Nair and Pandian, 2012; Stewart, 1994):

- Fully integrated touch screen computer operating systems with Windows<sup>®</sup> software and, when needed, remote online troubleshooting.
- · Automatic dispensing of dyes and other chemical auxiliaries.
- · Low liquor ratios compared with paddle dyeing machines.

- Flexible basket configuration to provide one or more dyeing compartments the D-pocket, which consists of two compartments, the Y-pocket, which consists of three compartments and still others with four compartments. Compartments have the additional advantage of reducing tumbling effects and hence minimise damage to garments.
- · Sophisticated heating and cooling using heat exchangers.
- · Variable speed controls for agitation control and reversal capability.
- · Water volume controls with overflow rinsing capabilities.
- Auto-balancing drums.
- Dyeing up to a temperature of 135 °C, which is useful when dyeing denim blends.
- Easy loading and unloading via tilting mechanisms or automatic robotised loaders, obviating the need for manual handling and thereby saving time.
- External circulation of dye liquor that aids in good penetration of dye into seams.
- · Lint filters to remove loose fibres to prevent re-deposition onto the garments.
- Centrifugal hydro extraction to ensure minimal moisture content before drying.
- · Dye liquor recovery and sampling ports for examination of garments.

A leading manufacturer of innovative garment dyeing machines is Tonello s.r.l., Italy. The range of machines offered by Tonello includes sampling to high volume production machines. A notable technology enhancement is a jet system that reduces the liquor ratio to 1:2, which is a vast improvement from a liquor ratio of 1:10 in traditional garment dyeing machines. In addition, some machines are designed specifically for pigment colouration (Tonello, 2014). Maino s.r.l., Italy has also patented its own system for the reduced liquor ratio and lower dyeing times. In this system, continuous circulation of the bath is achieved through the centre of the rotary drum via a turbine nebuliser. The function of the nebuliser is to distribute the liquor uniformly inside the machine while allowing the introduction of dyeing auxiliaries without the need to unload the machine (Maino, 2014).

Other notable manufacturers that have designed machines with ecological considerations include Flainox, Italy; Cosmotex, Spain; Danis, Turkey; and Hisaka, Japan. Flainox offers rotary machines with capabilities of using low water levels and indirect cooling water reuse. Cosmotex dyeing machines reduces the liquor ratio to 1:3, leading to a reduction in water and chemicals. Danis garment dyeing machines have special steam collectors to reduce heating time and save energy costs.

## 9.4 Advances in garment dyeing

In the past decade, the textile industry has enthusiastically joined the march toward sustainable manufacturing practices. Within the wet processing segment of the industry, research and development efforts have been directed toward reducing the use of traditional chemicals with environmentally benign alternatives. Research toward reducing energy costs in wet processing has also been the focus of many studies. It is hoped that fruits of these endeavours will eventually find widespread application in dyeing technologies in the near future including garment dyeing of cotton denim.

In an aqueous medium, cotton fibres have anionic sites owing to the oxygen of the hydroxyl groups along the anhydroglucosidic chain. Because of the slightly negative

charges, anionic dyes such as direct dyes and reactive dyes have scant attraction for cotton fibres. Therefore, in the dyeing process copious amounts of electrolyte are needed to overcome the repulsion between fibre and dye and exhaust these dyes onto the cotton fibres. Reduction of electrolyte for dyeing cotton has been a Holy Grail and the subject of intense research for over 40 years. Chemically modifying cotton to provide cationic sites thereby enhancing dyeability and reducing use of electrolyte is one method to achieve this goal. Earlier chemical modifications used quaternary nitrogen containing compounds that were chemically linked to the fibre via an ether linkage. An example of such a compound is glycidyl trimethyl ammonium chloride (Stone and Harper, 1986).

Other approaches include grafting of cationic groups to cotton using epichloro reactive products as well as mono and bis-quaternary halogen heterocyclic compounds. However, a drawback of these compounds was unacceptable light fastness of the treated and dyed cottons (Stone and Harper, 1986). A multifunctional approach was to use choline quaternary as a reactive additive. Choline chloride was bound to cotton via a cross-linking agent such as DMDHEU or trimethylol acetylenediuriene. The advantage of this approach was that treatment imparted durable press properties while conferring enhanced dyeability on the cross-linked cotton. In theory, this treatment was a potential process for dyeing cotton garments with easy care performance properties (Stone and Harper, 1986). However, problems were reported when more than one dye was used in the dye recipe formulation. Untreated parts of the garment such as sewing thread and trims dyed a different shade than the treated body of the garment owing to selective dye uptake (AATCC Northern Piedmont Section, 1987).

More recent efforts to provide cotton with cationic dye sites have been reported in the literature. A widely studied cationic reagent is 3-chloro-2-hydroxypropyltrimethyl ammonium chloride (CHPTAC). By itself, CHPTAC does not react with cellulose. It has to be converted into 2-3-epoxypropyltrimethyl ammonium chloride (EPTAC) by reacting with alkali. EPTAC reacts with the hydroxyl groups on cotton fibre under alkaline conditions to form cationised cotton. In studies by Tabba and Hauser (2000, 2001, 2002), cotton was treated with EPTAC using the cold pad batch method. After the cationisation reaction, fibre reactive dyes were used to dye the treated cotton. The colour yield on treated cotton was significantly higher than untreated cotton because of the electrostatic attraction between the anionic charges on the reactive dye molecules and the cationic cotton.

Although all reactive dye chemistries increased colour yield, individual dyes demonstrated widely varying colour yields. Depending on interaction between dyes, caution will therefore be needed when working on and correcting dye formulations. In addition to increased dye yield, the cotton could be dyed without the need for electrolytes. Colour fastness results with regard to washing, crocking and light were also not adversely affected by the cationic treatment. Ultra deep shades on cotton were also possible using the cationisation method combined with mercerisation (Fu et al., 2013). In other studies with direct dyes, cationised cotton showed considerably reduced dyeing time and complete exhaustion without salt compared with untreated cotton, thus further enhancing the environmental and potential economic benefits (Draper et al., 2002; Sharif et al., 2008).

Translating laboratory results into successful economical industrial use is fraught with pitfalls and cationic dyeing of cotton is not an exception. In addition, questions have been raised about the biodegradation properties of the cationic compounds themselves as well as the robustness of the treatment to repeated washings because of the reaction of these compounds to form salt with anionic surfactants and hence release of the immobilised dye molecules (Schindler and Hauser, 2004). Cost-benefit analysis and results of industrial scale application of cationised cotton dyeing are also sorely missing in the published literature. Some answers in response to these questions were included in a study that addressed the safety and cost of large scale cationisation (Farrell and Hauser, 2013). The report emphasised that both CHPTAC and EPTAC should be handled with care and proper use of personal protective equipment. Large scale cationisation of cotton sample lots was also shown to be possible. Cold pad batch cationisation and subsequent dyeing resulted in cost savings. However, exhaust cationisation and subsequent dyeing increased the overall processing costs but used less water compared with a traditional fibre reactive process (Farrell and Hauser, 2013). There are also some reports (Mowbray, 2012) regarding a company that uses cationic technology along with other proprietary fibre treatments to dye cotton fabrics without using salt or alkali.

Other technologies for sustainable denim dyeing have received attention in recent years. Burlington Solutions and Cone Denim introduced a new Affinity Garment Dyed Colour Denim. This patented yarn pretreatment allows a denim ring dye effect to be achieved on warp yarns when garment dyed with Garmon's HI White dyes. The specially formulated dyes have an affinity for the treated warp yarns and will dye only the warp yarns, leaving the untreated filling yarns undyed, in consequence essentially mimicking a yarn dyed denim. The process does not need salts or other auxiliaries in the dye bath and requires 50–60% of the heat energy compared with conventional garment dyeing, therefore minimising adverse impact on the environment (Burlington Solutions, 2014; Holme, 2012).

Another exciting process for sustainable denim was presented at the American Chemical Society's 16th Annual Green Chemistry and Engineering Conference (Sanchez, 2012). The process, called Advanced Denim, by Archroma Textile Specialties, Singapore, claims to use 92% less water and up to 30% less energy than conventional warp dyeing. It also completely eliminates the use of indigo. Instead, a new generation of liquid sulphur dyes is used. The process requires only a single sugar based reducing agent and a single dyeing box compared with a conventional 12-box dyeing process. In addition, a combined oxidation and sizing process further shortens the production process and reduces waste. The process is compliant with the EU Ecolabel, the Oeko-Tex® Standard 100, the Global Organic Textile Standard and the Bluesign® standard (Archroma, 2014). In partnership with Tonello s.r.l., Italy, this innovative sulphur dyeing process has been extrapolated to dyeing denim garments under a nitrogen atmosphere using an extremely low liquor ratio (Figure 9.4: courtesy of Tonello s.r.l., Italy; reprinted with permission). Garment dyeing of denim with the nitrogen dyeing machine uses a sulphide free reducing system and peroxide based eco-friendly oxidation (Tonello, 2014).

Novel dye chemistry is another route to sustainability. A new tri-reactive dye range for cellulosic fibres claims to reduce water and energy consumption significantly by ensuring rapid and high exhaustion and fixation at lower temperatures with a concomitant reduction in the number of rinsing baths (Huntsman International, 2013). Other

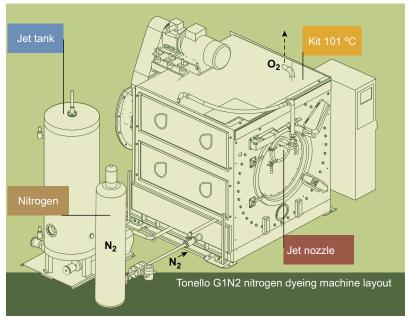


Figure 9.4 Garment dyeing under nitrogen atmosphere. Tonello s.r.l.

suggested routes include dyeing denim with natural dyes using eco-friendly mordants such as tannic acid and tartaric acid instead of metallic mordants. Denim dyed with onion extract, turmeric (*Curcuma tinctoria*) and Indian madder (*Rubia cadifolia*) exhibited comparable wash, light and crocking colour fastness properties with denim dyed using metallic mordants such as copper sulphate and stannous chloride (Deo and Paul, 2000, 2003).

## 9.5 Testing and quality assurance

For excellent quality outcomes in garment dyeing, a holistic approach from the fibre to the dyed and finished garment is critically important. However, this is not an easy task to accomplish because in most cases garment dyeing occurs at a facility physically and geographically far from the garments' origins as a raw fibre through yarn and griege fabric formation followed by fabric preparation and ultimately garment fabrication. Nevertheless, the value of instituting a quality assurance protocol in the processing chain cannot be overstated (Houser, 1991; Pensa, 1994). The quality of a garment is first and foremost determined by the quality of the raw fibre and yarn spinning procedures. For example, natural impurities in cotton fibre vary by growing location (Saravanan and Ramachandran, 2009).

Variations in yarn size and twist can lead to problems with garment size and appearance (Houser, 1991). Second, quality garments are virtually impossible without

superior fabric construction and attention to detail such as strict control of fabric count (Houser, 1991). Third, as discussed previously, proper and complete preparation of fabric before cut and sew operations is important to ensure shade uniformity. Fourth, garment fabrication should be from the same prepared roll and garment design should factor for expected shrinkage and puckering owing to improper tension or poor dimensional stability of sewing threads (Saravanan and Ramachandran, 2009). Fifth, before production dyeing all required attributes of the garment such as shade, aesthetic characteristics of hand, functional characteristics of durable press, water repellency and other desired functionalities must be reproduced and verified in a laboratory. Potential problems such as seam slippage, needle holes, incorrect sewing threads and shrinkage can be identified and solutions identified at this stage. Written standard operating procedures for dyes and chemicals analysis and dyeing procedures should be specified.

Dyeing procedures should include optimum liquor ratios, rate of heating, temperature and concentrations of electrolyte and other auxiliaries. A sample production run should be next to determine lab-to-bulk reproducibility. Thereafter, every dyed batch should be assessed against standards: visual and instrumental colour standards, aesthetic standards and performance standards to meet the specifications of the intended end use. It is imperative that colourfastness tests relative to crocking, light and washing be performed using standard procedures detailed in American Association of Textile Chemists and Colourists (AATCC), American Society for Testing and Materials or International Organisation for Standardisation test methods. For garment dyed denim fabrics, AATCC Test Method 8: Colour fastness to crocking: crockmetre method and AATCC Test Method 116: Colourfastness to crocking: rotary vertical crockmetre method are particularly relevant to evaluate colourfastness to crocking. In addition, dyed garments should be analysed for poorly dyed seams, inferior dyeing quality around zippers, buttons and other metallic embellishments and creases and streak marks resulting in uneven dyeing. Finally, quality assessment should continue as the finished garments enter the retail stream and are critically evaluated by the definitive quality control adjudicator – the consumer (Pensa, 1994).

#### 9.6 Future trends

Future trends in dyeing technology include water free dyeing systems such as DyeCoo<sup>®</sup> technology, which uses supercritical carbon dioxide (DyeCoo Textile Systems, 2014), and AirDye<sup>®</sup> technology (AirDye Solutions, 2014), which uses air to transport dye. However, currently DyeCoo<sup>®</sup> and AirDye<sup>®</sup> are limited to dyeing of synthetic fibres and are not applicable to cotton denim, although research is under way for application to cellulosic fibres. For denim dyeing, future trends will be application of results from additional research into environmentally friendlier reduction and oxidation systems when using vat and sulphur dyes. These systems might be as simple as using experimentally established optimal quantities of current reducing and oxidation agents to electrochemical and physical methods (Bozic and Kokol, 2008). Both indirect and direct electrochemical techniques have been reported in the literature. Indirect methods rely on reversible redox electron-carrier mediator systems that reduce the dye and are themselves oxidised. At the cathode the mediators are converted back to the reduced form and the process is repeated. Direct electrochemical reduction of indigo dye has been

achieved using graphite as the electrode material. Physical methods might employ ultrasonic energy to accelerate dye uptake and thereby reduce consumption of all chemicals in the dyeing process (Bozic and Kokol, 2008). The use of small amounts of a polymer such as polyvinylpyrrolidone to promote improved distribution of dye throughout the textile substrate during garment dyeing also needs to be explored with the purpose of reducing chemical consumption in garment dyeing (Etters and Tyndall, 1999).

Reducing effluent volumes by investigating the economic and environmental viability of reusing indigo dye baths for shade development instead of using fresh dye baths could be a future trend as well. A preliminary study found no significant differences in colour yield and hue between reused and fresh dye baths up to a certain level of reuse (Deo and Paul, 2004a). In addition, repeated use of an indigo vat of very high concentration provided a wide range of lighter shades on denim with considerable cost savings and offered the possibility of reusing the exhausted bath by replenishing (Deo and Paul, 2004b).

#### 9.7 Conclusion

Since its adoption as an important commercial method of dyeing denim approximately 30 years ago, garment dyeing has continuously evolved and adapted to changes in fashion, culture and technological advances. Looking toward the future, denim and in particular denim garment dyeing appear to be moving in the right direction toward implementing sustainable industrial practices. Moving forward, in the area of sustainable denim garment dyeing, more research is needed to realise viable and profitable denim production using optimum amount of chemicals, dyes, water and consumption of energy.

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# Digital printing techniques for denim jeans



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## 10.1 Introduction

Digital textile printing (DTP) has been constantly evolving since the early years of the past decade and is now reaching a level of maturity and dissemination that was not expected, even among those who enthusiastically proclaimed its specific advantages compared with the dominant analogue production processes of flatbed and rotary screen printing.

Digital textile printing is far beyond the proof of concept stage and has definitively brooked with the prototype market. This rapidly changing technology is currently being driven forward by several different factors such as supply chain requirements, the globalisation context and the buyer's demands. The urge for short production cycles, reduced time to reach the market, diminished inventory, cost and waste minimisation and better personalisation and customisation led printer manufacturers and related suppliers into developing new printers with enhanced capabilities, innovative inks with a broader range of fabric applications and software turnkey solutions for entire management of the process, from artistic creation to shop floor control. In addition, new players (fashion houses, fabric designers, cloth companies and hardware and software vendors) are entering this market and expanding it with their product proposals and personnel business vision.

Taking into account several sources of information, it is common knowledge that the total global production volume of printed textiles currently ranges from 25 to 30 billion metres per year with a 97% analogue and 3% digital printing distribution. Observing the growing rate of the latter technology, it is expected that in the medium term, DTP will have an up to 15% share of the globally printed textiles market.

The most important application fields in textile DTP so far, particularly inkjet printing, have been preprinting (proofing and sampling) and small run printing, also referred to as 'agile manufacturing model'. More recently, with technological advances in industrial printing machines, DTP began to reach production speed and reliabilities for robust bulk production with which some medium scale production prints are already being performed using this technology, with similar quality and a competitive price compared with the traditional analogue method of rotary screen printing. Digital textile printing is composed of a vast set of technologies that are used to transfer a digital image onto the surface of a textile substrate. This novel technological solution emerged in the late 1980s from the search for a faster and cheaper alternative to classical analogue printing methods. In fact, inkjet printing on textiles has become significant, slowly replacing traditional screen printing (Antunovic, 2009; Pai and Paul, 2005). Its advantages and versatility led the development of new and innovative fashion products, changing the way textile and fashion designers and artists interact with fabrics, stimulating their creativity within a digital frame (Campbell and Parsons, 2005; Ibrahim, 2012; Treadaway, 2007).

Digital printing technologies can be considered cleaner than other traditional processes of colouring textiles (Campbell, 2006; Tyler, 2005), mainly because the amount of colourant applied to the fabric can be controlled with less ink waste, water and energy (Polston, 2011). Regarding denim, the use of inkjet printing has grown much in the same way as for other fabrics, mainly for motif printing, following fashion trends such as floral, animal and cosmic patterns, reproducing handcrafted work, or even reproducing denim fabric structure in other types of substrate.

In the case of denim, colouration is a possible use for inkjet printing. The conventional dyeing process of denim with blue indigo is considered one of the highest polluters. Because natural indigo is not soluble in water, the molecules have to be solubilised before dyeing by means of sodium hydrosulphite. Even with this process, the dyeing has to be repeated several times because adherence is poor, and the yarn has to be oxidised in the air every time, a process that requires a great amount of energy and water. It is estimated that 11,000L of water is necessary to produce the raw material and the final denim garment (Earth Pledge, 2007; *apud* Shuma, 2011). With pad/ sizing-ox, a new method recently developed to reduce these figures, savings of 92% of water, 30% of energy and 87% of cotton waste can be achieved and no effluents are generated (Archroma, 2014; Pricop et al., 2013). Yet, even with the more ecological dyeing processes, the amount of natural resources consumed is higher than that required by inkjet printing technology for colouration.

Compared with other printing methods such as traditional rotary screen printing, inkjet printing offers a reduction of industrial waste in addition to other important advantages such as minimal set up costs and short down time for set up. These allow for quick production and multiple variations and permit print on demand; there are no colour limitations depending on the type of ink (Dawson, 2003; European Commission, 2004; Hoppe and Saboor, 2011; Pai and Paul, 2005). In addition to the large amount of ink waste, traditional printing requires costly and time consuming templates/screens, a great number of which are discarded after sampling, thus generating further industrial waste (Riisberg, 2007). The most acknowledged disadvantages of digital printing are the high cost of inks and slow printing times, but these questions are currently being addressed by manufacturers (Dawson, 2003).

Denim production ends with the final washing and finishing stations. The final washing can be done on the fabric or sometimes on the garment itself, overdyed or using other treatments. Although most products used nowadays are environment friendly, water consumption remains the main problem. In finishing, substitute methods for conventional abrasion with stones or cellulase enzymes are in use, such as ozone (Schrott, 2011) and laser processes. Aside from ecological issues, conventional abrasion is most responsible for loss of strength and degradation of the fabric with time (Byrne, 1995).

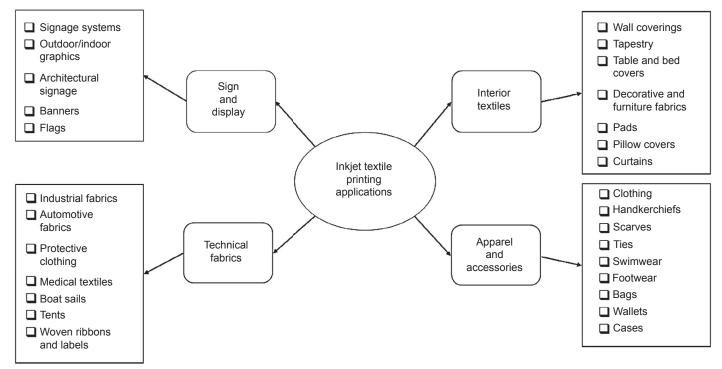
Jeanologia, Spain is a leader in the application of laser in denim finishing. This company conducted a case study regarding consumers' ecological awareness about denim garments, and realised that rather than water or energy waste issues, the use of no chemicals most concerns consumers and leads them to opt for a certain label. Hence, based on these results, they started a revolution by developing garment finishing with zero chemicals, using only laser technology. The main advantages of laser methods over chemical or mechanical abrasion are similar to those offered by inkjet printing in the simulation of traditional finishing effects and the reproduction of any type of images, colour fading and three dimensional effects: reduced water and energy waste (Ondogan et al., 2005; Ortiz-Morales et al., 2003; Ozguney, 2007).

The use of traditional finishing techniques with stones and chemicals as well as laser requires fabrics of higher quality to retain the main properties, because these processes usually involve degradation and abrasion of fabrics fibres (Khedher et al., 2011). The use of inkjet printing to achieve these effects does not require such high quality specifications and allows the use of less costly fabrics, which renders this process more cost effective in terms of raw material. Considering the characteristics of the processes described, it is evident that inkjet printing presents an ecological and cost effective alternative to denim's traditional colouration and finishing methods.

#### **10.2 Textile characteristics**

Digital printing has been widely used for printing different textile substrates that are employed for different end applications. A systematic classification of DTP can be made based on the product end use, as depicted in Figure 10.1. Textile characteristics are one of the biggest concerns if a quality print is to be achieved, because it strongly depends on various interactions between the type of ink and fabric. Printing ink diffusion is influenced by ink properties, fibre types, fabric construction characteristics and pretreatments applied before printing on the textile substrate (Kaimouz et al., 2010). Another concern to be taken into account is the colour gamut, which varies with different textile materials. Textile characteristics which should be taken in to consideration are yarn size, fabric structure and the hydrophilic/hydrophobic nature of the fabric (Ming Kai et al., 1998).

Fabric structure is the characteristic that most influences print quality because, unlike paper, fabric is a three dimensional substrate. Tse et al. (1998) found that plain weave fabrics followed by twill and sateen woven fabrics have the best performance, and knitted fabrics the lowest. Fabric composition influences the type of inks to be used, which will in turn influence the need for pre and post treatments. Most fabrics require chemical pretreatment before digital printing. This is the case of cotton and viscose fabrics printed with reactive dyes. If one makes a digital print using pigment inks, good results can be achieved on most substrates without pretreatment. Of course, in this case, because the inks are liquid, parameters such as fabric yarn densities are critical (Kaimouz et al., 2010).



**Figure 10.1** Application fields of DTP. Adapted from Paul and Iqbal (2012).

Digital textile printing requires also a post treatment. For example, for the ink types mentioned above, if one uses reactive dyes on pretreated cotton fabric, a steam process to fasten colours is needed, followed by washing to eliminate inks that are not fastened to the fabric. For printing with pigment inks, a dry heating process is required for colours to fasten to the printed fabrics. In these cases no laundering is usually required. Proper pretreatment promotes satisfactory appearance and colour related print quality, whereas proper post treatment allows colour fastness of prints.

In the development of digital denim on cotton fabrics, the traditional denim substrate, print is limited to the use of reactive dyes or pigments. With other fibrous compositions, pigments can be used, but reactive, acid and disperse dyes can also be considered. The use of pigments can be regarded as most advantageous because of the variety of substrates to which they can be applied, as well as the technological evolution, which exempts the process from pretreatment and allows better colour gamut. Also, post print is done through heat on a separate machine usually connected to the printer (Tyler, 2005).

## 10.3 Inkjet printing machines

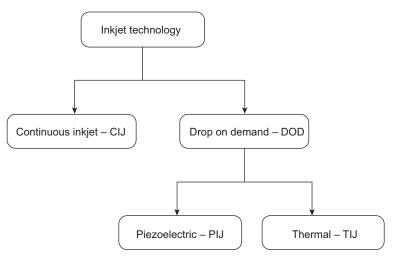
Printing on textile substrates demands in depth knowledge of all variables involved in the process and a specific printer for the job. In short, digital printing consists of a controlled and precise projection of tiny droplets onto the substrate while the print head is moving or, as in other proposals, the substrate is moving toward a fixed print head.

Bearing this principle in mind, machine manufacturers built different types of printers with a large variety of available options. However, in general, marketed inkjet printers used in the textile world can be classified into two major categories according to the technology used in their printing heads: drop-on-demand (DOD), sometimes referred to as bubble printing, and continuous inkjet printing, as shown in Figure 10.2.

The latter technology is the oldest and is based on a physical phenomenon named Plateau–Rayleigh instability, which seeks to explain the passage of a non viscous liquid with a circular cross section into droplets under the influence of some particular conditions. Accordingly, it is viable to interrupt a stream of ink intentionally and create a continuous stream of droplets, the direction of which, when electrically charged, can be controlled and precisely placed onto the textile substrate with the help of electromagnetic fields.

With this technology, printers can run extremely quickly and in a non contact mode, which offers the possibility of using other types of substrates and formats. However, the large majority of printer manufacturers prefer DOD technology. As is easily perceived by their designation, ink is mechanically expelled from the printer head only when needed and upon a digitally controlled request. Normally, these systems are distinguished according to the working principle used to produce the ink droplet: thermal (TIJ) or piezoelectric (PIJ) mechanism, which is undoubtedly the most common technology applied in textile printers (almost all models).

The former technology uses a computer signal to generate an impulse to activate the electrical heater inside each nozzle jet. The temperature is raised up to 300 °C in  $5 \,\mu$ s, causing local vaporisation and the formation of a water bubble. The high pressure



**Figure 10.2** Classification of inkjet printing technologies. Adapted from Freire (2006).

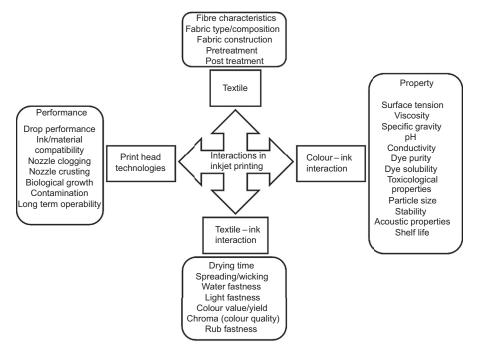
expansion causes the high speed ejection of an ink droplet from the nozzle onto the substrate. This process is also known as bubble printing.

Because of the TIJ characteristic working principle, inks or pigments are cyclically heated near to boiling temperature, which may cause inconsistent colour because of colourant or binder deposits on the print head resistor (Tincher, 2003). Taking into account that many fabrics need heat and moisture as a catalyst, this primary heating may bring about the loss of some binding power. For this reason, inks and pigments manufacturers had to create specific products that can successfully run through thermal printing heads and maintain their bonding and colour properties. This constraint imparts a reduction in the available colour gamut.

Owing to its explosive nature, control of the ejection mechanism is poor (only based on the pulse length and applied power), leading to splatters that reduce print quality (Campbell, 2006). High resolution can be obtained by using a small drop size but the throughput is reduced. Typically, thermal inkjet printers use water based inks and are tailored for low volume printing. The performance of their print heads decreases exponentially over time.

On the other hand, the PIJ technique is driven by the action of a piezoelectric transducer, typically made with lead zirconate titanate, which possesses the ability to change its form when submitted to a voltage, reducing the volume of the ink reservoir and propelling a droplet with sufficient size, speed and precision out of the nozzle jet onto the textile substrate (Freire, 2006).

In consequence of the purely mechanical mechanism of droplet formation, inks do not have to be modified to endure the temperatures that thermal heads require, widening the range of inks and pigments that can be used with this technology. Also, the architecture and materials used in the construction of the piezoelectric head (inert ceramic materials) contribute to enlarge the range of inks and pigments that can be used.



**Figure 10.3** Colour–textile–technology interactions in inkjet printing. Redrawn from Tyler (2011).

In addition, piezoelectric heads yield more control over drop formation than thermal heads. Electromagnetic pulses can be timed to adjust the amount of ink supplied and therefore the size of the ink droplet (Tyler, 2011). Drop volume is also manageable via the conjugate action of complex waveforms that control the pumping and merging of small droplets into a single drop after leaving the nozzle jet. They are able to produce the smallest droplet size in the world and are very well suited for high volume printing.

Because piezoelectric heads are permanently mounted in the printer, their replacement, when necessary, is a complex and harsh task. The performance of these heads rapidly decays with time. Another disadvantage is that piezoelectric printing heads are susceptible to air entrapment, which can lead to misfiring nozzles requiring multiple head cleanings (Baydo and Groscup, 2001). The major drawback of this technology is cost, because PIJ printers are priced higher than TIJ.

Along with printing head technology other factors affect the success of DTP in a complex and interlinked way. Decisions regarding one of them have a decisive influence on the others; consequently, some choices are excluded from the start owing to their negative impact on others. An overall view of this relationship is shown in Figure 10.3.

With ITMA 2011 digital textile printers reached a new standard level in their history, achieving normal production speeds ranging from 400 to  $600 \text{ m}^2/\text{h}$ . Some examples of various printers and their performance are shown in Table 10.1.

| Company                  | Model               | Speed (m <sup>2</sup> /h) |
|--------------------------|---------------------|---------------------------|
| Kornit digital           | Allegro             | 400                       |
| Zimmer                   | Colaris             | 366                       |
| Durst                    | Kappa 180           | 297                       |
| Hangzhou Honghua digital | Aprint 33X          | 250                       |
| La Mecanica              | QualiJet HS JV5 B   | 54                        |
| Konica Minolta           | Nassenger pro 1000  | 1000                      |
| Expand systems           | MS-LARIO            | 8100                      |
| Robustelli               | Mona Lisa Evo       | 675                       |
| Reggiani machine         | ReNOIR              | 428                       |
| Mutoh                    | ValueJet VJ-1628TD  | 24                        |
| DuPont                   | Artistri 3320       | 52                        |
| Stork                    | Sphene              | 555                       |
| Hollander                | Collor Booster 320s | 22                        |
| Mimaki                   | Tx400               | 99.1                      |

Table 10.1 Production speed of digital textile printers

Adapted from Ujiie (2012).

Nevertheless the normal working speed depends on a complex mix of several parameters. Thus, when considered individually, these speed values have no true expression regarding the real performance of the textile printer. Aside from the machine features, application field, ink and textile substrate characteristics, many other factors still directly affect the production speed. To have a better understanding of this reality, the example of Zimmer Colaris printer data is given in Table 10.2.

## 10.4 Colour technology and management

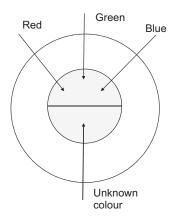
To have a clear understanding of the DTP technology applied to denim, it is important to have an idea of the basic principles of colour technology and colour management. It is well known that the additive colour combination occurs when light rays arising from different sources are blended together. White light can be synthesised as a unique achromatic sensation when the components are mixed in the right proportion (Figure 10.4).

There are several practical examples of combination of subtractive colour combination because the colour of objects results from the selective absorption by the object of light portions from the light beam falling on it, which results in a subtraction of the absorbed light portions from the reflected light beam. Plastics, dyed textiles, minerals, glass, pictures, and so forth have a given colour as a result of the partial removal of the light that falls on them. The term 'partitive' was introduced to describe the phenomenon of mixing colours by rotating disks with sectors of different colours or combining small coloured areas that can be easily isolated when magnified, but which blend with each other when observed from a distance.

Production (m<sup>2</sup>/h) 100% Coverage 1800 mm 2600 mm 3200 mm CMYK+4 Overprint dpi 27 g 18 g 36 g 36 g 54 g 72 g 2X CMYK 27 g 36 g 18 g 36 g 54 g 72 g

 Table 10.2
 Zimmer Colaris production data

Zimmer Maschinenbau GmbH (2013).



**Figure 10.4** Additive colour mixing using the primaries R, G and B. Lucas et al. (1996).

In waddition to Maxwell discs, other common cases of partitive combination of colours have been observed: for example, graphic reproduction using three or more colours, textiles with yarns with fibres of different colours close to each other, and so forth (Lucas, 2008).

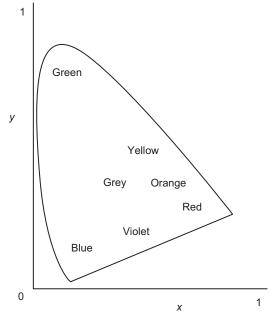
Negative specifications are inevitable in photography, printing and colour television. Any colour within the triangle formed by the primaries can be defined by positive amounts of these. The chromatic components become negative if the colour lies outside that triangle. To overcome this situation of negative values, a set of ideal primaries is derived (*X*, *Y* and *Z*) (Lucas et al., 1996).

#### 10.4.1 CIE chromaticity diagram

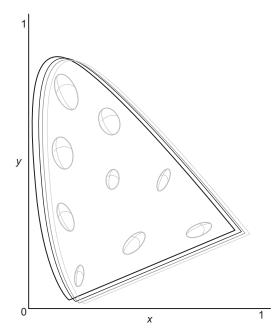
Based on the ideal primary colour *X*, *Y* and *Z*, the chromaticity diagram (*x*, *y*) of Commission Internationale de l'Eclairage (CIE) can be derived, which is based on a rectangular triangle, as shown in Figure 10.5. This diagram consists of a unitary plan of the colour space based on the chromatic ideal components mentioned above and for which the relations X+Y+Z = 1, x = X/(X+Y+Z) and y = Y/(X+Y+Z) apply (Billmeyer and Saltzman, 1966).

The relationship between sensation and stimulus is usually expressed by the Weber– Fechner law which, in turn, also characterises the response to touch and sounds. In a differential form, it tells us that the change of feeling,  $\Delta E$ , is proportional to the relative variation of the stimulus,  $\Delta R/R$ . Hence, two dark greys with a 5% average reflectance and differing only in 0.5% have the same visual difference as two light greys with a 50% average reflectance and a difference of 5%. In terms of colours this effect can be translated by the MacAdam ellipses using the CIE chromaticity diagram (magnified 10 times), as shown in Figure 10.6 (Roderick, 1997).

This relationship between the intensity of the colour and reflectance based on the Weber–Fechner law has a limited application. Other criteria determine this relationship: in particular, an empirical formula developed by Munsell to set the scale



**Figure 10.5** Chromaticity diagram (x, y) of CIE. Roderick (1997).



**Figure 10.6** CIE chromaticity diagram showing MacAdam ellipses. Roderick (1997).

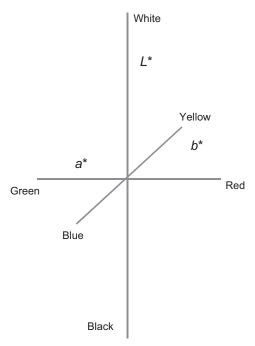


Figure 10.7 CIELAB colour space. Lucas et al. (1996).

intensities of a colour ordering system. Other formulas have been derived to establish a relationship between colour differences. A well known example is the CIELAB colour space, based on a set of relationships for luminance ( $L^*$ ), hue (h) and chroma ( $C^*$ ). The LAB colour space is a colour opponent space with dimension L for lightness and A and B for the colour opponent dimensions, based on nonlinearly compressed CIE XYZ colour space coordinates, as shown in Figure 10.7.

#### 10.4.2 Colour spaces based on additive mixing

A first objective of colour spaces concerns the use in colour television, as defined by the primaries R, G and B (red, green and blue). Another aim refers to the colour space for printing systems. A model consists of a three dimensional system and a subspace within which each viewable colour is represented by a dot. The colour models discussed here are all based on the RGB primary system, although any set of three primaries can be used.

Three closely related models of specific application are RGB, used in screens, YIQ (Y is the luminance; I stands for in-phase; and Q means quadrature, referring to the components used in quadrature amplitude modulation), applied in the television broadcasting system, and CMY (cyan, magenta and yellow) used in printing devices. Unfortunately, none of these models is particularly easy to control by a programmer or user because it does not relate to the intuitive notions of hue, saturation and intensity. Therefore, others derived, such as HSV (hue, saturation and value) and HLS (hue, lightness and saturation), were created.

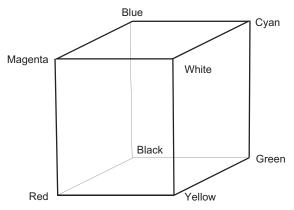


Figure 10.8 RGB colour cube. Lucas (2008).

#### 10.4.2.1 RGB colour model

The RGB colour model uses a Cartesian coordinate system. The subspace of interest in this case is the unit cube presented in Figure 10.8. The RGB primaries are additive, i.e. the individual contributions of each component add to form the result. The main diagonal of the cube for each equal primary quantity represents the greyscale. This model is of great interest owing to its use in colour television and in many colour computer monitors.

#### 10.4.2.2 CMY colour model

Cyan, magenta and yellow are complementary to red, green and blue, respectively. They are known as subtractive primaries because of their effect on subtracting part of white light radiation. The subspace of the Cartesian coordinate system the CMY model is the reverse of the RGB model, where the origin is white (W) instead of black (K).

Colours are specified by the radiation amount subtracted from white light, instead of an addition to black. Knowledge of the CMY model is important when working with printing devices applying coloured dyes or pigments on paper or textiles, for example. In practice, this system is not used nowadays. The inclusion of a fourth primary, black (K), brings about cost and image contour advantages, leading to the CMYK colour system.

#### 10.4.2.3 HLS and HSV colour models

The HLS colour model, whose parameters represent hue, lightness and saturation, is based on the Ostwald colour system. This model consists of a double pyramid, as shown in Figure 10.9. Analogous to the HSV system (a hexagonal inverted pyramid), the hue *H* is given by the angle around the vertical axis of the double pyramid, occupying red at the origin  $(H=0^{\circ})$ . Saturation (*S*) is represented by the distance from a colour to the vertical neutral axis. Lightness (*L*) ranges from 0 to 1, from black to white, respectively.

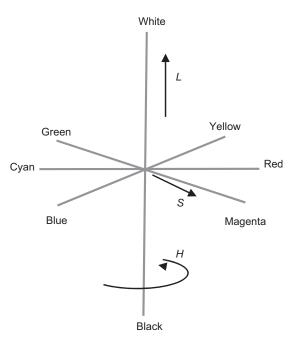


Figure 10.9 HLS colour model. Lucas (2008).

# 10.4.3 Colour management

The main issue in colour management is to reproduce colours accurately using a printer. The problem is that a given printer cannot reproduce all colours that the human eye can see. The colour gamut of a printer is reduced. The solution for the problem is composed of a correction based on the colours from the printer gamut, thus leading to an image with less saturated colours (Tyler, 2011). Several approaches to colour correction can be followed:

- The choice of the printing system: four colour printers have more out of gamut colours compared with six or eight colour printers.
- · Printing inks have been subjected to colour improvements to enable a wider colour gamut.
- Colour correction software will make a colour symmetric match of all out of gamut colours. This may lead to colour prints unsuitable for certain applications.
- Another way deals with the correction of all colours of an image, converting them to colours inside the printer gamut.

In practice, there are different methods for approaching how colours are electronically represented, either using a small spectrophotometer to read reflectance values of a swatch and converting this data into RGB values, using a collection of physical coloured samples (Pantone or other), or creating a set of colours in a palette using a printer and a given substrate. Of course, this last approach has to be carried out every time one changes the printer, the inks or the substrate. According to Tyler (2011) there is another problem regarding textile digital printing, because the starting point for colour selection by designers is not always the same; some work with a screen (RGB), others with a scanner (CMYK) and others with physical textile or card swathes. If colours fall out of the printer gamut, digital printing correction will have to be done.

#### 10.4.4 Computer aided design software for colour and design

Digitally developed denim, commonly known as digital denim, can be considered the final result of a process composed of a source or sources of inspiration, creativity, technical knowledge and design work combined with essential hardware and software accessories: namely, a textile printer and raster image processing (RIP). The combination of all of these factors permits the development of a highly engineered, customised piece of cloth.

Raster image processing software has an important role in image composition and management. Its many capabilities and inherent functions allow rapid layout transformations such as multi-image placement, rotation and scaling, the management of ink control functions such as saturation, the creation of colour catalogues, the definition of customised colour profiling of fabrics and inks, the representation of a colour gamut and more, in perfect accordance with the fabric and the textile printer features – in particular, the number and technology of the printing heads. This type of software can read computer aided design (CAD) files, as well as most common graphic file formats. In general, all CAD software applications can be used in pattern design and digital printing.

The large majority of textile printers accept digital images in the most popular graphic file formats, such as TIF, BMP and JPG. These are two dimensional data files gathering the hue, saturation and luminance attributes of each image pixel. These data files are called raster images and are large, not easily modifiable files required for digital printing.

Vector images are different from raster images. Vector graphic images can be easily changed because vectors are scalable, which means that they can be changed in terms of size, direction and shape. Vector files require much less memory space compared with raster or bitmap files. Because the creation of raster images requires a lot of computing, each digital printer usually has its own raster software.

# 10.5 Techniques for developing digital denim

Denim clothing is thought to be eternally young and fashionable and is undoubtedly the clothing of choice of today's youth. A variety of denim products such as pants, shirts, skirts, jackets, belts and caps, in their many forms, shapes, colours, effects, combinations and so forth, are massively available in the market nowadays. Denim gradually made its way into the consumers' everyday life. Currently, denim fabrics are a social statement and have gained increasing popularity because they provide comfort to the wearer in daily physical activities along with a certain aura of luxury and glamour.

In recent years, industrial companies worldwide have been consistently and increasingly taking heed of digitally printed textile goods, and among a large variety of textile products, denim caught their attention in particular, not only because of its market share but, above all, because of the public's interest in small, perfectly customised collections targeted for a particular niche.

This state of affairs requires a versatile and quick response production system that can timely deliver a quality product at a good price to a rapidly changing market. Hence, the textile industry turned its eyes to digital printing as a solution for this market demand. Nowadays, many renowned brands such as Diesel, Pepe Jeans, Hudson Jeans and Salsa have denim fabrics products printed with DTP.

Taking into account that traditional blue denim is a warp faced cotton fabric of indigo dyed warp and slightly grey weft, the best suitable printers for denim fabrics are those using either reactive dyes or pigments. Several studies explore the complexity and interaction of different parameters that govern a successful digital printing job; all of those are cognizant of and agree on the importance and key role of ink pigments.

Either solution offers advantages and disadvantages in which the use of dyes or pigments must be weighed according to their own specific characteristics. One particular dye or pigment does not behave like all of the others. Nevertheless, they can be broadly compared, as shown in Table 10.3.

#### 10.5.1 Image processing and pattern application

Denim is one of the most iconic fabrics in the world and traditionally was used in its natural state – raw denim – until the late 1970s. When fading designs became a worldwide fashion trend in denim jeans, digital textile printing of denim fabrics gained importance as a possible technical and economical alternative to produce such effects.

Typical characteristics of outworn and overwashed, the most popular designs among consumers, turned these new desired effects into a market trend that led to the creation of a whole new garment niche highly influenced by youth fashion trends (Ozguney, 2007). The visual appearance of denim has become an object of study and experimentation and has become a major factor of differentiation.

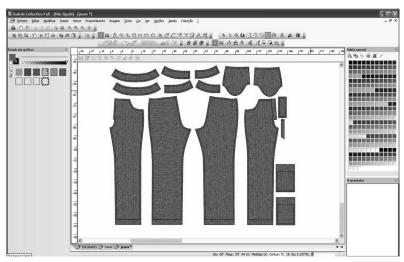
'Digital denim' refers to a concept explored by Carly Spano (2012), of the Cotton Incorporated, USA, who proposed the creation of denim like fabric through digital printing of colour and/or finishing effects into a non dyed twill fabric. In fact, it is textile digital printers and ink's technological evolution that renders the research of new forms of digital applications so attractive. These printers make it possible to create all types of images with a vast set of techniques and tools and creatively explore millions of colours in a single operation, which is not possible with analogue printing methods (Ryall, 2010; Treadaway, 2007).

Digital denim development always depends on fashion trends, which means that depending on the type of denim desired, the CAD work will be more or less complex. Various types of image processing software can be used in colour and finishing effects management, such as Adobe Photoshop, Illustrator, Corel Graphics Suite and Kaledo by Lectra Systems, among others.

Some of them are more suitable than others for a particular type of image or desired effect. For example Photoshop, Corel Photo Paint and Kaledo Print are more suitable to work with real photo images, whereas Illustrator, Corel Draw and Kaledo Collection are a better option when working with vector graphic images.

|                            | Dye based inks  | Pigment based inks   |
|----------------------------|---|--|
| Light fastness             | Dye molecules contain a chromophore that absorbs<br>certain wavelengths of light and reflects others<br>Wavelengths of ultraviolet radiation in sunlight can<br>energise chromogens, destroy their ability to absorb<br>wavelengths and reflect colour and result in fading   | Generally tolerates exposure to sunlight better than comparable dye<br>Properly selected and formulated, pigment based inks can be<br>significantly more durable when exposed to sunlight than dye<br>based inks   |
| Crock fastness             | Dyes that are chemically bound or encapsulated in fibre<br>withstand abrasion and rubbing better than pigments<br>that adhere to the surface<br>Both sublimated and disperse dyed synthetic fabrics<br>exhibit little colour loss from crocking   | Typically less able to withstand crocking because pigmented inks<br>sit on the surface of the fabric   |
| Hand                       | Good hand. Dyes are absorbed into the fabric  | Fabrics printed with pigment based inks exhibit almost the same hand as dye based inks   |
| Colour                     | Offer more colour range and gamut; tend to be more vibrant and brilliant than pigment based inks  | Tend to offer better opacity than dyes but typically not as vibrant  |
| Stability and printability | Dyes are inherently more stable than pigment inks   | Depending on quality of ink and suitability to inkjet head, may<br>flocculate and clog heads<br>One of the most difficult problems for pigment ink manufacturers<br>is maintaining pigments in dispersion  |
| Cost and time              | <ul> <li>Require considerable post processing including steaming<br/>and washing. Capital investment and maintenance of<br/>steaming, washing, drying and wastewater treatment<br/>equipment can be substantial</li> <li>For a typical shop, running costs of post processing can<br/>add USD 20,000–USD 30,000 in production costs<br/>annually and days to each production run</li> </ul> | Curing can be a simple one step synchronised process using heat,<br>providing truly on demand digital textile printing<br>This greatly reduces the initial capital equipment investment and<br>ongoing production costs and greatly reduces total production<br>time |
| Sustainability             | Post treatments including steaming and washing require<br>much energy and produce waste wash water that con-<br>tains exhausted dyes, thickeners and other chemicals  | Synchronised inline finishing completely eliminates the<br>environmental impact of post processing associated with<br>dye based inks   |

# Table 10.3 Comparative analysis of dye and pigment based inks



**Figure 10.10** Jeans pattern with digital denim simulation. University of Beira Interior.

Kaledo programs (Kaledo Print, 2010; Kaledo Collection, 2010; Modaris V7, 2013) by Lectra Systèmes are highly reputed and well known in the textile industry and meet all the requirements necessary for the development of digital denim, because they have a range of specifications and resources that other software programs do not offer. Kaledo Print is a textile development product designed to create drawings in flat and halftone colours. Images can be scanned, imported or created in the design environment of the program. Design cleaning tools, colour reduction and the creation and management of colour palettes all interact easily with a wide range of drawing repetition functions. It is possible to create and modify images with painting and effects filters, previewing the final results. It also lets you work with large volumes of repetitions or rapports, such as those used in the field of interior decoration and design of fabric prints.

Colour is critical but hard to share. It has a huge impact on design; without the appropriate tools it takes many attempts to get it right. Effectively managing colour development, colour processing and colour communication can save money in the process. Kaledo Print supports several colour symmetric colour spaces, such as RGB, CMYK (Campbel, 2006), LAB, XYZ and HSV. It also supports spectral colour data and is compatible with spectrophotometers.

Another important feature of Lectra software is the possibility of interaction among programs. Garment patterns created on a pattern making program (Modaris) can be read on Kaledo Collection and the developed images on Kaledo Print can be placed in the developed patterns before digital printing, as depicted in Figure 10.10. Using other Lectra computer applications, it is possible to digitally print garment patterns with different prints on them (Kaledo Print, 2010; Kaledo Collection, 2010; Modaris V7, 2013).

During this process, after completing image development, it is necessary to choose the type of printing solution: in particular, printing a complete image, whether repeated or not, or alternatively, an engineered (localised) print. The printing of a complete



**Figure 10.11** Engineered print of flower painting on jeans pattern. University of Beira Interior.

image (rapport) requires only the correct pattern repetition, but when an engineered print is selected, other factors must be taken into consideration.

In the case of an engineered print, the developed image fits the garment pattern pieces. With this technique, when cloth pieces are assembled, the printed images show no broken or misaligned areas. This type of print can be used for aesthetic purposes but it also allows the reduction of fabric and ink waste by controlling the image to print as well as the amount of desired ink (overprint). There is no automatic way to apply this technique through the pattern pieces in one operation; it is necessary to adjust the image and decide where it will fit. This can be performed by matching images using, for example, the interaction possibilities of Lectra software (Bougourd and Delamore, 2007; Campbell and Parsons, 2005; Polston, 2011). This is a challenging process that requires not only technical but also creative skills from the designer. Figure 10.10 shows a jeans pattern with digital denim simulation, whereas Figure 10.11 shows an example of an engineered design.

#### 10.5.2 Sources of inspiration for digital printing

In the late 1960s, denim jeans stood as a symbol for youth rebellion and discontent, and its users were sending an antiestablishment message. Precisely at this time, several kinds of decorations, types of fabrics, colours and effects were developed. Among others, one of the currently most popular effects – stonewashed (using abrasive stones to accelerate the aging process) – is deemed to have been initially introduced by Nudie Cohn. This innovation is also related to the French brand Marithé François

Girbaud, which intended to express ideas through humanitarian denim (Huiguang and Lv, 2007). However, the Japanese brand Edwin claims to have been the first to launch stonewashed jeans commercially in 1975, a secret it kept from the world until its announcement of the process in 1979 (The Denim Bible Jeans Encyclopedia III, 2011).

There is an immense variety of finishing effects, most replicating vintage, damaged, overdyed, wrinkled or worn looks. For a vintage and/or faded look, effects simulating different stages of denim abrasion as well as washed and faded ones are the most popular and the main source of inspiration for the development of digital denim (Hoppe and Saboor, 2011). To obtain these artificial effects, physical and chemical processes such as sanding, spraying, brushing, prewashing, washing (stone, enzymes, sand or oil), bleaching and, more recently, laser technology have been used (Ozguney, 2007; Scheffer, 2008).

All of these operations involve the use of time, machinery, products, energy, manpower and so forth, which will significantly raise production costs. However, the same effects can be done more rapidly, efficiently and economically with this new technological solution – digital printing. A vast plethora of textures and finishing effects is possible with DTP. Using these types of software and layer methodology, a wide variety of denim products can be obtained. Figure 10.12. Illustrates an example of the digital denim development process.

The use of scanned or photographic images for traditional denim finishing effects is another starting option to develop and compose image solutions for digital denim, as shown in Figure 10.13. Besides typical finishing effects, digital

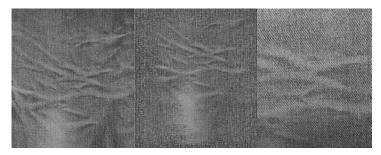
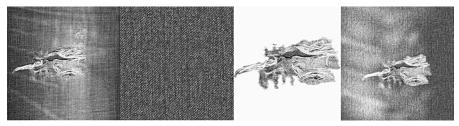
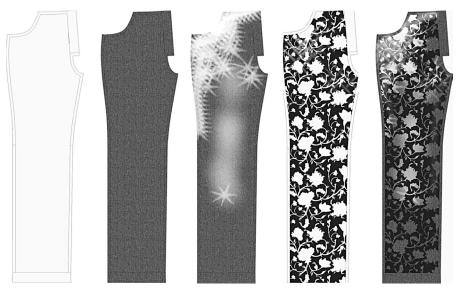


Figure 10.12 Digital denim with finishing effect.

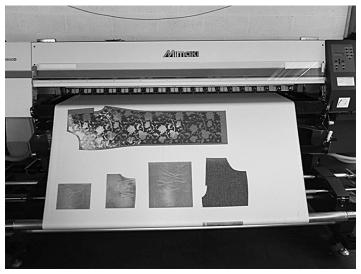
Left to right: 3D effect by traditional process; CAD development; 3D effect on digital print. University of Beira Interior.



**Figure 10.13** Digital denim based on a real denim photo. Left to right: traditional effect; denim fabric; finishing effect detail; digitally printed effect. University of Beira Interior.



**Figure 10.14** Digital denim with floral images and abrasion effect. University of Beira Interior.



**Figure 10.15** Digital printing of undyed denim with pigments. University of Beira Interior.

denim can replicate other aesthetic effects, such as patterned prints and embroidery, as illustrated in Figure 10.14. Similarly, Figure 10.15 shows digital denim printing of an undyed fabric with pigments using a Mimaki Textile Jet Tx400-1800D machine. Digital denim entails not only the idea of classical denim with current traditional applications, but also all the possibilities that the digital world might add, especially a new colour range and better image definition along with new sorts of finishing effects.

# 10.6 Future trends

At the current state of development, trade figures show that DTP is slowly gaining market share whereas analogue printing appears to be stable if not stagnated. Because of continued and steady evolution over the past decade, some researchers claim that DTP should be upgraded to surface imaging (Ujiie, 2012), to provide more aesthetic possibilities and innovative opportunities for a broader range of substrates.

To date, digital denim is able to offer new perspectives and enhanced potential for both designers and the industry, representing a major technological paradigm shift. Designers now have more artistic freedom to develop their compositions creatively. An almost limitless variety of motifs and patterns can be developed and printed onto denim fabrics. Costly and complex finishing effects, traditional or new, can easily be replaced by manipulated images that replicate them, and can ingeniously be applied onto denim fabrics using less time, manpower, energy and so forth (compared with conventional processes). Sampling and proofing of new digital denim prototypes can be carried out in a matter of hours, whereas the lead time for industrial production plunges. As a consequence of this operational flexibility, production can be smoothly adjusted to market demands. The possibility of swift production of a unique or customised specimen in small to medium size quantities with a profitable cost–benefit relation, compared with analogue printing, is also a major advantage.

Digital textile printing technology is constantly evolving, and the new developments will have an impact on every aspect of the process – from digital design to printing with industrial textile printers. Broadly speaking, it is reasonable to expect that forthcoming improvements will occur in the area of colour management: namely, in matching accuracy as in, for instance, amelioration of the input image, better calibrated monitors and spectrophotometers, as well as a printing process with improved final quality and increased speed. Furthermore, owing to software and hardware developments, the process will gain new capabilities and become more refined.

The computational infrastructure is expected to become more integrated and to emphasise convergence between the design workflow in preprinting packages and RIP software. Some RIP vendors are already trying to launch new programmes dedicated not only to drive digital printers but also to manage the entire workflow, controlling all aspects from the beginning to the final output. Printing systems with associated quality control inspection by image analysis techniques are another possibility. Some initial patents have expired or are about to expire, which can induce the entry of new players into the market, generating new knowledge and leading to more affordable textile printing systems.

Another aspect that may alter the prospects of this technology is continuous research in the area of printing ink, particularly in an increased penetration of colourants into the textile substrate; a wider range of applicable substrates; a broader colour gamut; the elimination of fabric requirements such as pre and post treatment; better printer head technologies with improved droplet formation control, fewer clogging problems and less maintenance; and new industrial printers with diminished consumption of resources and waste. In addition, the introduction of new improvements that might contribute to eliminate or at least minimise defects that are inherent to the current technological status of digital textile/denim printing, such as banding, misfire or smear, is also foreseeable. Furthermore, the incorporation of encapsulated nanoparticles into inks that convey important antimicrobial or odor control properties to the final product lays the foundation for a new market niche of functional textiles (Leelajariyakul et al., 2008). A major market extension can be achieved by applying digital printing in printed electronics on flexible substrates and with coating applications in the development of functional denim textiles.

# 10.7 Conclusion

Digital textile printing has come a long way since the introduction of adjusted wide format graphics printers to the production of dedicated high productivity machines. New machinery developments such as better print head performance and innovative inks, together with significant progress in preprinting and RIP software, led to the acceptance and adoption of this technology by the textile/denim industry. The possibility of a new aesthetic expression combined with the consumer's awareness of customised and personalised products manufactured by means of a more ecological technology also contributed toward its consolidation.

The current status of denim digital printing is characterised by the coexistence of hybrid mills equipped with conventional printing machinery and some digital printers for specific jobs, companies that definitely place their bets on this new alternative method and operate exclusively with digital printers and, finally, small companies evolved out of design studios that are making an effort to produce some novelties aimed at a more customised luxury market. This technology enables creative designers and producers to work closely and in a timely manner with retail distribution networks in a quick response model. The addition of electronic data interchange capabilities to this equation perfects the model and constitutes a strong asset for companies' competitiveness, materialising a concept usually referred to as fast fashion.

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# Washing techniques for denim jeans

# 11

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# 11.1 Introduction

Over the past few decades, different denim washing techniques have been developed and used on different materials to create a large variety of designs for trendy denim garments and jeans. Special colour effects and washed/vintage looks are often achieved in denim garments. The hand feel of the washed goods is relatively superior, which makes them suitable for leisure wear. These effects are difficult to achieve through other processing techniques.

The results obtained from denim washing represent a combined effect of colour dissolution, destruction of the dye and mechanical abrasion, which sometimes causes the removal of surface fibres from the materials. Thus surface dyed (ring dyed effect) colours in denim garments are more easily washed down during the washing processes.

According to textile terms and definition (McIntyre and Daniels, 1995), denim is defined as 'Traditionally a 3/1 warp faced twill fabric made from yarn dyed warp and undyed weft yarn. Typical construction of the fabric is  $32 \times 19$ ;  $45 \times 54$  tex;  $310 \text{ g/m}^2$ . More recently, other weaves have been used with lighter constructions'. Jeans are defined as 'A 2/1 or 3/1 warp faced twill fabric used chiefly for overalls or casual wear with a typical construction of  $35 \times 24$ ;  $32 \times 21$  tex cotton'. Although by definition, denim and jeans refer to different things, they now mean the same thing in the market. Conventionally, warp yarn in denim fabric is dyed with indigo with a ring dyed effect. As a result, the washing technique and effect described in this chapter are based on indigo dyed fabric.

# 11.1.1 Evolution of denim garment washing

Denim garments in the market are originally stiff and uncomfortable when first purchased because of the finishing system used for denim fabrics. Generally speaking, after weaving, the heavily sized fabric is subjected to desizing and compressive shrinkage treatments. After the treatments, the softness of the denim fabric is seriously affected. In the past, many consumers used to take a newly purchased pair of jeans home and soften it by washing once or several times before the first wearing (Swicegood, 1994; Paul and Paradeshi, 2003).

Swicegood (1994) reviewed the evolution of denim garment washing. In the earliest evolution, the garments were laundered (prewashing) by the manufacturer before selling. These 'prewashed' denim garments had a slightly faded appearance and a softer

hand that felt comfortable. These prewashed garments generated a trend of fashion and consumers were willing to pay the extra cost involved in this additional processing.

As the popularity of prewashed garments grew, the idea of using abrasive stones to accelerate the colour fading process was developed and 'stone washing' became the second step in the evolution. Pumice stones were included in the washing process, or tumbled with the damp garments to wear down the stiffest portions, for example, belt areas, cuffs and pockets. The third development was the use of chlorine (e.g. sodium hypochlorite as a bleaching agent) in the washing process. A new and colour lightened blue denim garments category was the result. With the use of chlorine bleaching, in 1987–1989, 'ice washing' was developed, in which the pumice stones were first presoaked in the bleaching agent and then tumbled with dry or slightly damp garments. In the industry, 'ice washing' has alternative names such as 'acid wash', 'snow wash', 'white wash' and frosting, etc. Actually, the term 'acid wash' is a misleading term because mineral acids are not used for this process (Swicegood, 1994).

Other than bleaching agent, the use of enzyme (cellulase) treatment to obtain the colour fading effect similar to stone washing effect in denim garments has attracted considerable interest over the past several years (Swicegood, 1994; Tarhan and Sariisik, 2009). The primary attraction is to reduce or eliminate the need for stones or to reduce the time needed to obtain the desired abrasion effect. Moreover, using pumice stones to abrade denim garments is destructive to equipment. In addition, the pumice stones, after washing, get entrapped in pockets of denim garments which must be removed by hand, leading to increased labour and production cost. Also, stone particles and gritt play havoc in the effluent. For these reasons, the use of cellulase was promoted with the promise of eliminating stone as the abrasive agent for achieving the 'stone wash' look. However, because of the increased time and other considerations, the trend today is to use combinations of stone and cellulase to achieve the worn and faded look in denim garments (Swicegood, 1994; Zhao, 2008; Tarhan and Sariisik, 2009).

With the increasing awareness about and concern for environmental issues, such as large amounts of effluents produced and high consumption of water and energy, wet processes related to denim washing are considered as not environmentally friendly. To address the environmental concerns, dry finishing techniques such as plasma (Ghoranneviss et al., 2007; Kan and Yuen, 2008, 2012) and laser (Dascalu et al., 2000; Hung et al., 2014; Kan, 2014; Kan et al., 2010; Kan and Yuen, 2008; Ortiz-Morales et al., 2003; Ozguney et al., 2009) treatments have been introduced as an alternative to the conventional wet processing.

#### 11.1.2 Washing as final process of denim garments

Washing can be considered as the final process in denim production and is the core of denim finishing (Swicegood, 1994; Zhao, 2008; Paul and Naik, 1997a,b). The washing of denim is directly related to the aesthetic, quality and value of denim garments. In processing, sizing and colouration form the base of colour in denim garments (Wang, 1995). However, the washing process is the key to create the style in denim garments which is now becoming an art of creating fashion trends (Zheng, 2009). The three dimensional (3D) effect and worn look can be achieved through different types

of finishing and washing processes (Lin and Liu, 2009; Li and Liu, 2013). Under the influence of different chemicals, washing conditions and washing equipment used, different final effects can be achieved in denim garments. As a result, the washing of denim and jeans is aimed at (Lin and Liu, 2009; Li and Liu, 2013):

- Preshrinking for good dimensional stability during selling and use.
- Removing sizing agent and unfixed dyes to remove contaminants added during the manufacturing process so as to generate 'clean' denim garments. Also, the washing can increase the surface lustre and lightness of the fabric.
- Improving the hand feel through various finishing processes such as softening, stiffening or polishing to enhance the comfort of denim garments.
- Improving aesthetic properties through fading, bleaching or tinting processes. After these treatments, cloudy, frosted, wrinkle, grinded or peach skin effects are achieved which finally affect aesthetic properties.
- Improving the functional properties such as wrinkle free, anti soil, water repellence, oil repellence or antistatic, etc.
- Improving the quality in cases of poor colour yield, dimensional stability, colour fastness or improper surface treatment.

# 11.2 Classification of washing techniques

### 11.2.1 General finishing sequence of denim

There are almost countless variations of processing techniques used by designers and textile chemists to achieve fashionable looks that are distinctive and desirable. Only the basic treatment conditions are addressed in this chapter; the number of variations is very large and the evolution of chemical and mechanical techniques is continuing. There often are some secretive and proprietary methods. Regardless of the specific look and name chosen, the following are the process steps normally used to attain the desired results (Li and Liu, 2013).

Desizing  $\rightarrow$  Rinsing  $\rightarrow$  Washing (abrasion)  $\rightarrow$  Rinsing  $\rightarrow$  Softening  $\rightarrow$  Drying  $\rightarrow$  Packing (Li and Liu, 2013).

In denim garments, preparation consists primarily of desizing, which enables subsequent chemical and mechanical treatments (washing/abrasion) by removing the previously applied warp size. Untreated denim garments are extremely rigid due to the size applied at the yarn stage for increasing weaving efficiency, by coating the yarn with a protective outer layer which retards yarn breakage. The sizing remains in the yarn after the fabric is woven and, therefore, provides fabric stiffness necessary for more efficient sewing of garments. Sizing is typically made up of starch (or polyvinyl alcohol/starch), binders and waxes and lubricants (The Hong Kong Cotton Spinners Association, 2007). Additionally, finishes containing starch and/or polyvinyl alcohol are applied to denim as a topical finish before the fabric is shipped to the sewing plant. After desizing, denim garments are rinsed to remove all size materials before washing/ abrasion. Different washing/abrasion techniques are introduced in the following sections. Again after the washing/abrasion processes, denim garments are rinsed to remove unwanted materials from fabric surface. Then a softening process enhances the hand feel and softness of the denim garments. Finally the denim garments are dried and packed for delivery.

#### 11.2.2 Desizing

The most popular method of removing starch from denim garments is to use amylase enzyme. This product can break down the long starch molecular chains (water insoluble) into smaller molecules (water soluble) which can be more easily washed away. The removal of starch from the fabric being desized can also usually release some quantities of indigo into the bath. Therefore, a neutral pH nonionic surfactant is used for suspending loose dye in the water, to prevent redeposition onto the garments as well as to aid penetration of the desizing liquor into the interior of the fibres. It is also important to follow the desizing bath with a hot water rinse. Introduction of cold water onto the denim garments at this point can resolidify the fats and waxes, and tends to redeposit the gelatinous components unevenly on surface (Swicegood, 1994).

#### 11.2.3 Regular washing

Regular washing is the simplest and most commonly used washing method for denim garments. The degree of colour fading using regular washing is comparatively slight, but it provides uniformity, depending on whether it is deeply dyed classic denim or only moderately dyed with poor penetration. Generally speaking, detergent is used for regular washing for about 15 min at temperatures between 60 °C and 90 °C. Softening is applied after the washing process. Regular washing can improve the softness and comfort properties of denim garments as well as enhance aesthetic property. Depending on the time and amount of chemicals used, regular washing can be classified into (1) light washing (washing time about 5 min); (2) normal washing (washing time about 15 min); and (3) heavy washing (washing time about 30 min). However, there is no significant distinction between light, normal and heavy regular washing as it depends on the actual washing conditions (Chong, 1994; Zhao, 2008; Li and Liu, 2013). General regular washing process is as follows:

Wetting  $\rightarrow$  Desizing  $\rightarrow$  Regular washing  $\rightarrow$  Softening.

#### 11.2.4 Bleach washing

Bleach washing is normally carried out with a strong oxidative bleaching agent such as sodium hypochlorite (NaOCl) or potassium permanganate (KMnO4). Bleach washing may be carried out with or without the addition of stone. The bleach washing effect and decolouration usually depend on strength of the bleach liquor, liquor quantity, temperature and treatment time. The bleached fabric materials should be properly antichlored or after washed with peroxide to reduce the subsequent yellowing or tendering of the bleached denim fabric. The basic steps of denim bleach washing are as follows (Chong, 1994; Zhao, 2008; Pal, 2010):

Garment loading with or without stone  $\rightarrow$  Desizing (10–15 min, at 55–60 °C) $\rightarrow$ Rinsing  $\rightarrow$  Bleaching (15–30 min) $\rightarrow$  Rinsing  $\rightarrow$  Bleaching with cold water  $\rightarrow$  Optical brightening  $\rightarrow$  Softening (Chong, 1994).

At any process stage, if sodium hypochlorite is used, characteristics of the chemical must be taken into account to assure minimum fabric degradation while achieving the desired colour fading effect. In storage, the active chlorine content of sodium hypochlorite solution loses daily especially in hot weather. Therefore, concentration should be checked before dosing the washer. The pH range used in sodium hypochlorite bleach washing is critical because of the formation of hypochlorous acid. It is often not possible to use pH paper for measuring sodium hypochlorite solutions because many indicators get bleached during the measurement. However, when a slight excess of hydrogen peroxide is added to the test solution, the hypochlorite is destroyed without altering the pH. There are many indicators such as universal indicators, phenolphthalein and thymol blue which are not sensitive to traces of hydrogen peroxide. There is greater danger in pH when used in bleaching than is the case with sodium hypochlorite because of carbonate formations (from atmospheric carbon dioxide). Sodium carbonate is formed in the solution which can help buffer the pH. However, an alkaline buffer is recommended for sodium hypochlorite bath (Swicegood, 1994).

In the sodium hypochlorite process, as an after treatment, all chlorine must be cleared from the fabric by use of an antichlor, such as hydrogen peroxide, sodium bisulphite or sodium thiosulphate. Hydrogen peroxide is often chosen as it not only neutralises chlorine but also offers the advantage of additional whitening during the process. On the other hand, bisulphite or thiosulphate are used for the antichlor process.

The normal pH use range for sodium hypochlorite bleaching is 9-11.5, where bleaching species of the chemical are most stable. The stability decreases rapidly above 55-60 °C. Therefore, these variables must be controlled to ensure that the cellulose substrate is not damaged. If damage is occurring, lower temperature or concentration or a shorter cycle should be considered. Buffers should also be added to sodium hypochlorite bath to aid controlling of the pH. Some surfactants perform this role, acting as dual agents to provide alkalinity and aiding in wetting and penetration of the fabric by the chemical bath. Another negative property of sodium hypochlorite is the ability to form chloramines with protein impurities in cotton, which tend toward yellowing and ageing. This source of yellowing is a function of impurities in cotton itself.

In case of potassium permanganate, manganese oxide (MnO<sub>2</sub>), a brown and water insoluble compound (Swicegood, 1994) is produced as a by-product. Some of the preventive methods involve high temperature water rinsing, use of chelating agents, good detergent and mechanical agitation, and especially a sufficient number of reduction stages, scouring and rinses to completely remove the residual materials. However, the

most effective way to remove  $MnO_2$  is treating the fabric with oxalic acid (Li and Liu, 2013). Limitations of bleach washing (Pal, 2010):

- The same level of bleaching is very difficult to achieve in repeated runs.
- Bleaching treatment sometimes damages cellulose, resulting in strength loss and or pinholes at the seam, pocket, etc.
- Bleaching liquor is harmful to human health. This may also cause corrosion to machine parts.
- Bleaching treatment needs antichlor treatment to eliminate the subsequent yellowness in the fabric.
- Chlorinated substances occur as abundant products in bleaching, and pass into the effluent where they cause severe environmental pollution.

#### 11.2.5 Stone washing

Volcanic rocks or pumice stones (Figure 11.1) are added during washing as abradants. The colour fading is more apparent but less uniform. The degree of colour fading depends on the washing time (60–120 min), stone ratio (weight of stones relative to weight of the garment) (0.5: 1–3:1), size of stones (diameter: 1–7 cm), liquor ratio (~10:1) and garment load (Chong, 1994; Pal, 2010; Li and Liu, 2013). The world's major pumice stone supplying countries include the USA, Turkey, Italy, Germany, Iceland, New Zealand, Japan, Indonesia and Philippines. The basic steps of denim stone washing are as follows (Chong, 1994):

Desizing  $(10-15 \text{ min}) \rightarrow \text{Rinsing} \rightarrow \text{Stone washing} \rightarrow \text{Rinsing}$  (with perborate and optical brightener if necessary)  $\rightarrow$  Softening.



Figure 11.1 Pumice stones.

This is due to the varying degree of abrasion in the garment. Traditionally, stone washing of denim garments is carried out with pumice stones to achieve a soft hand and desirable look. The pumice stones having an oval and round shape with a rough surface work as an abradant in washing cycle. The variations in shape, composition, hardness and porosity result in different washing effects in the denim fabric. During washing, these stones scrape off dye particles from the surface of the yarn of the denim fabric which shows a faded, worn out and brilliance effect in the denim fabric. From ring dyeing of denim fabric and heavy abrasion during stone washing, the fading is more apparent but less uniform. Stone washing makes the denim garments more supple so that they fit comfortably. To get the desired washed effect, the stone should be of proper hardness, shape and size. For heavy weight denim fabric, large and hard stones are suitable and also last longer. Similarly, smaller and softer stones are suitable for lightweight denim fabrics (Pal, 2010; Paul and Naik, 1997c).

# 11.2.5.1 Effect of stone ratio

Figure 11.2 shows that with stone ratio below 0.5:1, no significant colour fading effect in the denim garments is noted. When the stone ratio is high, the colour fading effect becomes enhanced. However, too high a stone ratio may cause severe abrasion leading to fabric damage (Kan, unpublished data).

# 11.2.5.2 Effect of stone size

Figure 11.3 shows the effect of stone size on the colour fading effect. It is noted that the smaller the stone size, the better is the colour fading effect. In addition,

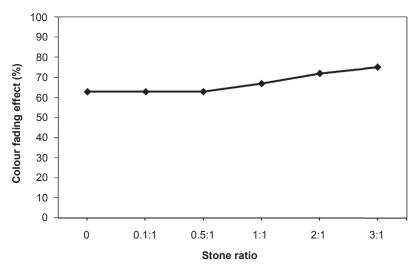
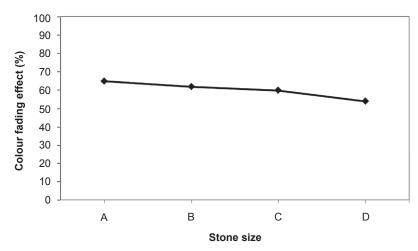


Figure 11.2 Effect of stone ratio on the colour fading effect.



**Figure 11.3** Effect of stone size on the colour fading effect. A: diameter = 2.0-3.5 cm; B: diameter = 3.6-5.0 cm; C: diameter = 5.1-6.5 cm; D: diameter = 5.5-7.0 cm.

small stones can provide an even and uniform abrasion effect, but the colour contrast produced is not good when compared with large stones (Kan, unpublished data).

# 11.2.5.3 Effect of stone washing time

Figure 11.4 shows the colour fading effect under the influence of stone washing time. It is shown that after 90 min, there is no further increase in the colour fading in denim garments (Kan, unpublished data). Stone washing of denim fabric with pumice stones has some disadvantages and limitations, such as (Pal, 2010):

- Stones may cause wear and tear of the fabric and may damage the washing machine from abrasion of the stone with fabric or machinery parts.
- It may also create the problem of environmental disposition of waste of the grit produced by the stones.
- Increase the labour cost required to remove stone dust from finished garments. Denim garments are required to be washed several times for complete removal of the stones.
- The stone washing process may cause back staining and redeposition.
- The process is nonselective.
- Metal buttons and rivets in the garments as well as the drum of the washing machine sometimes get abraded which substantially reduces the quality of the garment and the life of the equipment.

# 11.2.6 Enzyme washing

In enzyme washing, cellulase enzymes are used. Hydrolysis of the cellulose, which is catalysed by cellulase, causes the surface fibres to become weakened and later they get removed when there is either fabric-to-fabric abrasion or fabric-to-stone abrasion

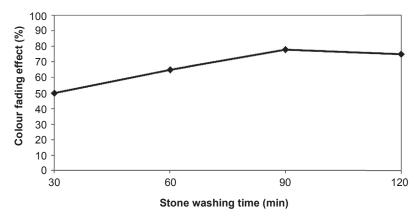


Figure 11.4 Effect of stone washing time on the colour fading effect.

during washing. The temperature and the pH used are specific to the type of cellulase employed. Usually neutral cellulases are applied at pH 6–7, while acid cellulases are applied at pH 4.5–5.5 (Swicegood, 1994). However, the latter result in a greater extent of back staining, being more penetrative. An enzyme dose of 2–4 g/L is normally sufficient, provided that the enzyme activity is not impaired. In general, the colour of the enzyme washed goods is more uniform, particularly when stone is not added. Because cellulases are reactive only on cellulose, any size materials or other impurities must be removed before the cellulase treatment. The basic steps of denim enzyme washing are shown as follows (Chong, 1994; Zhao, 2008):

Desizing  $(10-15 \text{ min}) \rightarrow \text{Rinsing} \rightarrow \text{Enzyme washing}$ , e.g. 30-60 min at 50-60 °C with pH 4.5–5.5  $\rightarrow$  Hot rinsing, e.g.  $80 \text{ °C} \rightarrow \text{Softening}$  (Chong, 1994).

Temperature is the most important factor in enzyme treatment. Generally speaking, enzyme reaction increases with temperature but it is only activated within a temperature range in which the enzyme structure remains stable and unchanged. Beyond this optimum range, the enzyme activity decreases sharply as the protein structure of enzyme is tangled through thermal agitation. There is a trend of increase of colour fading effect when temperature increases from 50 °C to 60 °C (Kan, unpublished data). This is because the enzyme reaction is activated by higher temperature within the optimum temperature range and thus more surface fibres are hydrolysed by cellulase (Aly et al., 2004) and the weakened fibres are removed by abrasion of fabrics and mechanical agitation (Dhurai and Natarajan, 2007). The indigo dye particles are also removed along with the cotton fibres.

The mechanical action can provide colour fading effect of denim garments in enzyme washing. The specimen treated without any agitation has better colour fading effect than that treated with mild and vigorous agitation because the fibres are weakened after treating with enzyme alone and are not well removed by mechanical agitation (Vishnu Vardhini and Selvakumar, 2006; Kan and Wong, 2011). The surface of fabric becomes more hairy and a layer of fuzz gets formed on the surface

(Cavaco-Paulo, 1998). For specimens treated under vigorous agitation, a biopolishing effect is obtained. The weakened fibres are well removed by strong mechanical agitation, and thus a cleaner and smoother surface is produced and the fabric has a lighter shade as dye particles are also removed with cellulose fibres (Kan, unpublished data).

Longer enzyme treatment time prolongs enzymatic degradation of cellulose and the time for further abrasion. It is shown that the colour fading effect increases with increased treatment time. The increase in colour fading effect is mainly due to desorption of dye particles that are weakly adsorbed on fabric. In addition, the increased colour fading effect with more time is also due to the fuzziness of fabric caused by prolongation of the enzyme treatment. With a longer treatment time, cellulase effectively hydrolyses fragments of cotton fibrils (Aly et al., 2004; Kan and Wong, 2011) and thus the fabric is less fuzzy than the original (Kan and Wong, 2011). Usage of cellulase has some distinct advantages, such as (Pal, 2010):

- Cellulase is economical and environmentally friendly as compared with stone washing using
  pumice stones. The percentage of fabric damages is reduced with cellulase treatment. The
  enzymatic treatment of denim fabric ensures the same result but consumes less water and
  time, resulting in less waste and damage to machines. The pollution, quality variability and
  imperfections are also reduced in enzymatic treatment.
- Enzymes can be recycled.
- The productivity of washing is increased due to the space formerly taken up by the pumice stones; the same washing machines can handle more jeans.
- The time consumption for removing stone fragments from the denim garments is eliminated in the case of cellulase treatment.
- The duration or number of rinse washing after enzyme treatment is less than pumice stone washing.
- A small quantity of enzyme can replace several kilograms of pumice stones during washing, which ultimately leads to less damage to garments and machines.
- · Washed garments with a softer feel and better appearance is achieved in cellulase treatment.

Cellulase treatment of denim fabric has some disadvantages, too. There may be chances of backstaining in cellulase treatment. To remove the backstaining, the garments are rigorously washed. However, this adds to usage of water for the washing (Pal, 2010; Kan and Wong, 2011).

#### 11.2.7 Acid washing

Pumice stones are first presoaked in a solution of a strong oxidising agent (either sodium hypochlorite (5-10%) or potassium permanganate (3-6%)) and are then applied to the garments by means of dry tumbling. This results in a localised washing effect with clear blue/white contrast. This technique is also termed 'acid washing', 'snow washing' or 'ice washing' (Chong, 1994; Swicegood, 1994; Pal, 2010).

After the stones are soaked in a strong oxidising agent such as sodium hypochlorite or potassium permanganate, the excess liquor is removed. This can be accomplished by placing stones in net or mesh fabric before soaking. Then the stones can be removed and the excess liquor drained off. Another alternative is to place the stones in a rotary tumble machine along with 'waste' fabric and tumbling for several minutes to remove the excess solution. Another alternative is to use presoaked stones. There are many shapes, varying levels of chemicals and other additives which produce different effects. After soaking the stones, stones and denim garments are put into the machine for tumbling for 10–30min or until the desired effects are achieved. Results are dependent upon dyestuff, fabric, concentration of chemicals, stones and equipment. In some cases, the stones can be reused for another load before resoaking, depending upon their porosity. It is advantageous to remove the denim garments from the machine and transfer them to another machine for washing to minimise the number of machines used for acid washing (Swicegood, 1994).

After getting the desired effect, the machine is filled with water for rinsing for 5 min to remove the stone dust. If potassium permanganate is used, manganese dioxide gets formed (a brown/orange colour) and must be removed by rinsing with oxalic acid. In the case of sodium hypochlorite, a reduction process, antichlor with a reducing agent (e.g. sodium bisulphite) is used for removing the residual chlorine (Swicegood, 1994; Li and Liu, 2013).

In acid washing, the addition of water is not required. The colour contrast after tumbling can be further enhanced by a subsequent optical brightening process. Soft stones that dust off easily are more suitable for this process. The basic steps of denim acid washing are shown as follows (Chong, 1994):

Desizing  $(10-15 \text{ min}) \rightarrow \text{Soaking stones}$  with strong oxidising agent $\rightarrow$ Draining excess liquor $\rightarrow$ Dry tumbling  $(10-30 \text{ min}) \rightarrow$ Rinsing to remove stone dust $\rightarrow$ Rinsing with oxalic acid (in case of potassium permanganate)/antichlor with reducing agent (in case of sodium hypochlorite) $\rightarrow$ Optical brightening $\rightarrow$ Softening.

#### 11.2.8 Sand blasting

Sand blasting is a mechanical process in which localised abrasion or colour change on the denim garment is created (Pal, 2010; Zhao, 2008). The process involves blasting an abrasive material in granular, powdered form at a very high speed and pressure through a nozzle, on certain areas of the garment such as knees and elbows as shown in Figure 11.5 (Pal, 2010). The treated surface shows distressed/abraded/used look. The common blasting materials used are sand and metal granules. During sand blasting process, denim garments are first subjected to stone washing to the desired degree of washing and are then sand blasted. A solution of sodium hypochlorite or potassium permanganate is often sprayed on the desired area of the garment in order to obtain the same look. The garment is then neutralised, rinsed, softened and dried. Sand blasting is a water free process and, therefore, no drying is required.

#### 11.2.8.1 Health problems

Sand blasting removes the dark indigo from a denim garment giving it a popular preworn look. This process involves smoothing, shaping and cleaning a hard surface by forcing abrasive particles across that surface at high speeds using special types of sands.



Figure 11.5 Sand blasting.

These are sprayed onto the selected parts of the denim garments at high pressure through air compressors to remove colour from those areas to create the desired design.

Sand blasting can be done manually or mechanically. The mechanical process encloses the sand and dust particles in blasting cabinets and is–if used correctly–therefore less hazardous for the operating workers. However, manual sandblasting is preferred by factories as it is cheaper because it does not require investment in advanced and expensive industrial equipment. Sand blasting also costs less than other fading methods (like hand sanding) which are more labour intensive. Whilst sandblasting to achieve a worn look on denim is a relatively new phenomenon in the clothing industry, similar methods have been widely used in mining and building industries for many decades and the link between the use of sand blasting and the risk of silicosis has long been acknowledged.

It was the high health risks associated with manual sand blasting process that prompted regulation of the technique in the Europe in the 1960s. Sand blasting can expose workers to extreme health hazards and can cause death within months or years of starting work as a sandblaster. Sand blasting using natural sand is especially problematic because workers inhale crystalline silica dust particles during production, causing serious damage to the respiratory passages. These particles are so tiny that they are invisible to the naked eye. The body is unable to expel the silica particles, causing diseases such as silicosis. The particles penetrate the pulmonary alveoli and the connective tissue, gradually impairing lung capacity and the workers' ability to oxygenate blood. Symptoms include shortness of breath; as the disease develops, this is common even when resting. This puts additional strain on the heart, eventually leading to death. However, the progress of silicosis can be slowed if symptoms are diagnosed at an early stage (Riddselius, 2010).

#### 11.2.9 Monkey wash

Monkey wash is a description of special colour fading effect normally at thigh and buttocks of denim jeans. In this process, denim jeans are sprayed with a strong oxidising agent such as potassium permanganate (Lin, 2009; Zheng, 2009; Zhao, 2008). Therefore, monkey wash can be technically termed as 'PP spray' (with PP being potassium



Figure 11.6 PP spraying.

permanganate). The denim garments should be laid flat or fixed in manikin properly (Figure 11.6) before PP spray. About 2–5% concentration of potassium permanganate is sprayed on the marked surface and the colour is then faded. After PP spraying, the brown colour of manganese oxide can be removed by oxalic acid or hydrogen peroxide. The basic steps of PP spray on denim garments are as follows:

PP spraying  $\rightarrow$  Washing  $\rightarrow$  Treating with oxalic acid or hydrogen peroxide to remove brown manganese oxide.

Or

Washing/abrasion $\rightarrow$  PP spraying $\rightarrow$  Treating with oxalic acid or hydrogen peroxide to remove brown manganese oxide.

PP spray is used for making a specific abraded area to appear whiter than the background indigo colour shade. This can be applied by a spray gun or a towel dipped in PP solution and rubbed on the desired area, followed by neutralisation in a wet process. This process can be done right after doing hand scraping/sanding/blasting or in the middle of the washing. Doing this after enzyme washing or bleach washing cycle gives more natural and white effect (Rai, 2009).

Potassium permanganate spray is best done in specific spray booths, where rubber dummies (manikins) are installed for holding denim garments. The garment is mounted on a dummy and air is filled so the garment is full-fit exposed. Specific dummies are used for different sizes and styles, such as for children, trousers, jackets and shirts. The booths are fitted with a proper air exhaust system. This system has a treatment room where the chemicals and air are mixed and the material is usually pass through water showers. PP is dissolved in water and clean air is blown. Shower water is further treated with mild quantities of a neutraliser before adding it to the main drain. But if the PP spray is used in low concentrations, there is no need to treat the fabric with shower water. This mild PP mixed water is rather useful for water reservoirs to keep the water clean and germ free.

PP spray concentrations range from 2% to 5% depending upon the required results and fabric types. Usually, indigo dyed fabrics are treated with low concentrations of PP, whereas black sulphur fabric requires high concentrations. Sulphur is not much affected by PP and hence requires high concentrations and sometimes even multiple sprays. It is more effective to add PP brushing to aid in the spray effect. It is very important to equip the operator with gloves, a gas mask and goggles. Breathing in PP spray over a long period may cause health complications, so proper preventive measures need to be taken (Denim Help, 2010a). Denim garments are mounted on air filled rubber dummies or mannequins and chemicals are sprayed on blasted areas. The variables in spray process are as follows (Denim Help, 2010a):

- Distance of spray gun to garment: less distance gives a more defined and sharp effect, whereas spray from a larger distance results in a more mild and merged effect. Distance ranges from 30.48 to 76.20 cm.
- Air to water ratio of gun: this is to be set very carefully. Low air pressure can result in PP drops on denim garments, causing bright white spots, whereas high pressure produces very few bright effects on areas where it is not required.
- PP concentration controls the extent to brightness.

#### 11.2.10 Brushing/grinding

Brushing/grinding (manual or mechanical) is used manually or mechanically for the worn-out effect, abraded look or used look. Some mechanical processes have been developed that are based on mechanical abrasion by which the indigo can be removed. Some of these processes are sueding, raising, immersing, peaching and brushing. Advantages of these processes (Zhao, 2008; Lin, 2009) are as follows:

- · Control of the abrasion.
- Different looks on the garment can be achieved.
- All are dry processes.
- · Economical, ecological and environmentally friendly.

Brushing is generally being done in a rigid form of garments to get the distressed look. Locations can be front thigh and seat or it can be overall/global application as is standard. In the case of hand brushing, emery paper is used to brush the garments in particular places and designs. Emery paper comes in different numbers, generally starting from 40 to 600 and higher; the higher the number the finer is the emery paper (i.e. a lower is a more coarse paper). In the garment industry, 220, 320 and 400 paper numbers are most popular and widely used (Rai, 2009).



Figure 11.7 Marking the location for brushing.

The purpose of this process is to impart a used worn look to the garments. The most important factor of brushing is to select the right sanding material according to the fabric strength and the intensity needed. Figures 11.7–11.9 show the brushing process in factory.

Grinding is done on pocket edges and bottom hems edges by rubbing them against an abrasive surface or stone to achieve a worn effect. Many different makes of machines and pen grinding tools are available in the market which run with pneumatic systems. Figures 11.10 and 11.11 show the grinding effect on pocket edges and bottom hems, respectively.

#### 11.2.11 Whisker

Whisker is one of the most important designs of used look denim garments and is taken from the worn out lines and impression patterns generated by natural wearing on hips and the front thigh area. In old jeans, several patterns can be found consequential to fabric, body shape of user or sitting posture (Denim Help, 2010b). There are two types of whiskers: two dimensional (2D) and three dimensional (3D) (Lin, 2009; Zhao, 2008).

#### 11.2.11.1 Two dimensional whisker

Various methods are designed to create a 2D whisker impression on jeans. Mostly, rubber balloons (e.g. manikin) are available with different pattern designs. Garments are mounted on balloons and filled with air to get whisker impressions. The garment is scrubbed over



Figure 11.8 Hand brushing.



Figure 11.9 Mechanical brushing.



Figure 11.10 Grinding mark on a pocket edge.



Figure 11.11 Grinding mark in a bottom hem.

the pattern carefully with sand paper on engraved pattern lines. This operation requires highly skilled labour who can handle uniformity and sequence in whisker lines. Fabric may get damaged during rubbing if care is not taken. But this method is more successful in industries where similar articles are produced in large quantities. This method is famous for high quality and cost effectiveness (Lin, 2009; Zhao, 2008; Denim Help, 2010b).

Engraved patterns on thick board like hard rubber sheets are widely used for imprinting whiskers. The idea is very simple, to draw lines on rubber sheets and engrave them with a blade. The garment is placed on a sheet and scraped on a specific area to draw this impression. Because of the low cost patterns, it is most frequently used in small industries, especially where the production is not consistent to style. In some workshops, it is done manually with the help of sharp edges rolled on fine wood sticks pasted on plastic material. Before starting, placement and pattern must be marked on the garment to help the operator execute the pattern correctly to match the aesthetics of the garment (Denim Help, 2010b). Figures 11.12–11.14 show the operation of producing 2D whisker manually. The basic steps of 2D whisker making in denim garments are as follows:

Sanding/grinding (manually or mechanically) $\rightarrow$  Desizing $\rightarrow$  Washing $\rightarrow$  Softening.

# 11.2.11.2 Three dimensional whisker

The 3D whisker is an aesthetic 3D effect (Figure 11.15) where resin (formaldehyde free) is used for achieving the 3D effect and a rigid look. This process can be done by spraying or dipping the garments into resin, catalyst, silicone and polyurethane in the



Figure 11.12 Sandpaper wrapping on a wooden stick.



Figure 11.13 Sanding of denim jeans.

right combination, according to the fabric strength and the desired effect (Rai, 2009; Hu and Fang, 2008).

After applying resin solution in the right proportion, a design is made manually or mechanically on the thigh, hip and behind the knee area to get 3D effects such as crease or fold. Then it is manually dried with hot press or hair dryer and is cured in an oven at the right temperature, with time being as mentioned in resin product manuals. If resin is not cured properly, the 3D effect is not permanent and can cause skin irritation/rashes to the wearer. Highly skilled operators are needed to execute this process in order to get consistency and uniformity (Rai, 2009).

The whole garment can have a crushed look after it is dipped in resin and crushed manually, followed by oven curing. Silicone plays an important role in getting a softer hand after oven curing. Special streaky effect and crackles are also achieved by



Figure 11.14 Finished jeans with whiskers.



Figure 11.15 Two and three dimensional whisker effects.

applying resin on the desired area, followed by scraping and potassium permanganate spray and then neutralisation (Hu and Fang, 2008). The basic steps of 3D whisker making in denim garments are as follows:

Spraying/dipping with resin $\rightarrow$  Making 3D effect $\rightarrow$  Drying $\rightarrow$  Curing.

# 11.2.12 Ozone fading

Ozone typically acts as a mild bleaching agent as well as a sterilising agent. In this technique of denim washing, the garment is bleached with ozone dissolved in water in a washing machine. However, this technique can also be carried out in a closed chamber by using ozone gas. The advantages of this method are: (1) a minimum loss of strength and (2) it is a simple method that is environmentally friendly. The ozonised water after laundering can easily be deozonised by ultraviolet radiation. Nowadays, ozone fading can also be achieved by plasma equipment (Jeanologia, 2011; Cheung et al., 2013a,b). Under the influence of plasma treatment, high energy electrons are formed. Some of the high energy electrons react with moisture in air and a mixture of radicals is generated (Zhang et al., 2008).

During the generation of ozone plasma, a combination of charged particles, free radicals and ultraviolet light is generated. The ultraviolet light, being the by-product of the plasma treatment process, also contributes to production of the •OH radical. Hydroxyl radical •OH is the most oxidative radical among radicals generated in the plasma process and is the main radical responsible for degradation of indigo dye in textile materials. The •OH can oxidise indigo dye molecules (RH) producing organic radicals R•, which are highly reactive and can be further oxidised (Khraisheh, 2003; Khan et al., 2010). As a result, the colour fading effect of the indigo dyed textile is achieved.

The K/S (in which K is the absorption coefficient at a specific wavelength and S is the scattering coefficient) values of different treated denim fabrics are shown in Table 11.1 (Kan and Yuen, 2012). From the results, it is noted that the differently treated denim fabrics have lower K/S values than the untreated denim fabric. The K/S value is linearly related to concentration of the colourant in the medium and it can be concluded that a paler shade is obtained after different treatments. Without the cellulase treatment, the plasma induced ozone treated denim fabric has a paler shade than the enzyme desized denim fabric because during the plasma induced ozone treatment, ozone oxidises indigo dyes on the denim fabric surface leading to a colour fading effect (Ghoranneviss et al., 2006;

| Fabric sample  | K/S value |
|--|-----------|
| Untreated  | 430.58    |
| Plasma induced ozone treated                                 | 382.18    |
| Enzyme desized   | 425.46    |
| Plasma induced ozone treated followed by cellulase treatment | 365.32    |
| Enzyme desized followed by cellulase treatment               | 378.90    |

#### Table 11.1 Colour properties of different denim fabrics

Kan and Yuen (2012).

Kan and Yuen, 2012). However, in the case of enzyme desizing, the enzyme only reacts with the sizing material at the fibre surface and no breakdown of indigo dyes molecules occurs. Therefore, no significant shade change takes place. In the case of cellulase treatment, cellulase in the aqueous medium can penetrate effectively into the denim fabric. The enzymatic hydrolysis induced by cellulase in the plasma induced ozone treated denim fabric is more severe than the enzyme desized denim fabric. As a result, the cellulase treatment for plasma induced ozone treated denim fabric gives a paler shade than the enzyme desized denim fabric.

#### 11.2.13 Laser treatment

The  $CO_2$  laser treatment has been used in different areas of textile industry for several years because it allows short time surface designing of patterns with good precision, desirable effects, various sizes and intensity without causing much damage to the bulk properties of the textile materials (Hung et al., 2011, 2014; Ondogan et al., 2005). The  $CO_2$  laser treatment, considered a dry treatment, can be applied to textile materials as an alternative to conventional wet treatments such as stone washing, sand washing and bleaching for achieving faded look and worn out effects (Dascalu et al., 2000; Ozguney, 2007; Tarhan and Sariisik, 2009). In the case of denim fabric,  $CO_2$  laser treatment is proved to be an effective method for fading the colour from denim fabric surface in a short time depending much on the laser process parameters (Kan et al., 2010; Kan, 2014). Figure 11.16 shows the colour fading effect on denim fabric under the influence of various combinations of resolution and pixel time (Kan, 2014). It is clearly shown that with increase of resolution and pixel time, the colour fading effect in the denim fabric increases accordingly.

# 11.2.14 Waterjet fading

Hydrojet treatment has been developed for patterning and/or enhancing the surface finish, texture, durability and other characteristics of denim garments (Shalini, 2013).

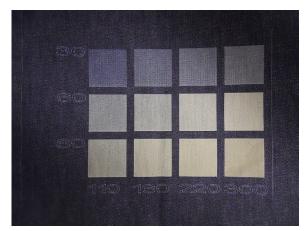


Figure 11.16 Effect of resolution and pixel time on colour fading.

Hydrojet treatment generally involves exposing one or both surfaces of the garment through hydrojet nozzles. The degree of colour washout, clarity of patterns and softness of the resulting fabric are related to the type of dye in the fabric and the amount and manner of fluid impact energy applied to the fabric. Particularly good results are obtained with blue indigo dyed denim. As this process does not involve any chemical, it is pollution free. A water recycling system can make this a very economical and environmentally friendly way of denim processing. Colour washout of dye in the striped areas produces a faded effect without blurring, loss of fabric strength or durability, or excessive warp shrinkage.

# 11.2.15 Dip dyeing

In dip dyeing, dip dyeing machine is used to achieve special effects on denim garments (AKDMKS, 2009). Direct dye is commonly used but the colour fastness is comparatively poor and therefore fixation is required to improve fastness. Pigments can also be used for dip dyeing. If a bleaching agent is used, bleaching effect can be achieved on garments.

## 11.2.16 Pigment washing

Pigment washing is generally used on pigment dyed or printed garments by applying pigments. Pigment washing is required for the following reasons (Lin, 2009; Kiron, 2012a):

- · To get fading effect/old looking effect on garments and also the seam area.
- For a soft feel to wear the garment after purchasing.
- · To achieve the buyer's washing standard.
- To increase the colour and rubbing fastness.

The basic steps of pigment washing are as follows:

Immersing garment in pigment  $\rightarrow$  Drying  $\rightarrow$  Baking (130–150 °C)  $\rightarrow$  Washing (with or without pumice stones/with or without enzyme, 30–90 min)  $\rightarrow$  Washing twice with water at 70 °C  $\rightarrow$  Removing stones  $\rightarrow$  Softening  $\rightarrow$  Drying.

# 11.2.17 Tinting

After denim jeans have been faded, they are dyed with very light colour (0.001% or 0.002% yellow or pink). This dyeing process is called tinting/overdyeing (Lin, 2009; Zhao, 2008; Kiron, 2012b) that is applied only on garments, not in fabric or yarn. The reasons of tinting are:

- For making new fashion designs.
- To give the finished garments a better appearance.
- For inventing a new process.

A very small amount of dye is used in tinting (Kiron, 2012b). The process changes the hue/cast/tone of indigo. As soon as the tinting colour covers up the indigo, it reaches the level of dyeing. Tinting gives garments a used/vintage and muddy look. This process takes from 5 to 15 min and for better results it is followed by dye fixing and clean up of the superficial dye. Dyeing is done on very light shades of indigo, grey denim and ready for dyeing denim. There are various types of dyes that can be used for tinting: (1) direct dyes; (2) reactive dyes; (3) pigment colours; and (4) sulphur dyes. The basic steps of tinting of denim garments are given in Table 11.2 (Lin and Liu, 2009; Kiron, 2012b).

#### 11.2.17.1 Tinting without changing indigo tone

Tinting is achieved by applying direct/reactive dyes. In the case of direct dyes, the second application is dye fixing agent for adequate fastness. In case of reactive dyes, the fixing chemical goes along with the dyestuff. After the application, the treated garment is dried in the air or in a tumble drier for adequate fastness. If tinting is done by the immersion method, the tint is all over the garment. However, if a localised area is the target, a spray method is used. In either case, tinting, as the term signifies, is done very lightly to achieve a particular cast, either overall or localised. If indigo does not change tone, it looks like a print with a sharp boundary. When tone changes the fading gradient, the effect looks more aesthetically appealing and is considered desirable. The tone change should be gradual and not abrupt (Kiron, 2012b).

#### 11.2.17.2 Tinting with white discharge effect

The standard route to blasting (scraping)/discharging/tinting is quite elaborate, considering three effects are imparted to the same garment. There have been shortcuts, which may be right/wrong/ingenious. If tinting is done on blasted/discharged areas,

| Desizing→Bleach washing/enzyme washing→Tinting <sup>*,†</sup> →Rinsing (25 °C, 2 min)→Colour fixing→Rinsing (25 °C, 2 min)→Softening→Hydroextracting→Drying. |  |  |  |
|--|--|--|--|
| *Tinting with direct dye:  |  |  |  |
| Direct dye<br>Salt<br>Temperature<br>Time  | ×g/L<br>3g/L<br>60°C<br>6 min                |  |  |
| <sup>†</sup> Tinting with sulphur dye:<br>Sulphur dye<br>Sodium sulphide<br>Temperature<br>Time  | × g/L<br>0.85 × g/L<br>90–95 °C<br>20–30 min |  |  |

#### Table 11.2 Tinting with direct and sulphur dyes

it obviously remains a spray method. However, if the tinting is overall, it follows the dyeing route. The process starts on grey denim garments being hand blasted (scraped), followed by desizing and enzyme washing. After drying the garment, a tint spray is followed by air/machine drying and finishing. For tinting by dyeing method, the enzyme washed garment can straight away go for tinting wet-on-wet followed by finishing and drying (Kiron, 2012b).

In the case of white discharge tinting, the route starts with desizing-enzyme washing of grey garment. After drying the garment, a potassium permanganate spray is applied to areas where the white discharge is required. After air drying for about 10–15 min, a neutralisation step consisting of providing acetic acid is applied, which is followed by hot and cold rinses. In the case of spray tinting, the garment has to be dried first, whereas for overall tinting, dyeing can be followed wet-on-wet. Finally the finishing and drying complete the process (Kiron, 2012b; Lin and Liu, 2009).

#### 11.2.18 Tie dyeing

In tie dyeing, a rubber band or similar material is used to tie/bunch the denim garment to make different patterns (Zhao, 2008; Lin, 2009). Then when carrying out dyeing with a direct dye, the dye cannot enter the tied portion. After dyeing, patterns can be created and fixation is needed. Pigments can also be used in tie dyeing. If bleaching agent is used, bleaching effect can be obtained, which is called 'tie bleach' (Denim Trends, 2013).

## 11.3 Denim and jeans washing machines

In the past decade, there have been many developments in denim washing machines. Many machine manufacturers offer various kinds of denim washing machines. This section summarises the development of different denim washing related machines exhibited in the International Textile Market Association 2007 (Kan and Yuen, 2008) and International Textile Market Association 2011 shows by different manufacturers (Kan, 2012). For more information related to the recent development in denim washing machines, please visit the manufacturers' Websites.

#### 11.3.1 AVANTEC

The *Turbo Pintora* garment dyeing machine from Avantec S.R.L., Italy, has different operating volumes (Avantec S.R.L., 2007a), 1300L (*Turbo Pintora 1.3*), 2200L (*Turbo Pintora 2.2*), 3100L (*Turbo Pintora 3.1*), 4100L (*Turbo Pintora 4.1*) and 5000L (*Turbo Pintora 5.0*). The machine is driven by two motors to provide maximum basket rotation flexibility and has a self-balancing system with special electro-pneumatic shock absorbers to ensure perfect stability during the centrifuging phase. It has special fixed and removable beaters to ensure the most appropriate movement of the garments. The *Turbo Pintora* allows very low liquor ratios. The machine can be equipped with a colour kitchen which includes: (1) a tank for chemical products introduction; (2) a tank for dissolving and introducing dyestuff and (3) a tank for dissolving and dosing auxiliaries. All of these systems are controlled by a microprocessor. The *Super Pintora* is a new dyeing system that reduces the dyeing time; consequently, there is a considerable reduction in the relevant dyeing costs of about 30% (Avantec S.R.L., 2011a). The *Super Pintora* can work at a very low bath ratio, between 1:4 and 1:5, and can avoid those annoying problems of abrasion and mechanical friction of the garments that industrial washers often have.

The *OLA LIMPIA* washing machine is an industrial 'Superspin' machine for readymade garments. It is particularly suited to water washes, 'stone wash' treatments with enzymes and chemical treatments (Avantec S.R.L., 2007b). In this washing machine, a microprocessor permits manual and automatic control of all machine functions. *Solarium* is constituted by a 'double mannequin', one opposite to the other, rotating 180° and a drying area, in which the 3D effects are fixed at a maximum temperature of 80 °C (Avantec S.R.L., 2011b). After that, complete polymerisation of the resin is done in a traditional static oven, the versatility of this machine allows easy and simple interchangeability (less than 1 min) of the manikins, to perform, besides the traditional horizontal moustaches, also new 3D effects like the new diagonal moustaches or analogous applications on jackets and sports jackets.

*Diablo* laser machine with software permits change of parameters like power, frequency and speed to reproduce on the garment any kind of effect, like personalised drawing, images, trading marks, whisker effect and stripes (Avantec S.R.L., 2011c).

#### 11.3.2 BRONCO

BRONCO S.R.L., Italy, provides different machines for washing and dyeing of readymade garments. The rotary machine model *LCOs* are machines designed for all kinds of treatments on ready made garments such as enzyme stone wash, rinsing, softeners, milling and dyeing. Front loading washing machines are particularly designed for treatments such pumice stone wash (Bronco S.R.L., 2007).

#### 11.3.3 BLASTEX

BLASTEX, Brazil, offers different jeans finishing systems (Blastex, 2007a). The *BPR100 Compact model* is a single head compact form thermic press. The *BPR150 Simple model* has a single Teflon covered head and large format thermic press. The *BPR200 Twin compact* is a double Teflon covered head and compact form thermic press. The *BPR200 Twin compact* is a double Teflon covered head and compact form thermic press. The *BPR200 Twin compact* is a double Teflon covered head and compact form thermic press. The *BPR200 Twin compact* is a double Teflon covered head and compact form thermic press. The *BPR200 Twin compact* is a double Teflon covered head and compact form thermic press. The *BPR200 Twin compact* is a double Teflon covered head and compact form thermic press. The *BPR200 Twin compact* is a double Teflon covered head and compact form thermic press. The *BPR200 Twin compact* is a double Teflon covered head and compact form thermic press. The *BPR200 Twin compact* is a double Teflon covered head and compact form thermic press. The *BPR200 Twin compact* is a double Teflon covered head and compact form thermic press. The *BPR200 Twin compact* is a double to a digital time and temperature control. The *BPA 700 Thermic* is a double head thermic press for wrinkle effects. This machine is fully automatic, controlled with pneumatic actuation with digital programmable-logic controller to program, time, speed and temperature. The *C1* is a dextramer with pneumatic auctioning that produces popping or popcorn effect with quality and repeatability. The *X2* is a hand sanding equipment with vertical double dummy hand sanding system, rotating and articulated dummies, equipped with trigger action and rotating sandpaper cartridges brush supported by ergonomic balancer with

more productivity and less effort. The *L2eL2 automática* is a horizontal hand sanding dummy with two rotating articulated and inflatable legs. It is easily hand manipulated with automatic pressure controller for inflatable dummies. The *J1* works in vertical and horizontal positions. The dummy rotates, allowing brushing on both sides. The movements and inflation are controlled by a pedal. The *Laser Smart 250* is a laser engraving machine operated with 250W plus auto focus correction mirrors marking technology (Blastex, 2007a). The laser machine is equipped with height and printing area digital adjustment. The *P3 Dry Spraying Cabin* consists of twin dry filter cartridges with easy filter cleaning system so that 98% of potassium permanganate can be retained (Blastex, 2007a). This machine is operated with pneumatic ergonomic pedal trigger for faster application and higher production speed. The series *WAVE* is a washing machine suitable for all kinds of washing processes on ready-made garments (Blastex, 2007b).

#### 11.3.4 CELIKHAN

CELIKHAN, Turkey, offers *A6 Jumbo* washing machine which provides advantages of: (1) saving 50% of process time and producing effects or bleach without using any chemical substance; (2) reducing 90% of chemical substances, 60% electricity and labour cost; (3) eliminating back staining problems; (4) cleaning the agricultural wastes; and (5) providing the effects from grey to blue bleach on the same garments (Celikhan, 2011).

#### 11.3.5 CIBITEX

CIBITEX S.R.L., Italy, offers denim finishing plants which consist of machines for finishing and achieving dimensional stability on denim fabric (Cibitex S.R.L., 2007). CIBITEX denim finishing lines lead to a flawless result as regards final dimensional stability. To obtain a flawless shrinkage and facilitate the shrinkage of this fabric, it is necessary that moisture penetrates into the cotton fibre with a residual moisture percentage (before entering the shrinkage unit) ranging from 13% to 15%. The best system to achieve this moisture content is full impregnation followed by drying adjusted by a moisture control system which ensures the requested moisture percentage.

#### 11.3.6 GFK

GFK, Spain (a brand under Jeanologia), developed high technology solutions for garment finishing (GFK, 2007). The *MAORI* is customised dyeing machine which allows the user to achieve a number of different garment dye effects on wool, cotton and its blends. The *MARGARITA* is an automatic machine for industrial use aiming at obtaining 3D effects (3D scratch) such as round shaped moustache and back knee effect on trousers. Its unique technology offers various applications with the features: (1) a single operator working the machine; (2) the whisker form is made in 5 s; and (3) production up to 40–50 garments per hour. The *SCRUNCH* is a high speed garment packing machine for tie-dye, tie-bleach and other localised permanent wrinkling. The *POPPING* is a high performance fabric punching machine to create personalised break points on garments in automatic mode with the features of: (1) automatic mode adjustment; (2) needle penetration adjustment; (3) needle holding mould; and (4) easy garment handling. The *KNEEMATIC* is a machine for permanent fabric widening to produce authentic bombed knee effect. It is the first and unique technology to create vintage knee shape on denim and twills. The *TECA* is a machine for creating authentic 3D wrinkles on any area of the garment (moustache, back knee, waist belt, bottom, etc.). The *FGM* is a fabric grinding machine with the fastest and most controllable technology of GFK for automated warp removal to achieve vintage worn effects and breaks on garments.

## 11.3.7 JEANOLOGIA

JEANOLOGIA, Spain, (Jeanologia, 2011) presents the *Plug & Design system* for laser treatment which allows creating and improving the art of jeans without waste of time in preproduction. The *Rotatex Technology* is a rotating table with transition in 1.3 s with absolute precision in laser treatment. The *G2* is a colour fading technology which can be considered as an ecological production process without (1) any toxic emissions to the atmosphere; (2) any water consumption; (3) any toxic dumping; (4) any chemicals consumption; and (5) large energy consumption (reduce more than 65% energy for 100 kg of fabric).

## 11.3.8 Laser system technology

Laser System Technology, Turkey offers the *LSTTEX laser system* which provides efficient, fast and cost effective solutions for all localised abrasion needs on garments (Laser System Technology, 2011). Creating authentic looking garments with whiskers, chevrons, damages and 3D effects is easy with the system. Multipreview mode and continuous printing is used and while one design is being printed, a second design is visually marked on the printing area with a second marking head so that the operator can exactly position the next garment to the subsequent printing area. This feature virtually eliminates manipulation time and thus increases production. Automatic filed size and height adjustment are available and therefore no lenses are needed to be changed during operation.

## 11.3.9 OMI washing machinery

OMI Washing Machinery, Italy, offers automatic systems with modules for washing, stone washing, spinning and drying with automatic garment loading and unloading. The *LSCO 360 TSM High Speed Machine* is a machine for garment dyeing with loads varying from 40 to 200 kg (OMI Washing Machinery, 2007). This system is made of a motor driven pump with variable pressure, which picks up the dip from the machine, filters it and injects it with adjustable pressure through 500 nozzles distributed and mounted on the axis and also on the two lateral sides of the rotating basket of the machine. The radial injection takes place on the centre and on the length of the basket towards the external side and from the lateral sides to the opposite ones, creating a cross injection of the dip that permits a high dyeing

penetration on garments in a short time. The machine is extremely versatile even with very delicate garments.

#### 11.3.10 TUPESA maquinaria textil

TUPESA, Spain, offers a wide range of machines for garment processing (Tupesa Maquinaria Textil, 2007). For the washing process, washers model Stone is available from TUPESA which is a frontal machine for washing and treating garments with enzymatic and stone wash processes. The TUPESA wrinkle free curing ovens (e.g. WF-80-Gas) are specially designed for the processes and finished garments that need a curing process at high temperature. Its exclusive design guarantees a constant and homogenous circulation of the internal air, obtaining identical temperature in all its compartments. TUPESA makes several models of curing ovens with capacities from 10 to 80 garments and with production of 40–80 garments per hour at temperatures of up to 180 °C. The TUPESA curing ovens have a movable hangers system, divided in one or two internal departments depending on the model. The heating system can be operated by electricity or by gas. TUPESA also provides different types of mannikins for treating and brushing jeans like trousers or jackets which is easy to use and install. An independent blowing system is used with fast and simultaneous air discharge from both legs through a special wide opening drainage valve. Manual or pneumatic system clutches with blocking system in every position.

#### 11.3.11 TOLON

TOLON, Turkey, provides machines for garment processing (Tolon, 2011). The *Pro Wash series, THW 150, THW 300, THW 400 and THW 500* are heavy service machines used in stone washing and bleaching of denim garments. They are also used for rinsing and enzyme washing operations. The *Comfort Wash* washing machines, *THW 150CW, THW 300CW and THW 400CW*, are manufactured for the same use with *Pro Wash* washing machines and the same properties. They are different from *Pro Wash* machines in that they offer simplified compact structure, reduced drive system and maximum 40 rpm pre-extraction. This is also a heavy service machine type used in stone washing and bleaching of denim garments. It is also used in rinsing and enzyme washing operations.

#### 11.3.12 TONELLO

TONELLO S.R.L., Italy, offers garment finishing equipment (Tonello S.R.L., 2007a). The *Professional Compact* series are garment dyeing machines with a high speed and jet system. The garment dyeing machines are equipped with variable speed, extraction as well as automatic balancing system. They work with open basket and with the high speed dyeing system.

The *Brush Robot Model E4* (Tonello S.R.L., 2007b) has been developed for automatic brushing of jeans, that is to give them a 'used look' effect. This system is a valid alternative to the sand blasting or chemical processes. It is equipped with four brushes, two in front and the other two on the rear part of the jeans. To reduce down time, the machine is complete with two mannikins and so loading and unloading operations can be performed while the machine is working. The *Brush Robot Model E5* (Tonello S.R.L., 2007b) is used for automatic brushing of jeans that is to give them a 'used look' effect. This system is also a valid alternative to the sand blasting or chemical processes. Different from the *Brush Robot Model E4*, this machine works with one brush controlled by an anthropomorphic robot. One column, placed in the centre of the machine, supports a rotating device with three mannikins. One mannequin is in a loading and unloading position and the other two are in working positions. Different effects can be obtained using different types of brushes and changing their working conditions.

The *Bohemia* is an automatic spraying system and resin spraying can be done manually or automatically for producing: (1) spray wash effect and (2) 3D effect (Tonello S.R.L., 2007b). This system can also create special '3D Real Look' effects on the garments. The spraying on garments like jeans, jackets and shirts, etc., of chlorine derivatives, pigments and resins has the function to create on garments themselves special effects and particular finishing.

TONELLO has added a new manual equipment brand that sprays and brushes jeans, jackets and shirts, etc. The equipment mainly includes a spraying booth and accessories for manual spraying and brushing (Tonello S.R.L., 2007b). Spraying booths are of dry type with 'paint stop' filtering panels which can be easily removed for cleaning or replacing. They can be equipped with manikins from one to four. The booths are supplied with a differential pressure switch to signal filter clogging, lighting and electric board as well as with one or two centrifugal fans in relation to their sizes. The *LASER BLAZE* is a machine for treating denim and dyed garments with a laser (Tonello S.R.L., 2013). The action of the laser produces variations in intensity of colour and so produces a greater variety of different imaginative effects, images and designs. The intensity of the results depends as much on the power of the laser as on the characteristics of the fabric.

#### 11.3.13 VAV technology

VAV Technology GmbH, Germany, offers the *Picasso SS 330* robotic system (VAV Technology GmbH, 2011). With its two pieces of robotic arms and two modelled loading system, *Picasso SS 330* is two times faster than humans. Although humans have difficulty in spraying with one hand, *Picasso SS 330* reaches a production speed which humans can never reach by putting the right part of the trouser on one arm and left part of the trouser on the other. A process which takes 80s for a human is completed in 40s with *Picasso SS 330*. The *X-burner SR series* is an economical 3-Axis Galvo laser machine with its modern and ergonomic design (VAV Technology GmbH, 2011) and the specially designing Galvo Optical System. It can be used for denim and leather cutting. Its two-axis pointer system provides great speed and convenience in product locating. Although the operator places four to five jeans at once on the sliding stand depending on size of the model, the machine can burn four to five jeans preplaced on the other stand. Because this placement is very fast with the two-axis laser pointer, one operator can operate two *X-burner R series* laser machines by himself.

#### 11.3.14 YILMAK

YILMAK, Turkey, offers different types of wet processing machines for garments. The *OZYY* ozone washing machine is a high technology machine that uses ozone for bleaching, various finishing processes and to clean back staining in indigo dyed textiles (Yilmak, 2007a). The *HBM 50* is designed for sample washing and dyeing processes in laboratories with flexible construction which provides a wide range of loads for a wide range of treatments (enzyme, washing, reactive and direct dyeing, etc.) (Yilmak, 2007b). The *HBM 50* is installed with a heating battery for indirect heating as a standard unit. The *HBM 3860* (Yilmak, 2007c), *HBM 3860S* (Yilmak, 2007d) and *HBM 3860C* (Yilmak, 2007e) series are open pocket washing machines especially designed for denim and gabardine garments; stone, enzyme and/or any other washing treatments for best results with various drum rotation speeds, that is 0–125 rpm for *HBM3860* and 0–40 rpm for *HBM 3860S and HBM 3860C*.

The *Carousel Spray Robot* is a system designed and manufactured to spray on jeans, jackets and shirts various chemicals such as chlorine derivatives, pigments and resins (Yilmak, 2007f). It includes one robot and an overhead carousel with 12 mannikins. It reduces labour cost and increases efficiency. The system includes: (1) carousel designed and built mainly to carry out spraying and painting operations; (2) easy use which reduces labour cost and increases efficiency; (3) spraying system including a spray gun which includes pump, pressure regulator and connection equipment; and (4) spraying booth type of 'water curtain' with a special filter where the overspray is eliminated by the water curtain. The *Spraying and Brushing Booth* (Yilmak, 2007f) is also designed and manufactured for spraying on jeans, jackets and shirts various chemicals such as chlorine derivatives, pigments and resins. The *H1 106 Used Look machine* is designed for dry fashion treatment by special brushing device and pattern (Yilmak, 2007g). With the adjustable pressure, different special worn effects can be obtained.

#### 11.3.15 MACTEC

MACTEC, Italy, offers a wide range of washing equipment for denim garments (Mactec, 2013). The Margherita machine HD and Oven 2000 provides the path for 3D whiskers process in which 24 dummies are available in the Margherita machine. The 'Icelite' process makes use of carbon dioxide as a finishing agent to achieve similar effect as potassium permanganate spraying. In addition, the spray cabin system provided by MACTEC equips with weighing system to measure the exact quantity of resin sprayed on each part of denim garments.

# 11.4 Factors affecting washing effect

#### 11.4.1 Method of desizing

The Kubelka–Munk theory can be used for measuring the colour yield of denim fabrics washed with different desizing methods. The Kubelka–Munk theory states that colour yield (*K*/*S*) can be measured by  $K/S = (1 - R)^2/2R$  where *K* is the absorption coefficient at a specific wavelength; *S* is the scattering coefficient; and *R* is the reflectance at a specific

| Desizing method         | <i>K/S</i> value after bleach washing |
|-------------------------|---------------------------------------|
| Unbleached normal denim | 11.96                                 |
| Amylase enzyme desizing | 4.41                                  |
| Detergent               | 4.49                                  |
| Hot water               | 5.59                                  |

Table 11.3 Effects of desizing methods on the washing effects

Kan (unpublished data).

wavelength. *K/S* values of denim fabrics can be measured at 660 nm (Hong Kong Apparel Product Development and Marketing Research Center, 2002). Table 11.3 shows the results of bleach washed denim fabrics pretreated with different desizing methods (Kan, unpublished data). The results indicate that the amylase enzyme desizing can generate the lowest *K/S* value which indicates that the colour yield of the bleached fabric pretreated with amylase enzyme desizing is the lowest, implying that bleached fabric pretreated with amylase enzyme desizing has the palest colour when compared with others. This indicates that amylase enzyme desizing is the most effective method to remove sizing agents from denim fabrics. On the other hand, undesized denim fabric has the highest *K/S* value which means the darkest colour. It is because the sizing agent covers the yarn surface which prevents the chemical reaction between enzyme and the sizing agents.

## 11.4.2 Bleach washing

Increased concentration of sodium hypochlorite can effectively accelerate the colour fading effect. Generally speaking, the active chlorine content in sodium hypochlorite has an optimum value to achieve the best colour fading effect. If the concentration of sodium hypochlorite is higher than this optimum value, no further improvement in colour fading is obtained. The recommended active chlorine content is 12% when concentration of sodium hypochlorite is about 40 g/L. In addition, increase in temperature increases the bleaching reaction to fade the colour from denim garments. The optimum temperature is 70 °C; temperature higher than 70 °C does not enhance colour fading effect (Hong Kong Apparel Product Development and Marketing Research Center, 2002). The pH value used for bleach washing also affects colour fading. When pH=7 or pH<7, the bleaching reaction is very fast and the degree of colour fading is very difficult to control. When pH=9–10 (adjusted by adding alkali), the bleaching effect can be controlled by the bleaching time (Hong Kong Apparel Product Development and Marketing Research Center, 2002).

## 11.4.3 Stone washing

## 11.4.3.1 Stone ratio

Stone ratio is defined as the ratio of the quantity of stones used to the quantity of goods being treated. For example: stone ratio=2:1 means a 2 kg stone is used when 1 kg of

goods are washed. Generally speaking, the higher the stone ratio, the better will be the colour fading effect because more stones abrade the denim garment surface to have good colour fading effect. However, too high a stone ratio may prevent rotation of denim garments inside the washing machine and hence abrasion gets decreased. As a result, the colour fading effect is not good (Hong Kong Apparel Product Development and Marketing Research Center, 2002).

# 11.4.3.2 Size of stones

Generally speaking, stones of smaller sizes have better colour fading effects. However, because of the small stone size, abrasion on the denim garments is more uniform (than with stones of larger sizes) which means the colour contrast produced by small size stones is not good (Hong Kong Apparel Product Development and Marketing Research Center, 2002).

# 11.4.3.3 Stone washing time

The washing time affects colour fading effect in the stone washing process. It is recommended that after 90 min washing time, the colour fading effect is not further enhanced (Hong Kong Apparel Product Development and Marketing Research Center, 2002). Too long a stone washing time can lead to fibre damage also.

# 11.4.4 Enzyme washing

# 11.4.4.1 Choice of cellulase enzyme

Acid and neutral cellulases are commonly used for washing. A total of 1/5 to 1/10 the amount of acid cellulase can achieve similar colour fading effect as neutral cellulase. However, acid cellulase may cause backstaining and cause a certain degree of fabric damage (Hong Kong Apparel Product Development and Marketing Research Center, 2002).

# 11.4.4.2 pH value

In enzyme washing, the pH should be adjusted to suitable values for specific enzymes; neutral cellulases are applied at pH 6–7, whereas acid cellulases are applied at pH 4.5–5.5. Also the temperature of the washing liquor should be controlled to prevent change in pH value during enzyme washing (Swicegood, 1994).

# 11.4.4.3 Concentration of enzyme

Generally speaking, enzyme concentration between 0.5 and 2 g/L gives the best colour fading effect provided the enzyme used for washing has sufficient enzyme activity. The enzyme activity decreases upon storage and thus the shelf time of enzyme should be noted before preparing enzyme washing liquor. Some manufacturers provide enzyme in powder and granule forms which may contain a stabiliser and buffer to maintain the enzyme activity for a longer time (Hong Kong Apparel Product Development and Marketing Research Center, 2002).

# 11.4.5 Machine design parameters

## 11.4.5.1 Rotation speed

Speed of the washing machine affects the washing and abrasion effect. Generally speaking, high rotation speed increases the contact between garment/garment or garment/pumice stone.

## 11.4.5.2 Drum diameter

When the drum diameter of the washing machine is larger, more space is available inside the machine. During washing, the contact time between garment/garment or garment/pumice stone increases, leading to a better washing and abrasion effect.

# 11.4.5.3 Machine load

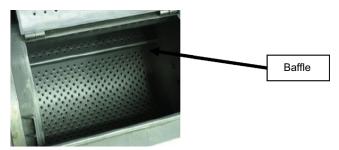
Machine load refers to the quantity of denim garments in a batch. Generally speaking, about 30–50% of space inside the washing machine is occupied by garments during the washing process. If the loading is too high, rotation of the garments inside the washing machine decreases and hence the washing and abrasion effect gets reduced. Moreover, if the garments are entangled together during washing, streak marks are formed.

# 11.4.5.4 Height of baffles

Baffles are the intrusions from the surface of the inner drum in a washing machine (Figure 11.17). The baffles help lift the garments from the bottom of the drum to the top before falling back to the bottom and into the washing liquor. If the height of the baffles is too low, they cannot carry the garments. The result may be a reduction in the total washing and abrasion effect in the final garments. If the height is increased, they can carry more garments and the washing and abrasion effects are improved.

# 11.4.5.5 Steaming

Steaming provides energy for the washing process and it helps better control of the temperature of washing instead of direct heating. Steaming is very important to control



**Figure 11.17** Baffle inside the washing machine. AKDMKS (2009).

the temperature of enzyme washing. If the temperature is too high, the enzyme gets deactivated but when the temperature is too low, the enzyme cannot function well.

#### 11.4.5.6 Liquor to goods ratio

Liquor ratio refers to the amount of washing liquor used based on the weight of denim garments to be washed. Generally speaking, if a large liquor ratio is used, garment movement inside the washing machine increases, leading to better washing and abrasion effect. However, usage of chemicals, water and energy also increase. On the other hand, if the liquor ratio is too short, usage of chemicals, water and energy decrease but movement of denim garments inside the washing machine is reduced and washing and abrasion effect becomes poorer. If the denim garments are entangled together, streak marks appear in the finished garments. Normally a liquor ratio of 10:1–15:1 is recommended but the ratio can be adjusted according to the desired effect.

# 11.5 Troubleshooting in denim washing

As with other textile dyeing and finishing processes, the quality of the final garments plays an important role in buyers' final decision of acceptance or rejection. There are a number of problems associated with denim washing (Li and Liu, 2013; Mei, 2009; Lin et al., 2012).

## 11.5.1 Washing marks

#### 11.5.1.1 Causes

- The fabric has synthetic fibres. During washing, the fabric becomes stiff. As a result, the stiff fabric abrades the washing machine, leading to washing marks.
- The fabric itself has creases formed during production or transportation. The existing creases are not removed before washing. Thus during washing, washing marks will form.
- The fabric was not wetted completely and the fabric was not evenly placed in the washing machine before starting the washing machine.
- The loose and long threads in the denim garments were not removed properly. Then during the washing process, the loose and long threads cause entanglement of the denim garments, leading to washing marks.
- The amount of water used for washing is too much or too little.
- Insufficient hydroextraction before drying or too much fabric being dried at the same time. Before drying, the denim garments were not properly placed in the dryer with too long a drying time and/or too high a drying temperature.

# 11.5.1.2 Remedial actions

- Before washing, fabric composition should be checked properly for synthetic fibres. In addition, existing crease marks should be found out.
- If possible, before washing, the garments should be completely wetted and placed evenly in the washing machine for washing.
- All loose and long threads must be removed before washing. The maximum length of loose threads should be less than 2 cm to prevent fabric entanglement during washing.

- The amount of water used for washing should be checked during washing. The washing machine may be stopped regularly to see whether there is entanglement during washing.
- The denim garments should be properly hydroextracted and placed evenly in the dryer for drying. The drying time and temperature should be carefully controlled.

## 11.5.2 Poor hand feel

#### 11.5.2.1 Causes

- Washing time: insufficient washing time may cause insufficient abrasion between denim garments. Generally speaking, longer the washing time, softer is the hand feel achieved.
- Washing method: different washing methods give different hand feels. For example, desized fabrics for stone washing have softer hand feel than nondesized fabrics for stone washing. However, if the washing process is not properly controlled, poor hand feel is the result.
- Amount of softening agent used for washing: there are many types of softening agents used for washing process, for example, nonionic type and cationic type. Generally speaking, cationic type softening agents are used in washing. However, silicone based softeners can also be used for washing. Nonsilicone based softening agents give good softness, whereas silicone based softening agents give good smoothness. Moreover, the amount of a softening agent used for washing should be carefully controlled. Although the more the softening agent is used for washing, the better the hand feel is, too much softening agent leads to wastage without improvement of hand feel.
- Softening process: softening treatment time and liquor to goods ratio affect the hand feel. Under normal circumstances, the softening process is carried out as an individual process. If rinsing and softening processes are carried out at the same time in the same bath, this leads to uneven rinsing and backstaining or insufficient hand feel. The softening process is generally carried out at room temperature (about 40 °C–60 °C) for 5–8 min. It should be noted that at too large a liquor to goods ratio, the amount of softening agent required is increased and the hand feel is not good. On the other hand, with too short a liquor to goods ratio, the softening agent may not be completely dissolved in water. The undissolved softening agent may cause 'oily' marks on the garment leading to 'seconds'.
- Drying time: the drying time affects the hand feel. Generally speaking, after washing, denim garments are hydroextracted to remove 80% of water content before drying. During drying, the amount of denim garments in the dryer should not be too great. Too many denim garments in the dryer need a longer drying time which increases the contact between the garments leading to backstaining.

## 11.5.2.2 Remedial action

- Washing time: proper control of washing time and checking the hand feel of the garments, if possible, during the washing process.
- Washing method: do preliminary trials to select the suitable washing method before the actual washing.
- Amount of softening agent used for washing: suitable softening agents should be selected, for example normal emulsion or microemulsion.
- Softening process: properly control the softening treatment parameters.
- Drying time: the drying time should be carefully controlled. Normally, about 95% water is removed in the drying process. After that, the denim fabric is cooled. The cooling time affects the hand feel. Too long a cooling time increases the contact between garments, leading to staining.

# 11.5.3 Backstaining in the pocket

## 11.5.3.1 Causes

- No antistaining detergent was added during the washing process. An example of backstaining is shown in Figure 11.18.
- The quality of washing chemicals is not good or the washing chemicals have lost functioning.
- Washing temperature is too high or too low in the case of enzyme washing, leading to deactivation or inactivation of enzyme.
- Hydroextraction was not properly conducted (water content in denim garments remains high) and the stacking time of hydroextracted fabric was too long. In addition, drying too many denim garments at the same time and at too high a temperature also cause backstaining.
- Insufficient rinsing and no rotation of washing machine during rinsing may cause backstaining.

# 11.5.3.2 Remedial action

- During washing, add antistaining detergent or increase the number of rinses and rotations in the washing machine during rinsing.
- In case of enzyme washing, the quality of the enzyme should be checked, for example for shelf time. In addition, washing time and temperature should be properly controlled.
- The hydroextraction and drying process should be carefully controlled.

# 11.5.4 Loss of elasticity after washing

## 11.5.4.1 Causes

• Spandex is a commonly used fibre in denim garments that increases the elasticity of the garment. At high temperatures, spandex decomposes, whereas with a strong alkali, it gets hydrolysed. Decomposition and hydrolysis damage the spandex, leading to loss of elasticity. Chlorine also damages spandex.



**Figure 11.18** Backstaining in the pocket. Denim Trends (2013).

# 11.5.4.2 Remedial action

- In desizing process, use enzyme instead of alkali for desizing.
- Generally speaking, the loss of elasticity is caused by a high water temperature in the washing machine during the washing process. Normally, the washing temperature should be kept at around 55 °C and should not exceed 60 °C. Otherwise, it produces irregular water marks.
- In the case of bleach washing, the amount of sodium hypochlorite used should be properly controlled.

# 11.5.5 Excess abrasion of background colour

# 11.5.5.1 Causes

• These situations are generally found in bleach washed, snow washed and enzyme-stone washed denim garments. In the washing process, if the washing time is not properly controlled, it causes excess abrasion of background colour. Once the background colour is overabraded in the washing stage, the following rinsing time should be shortened to reduce any further abrasion.

# 11.5.5.2 Remedial action

- To prevent excess abrasion, colour should be checked with the standard regularly during washing.
- · Before actual production, washing trial should be conducted to find the best condition.

# 11.5.6 Dimensional change after washing

## 11.5.6.1 Causes

• If the denim fabrics do not have proper shrinkage prevention treatment before being made into denim garments and jeans, dimensional change may occur after washing.

# 11.5.6.2 Remedial action

- If the size of the garment increases after washing, it may be put in the washing machine and washed with water only for gentle washing. This helps achieve a slight shrinkage in the denim garments. However, this gentle washing must not lead to colour change.
- Compressive shrinkage treatment should be conducted on the denim fabric. If the size of denim garment decreases after washing, it can be steamed inside the washing machine (without adding water) to improve the shrinkage problem.

# 11.5.7 Yellowing

## 11.5.7.1 Causes

• Yellowing of denim garments after washing is generally caused by excessive usage of sodium hypochlorite in bleach washing. If neutralisation is not carried out properly, the residual chlorine leads to yellowing.

- The unremoved impurities or metallic/mineral contents in pumice stones can possibly contribute to yellowing. Yellowing can also be caused from the softening agents. In addition, atmospheric contaminants/gases can accelerate the yellowing of washed denim on storage (Paul and Naik, 1997d).
- If the optical brightening process is not carried out properly, it causes yellowing.
- If the water used for washing contains a high amount of calcium or magnesium ion, it also causes yellowing.

# 11.5.7.2 Remedial action

- Neutralisation should be carried out thoroughly to remove residual chlorine after using sodium hypochlorite for washing.
- The operational parameters of optical brightening process should be properly controlled.
- The water used for washing should be free of hardness.

# 11.5.8 Odour

#### 11.5.8.1 Causes

• Odour is generally found in stone washing, bleach washing and enzyme washing. The main causes of odour are (1) insufficient rinsing; (2) incomplete neutralisation with residual chlorine; and (3) water quality used for rinsing is poor.

## 11.5.8.2 Remedial action

• After washing, denim garments should be properly neutralised and/or rinsed. Also, the water quality should be checked for washing.

# 11.5.9 Size marks

#### 11.5.9.1 Causes

• Size marks are generally found in stone washing, stone bleaching and stone abrasion processes. The cause of size mark is improper desizing which leads to incomplete desizing, that is uneven desizing or low desizing rate. Meanwhile, uneven sizing may also be a cause of size marks.

## 11.5.9.2 Remedial action

• The desizing process should be properly conducted and, after desizing, the residual size in the denim fabrics should be checked.

# 11.5.10 Damages

#### 11.5.10.1 Causes

• During washing, sharp parts in the washing machine may come in contact with the denim garments, causing damage. When using stones for washing, the stones may also get abraded along with the denim garment. Thus the quartz in the stone gets exposed and develops sharp points which may abrade on the garments leading to surface damage.

## 11.5.10.2 Remedial action

• When using stone, the hardness and size of the stone should be monitored to prevent excess abrasion which may cause surface damage.

## 11.5.11 Too light or dark final shade

#### 11.5.11.1 Causes

- Chemical variation occurs during the washing process or chemical variation occurs between each batch of washing.
- · Washing time and temperature are not properly controlled.
- Variation in colour of each lot of denim fabric.

## 11.5.11.2 Remedial action

- Check the concentration of chemical regularly to ensure that there is no loss of the function of chemical, for example enzyme activity of cellulase and active chlorine content in sodium hypochlorite.
- Conduct trial washing to minimise the colour variation between each lot of denim fabric and find the suitable washing condition. A trial run to find the variations of final shades in different lots of denim fabric after washing, as compared with the customer sample (black square) is shown in Figure 11.19.

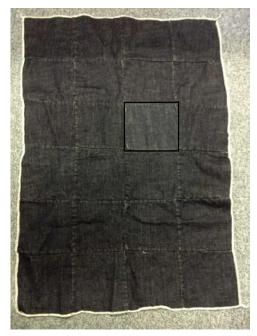


Figure 11.19 Variations of final shades as compared to customer sample. Note: black square: customer sample.

## 11.6 Future trends

The textile industry is striving to develop environmentally friendly wet processing techniques that can result in zero effluent discharge. Denim garment washing, being a type of textile wet processing treatment, cannot be separated from this trend for achieving sustainability. If the history of denim and jeans washing is reviewed, the washing depends much on the use of chemicals for achieving the colour fading effect. Even though enzymes have now replaced the oxidising agents to some extent, the process still involves water, and some chemicals may still be required to maintain the enzyme stability.

The dry treatments or nearly water free treatments are slowly becoming a sustainable trend for replacing traditional wet treatments in denim washing. Some of these techniques are promising and are commercially available such as laser treatment, ozone treatment and dry ice blasting. Laser treatment is a water free, colour fading treatment of denim and is an ecological and economical process. Laser can create local abrasion, fabric breaks and a used look effect with excellent reproducibility and higher productivity. Being an automatic system, chances of human error are eliminated in laser treatment. In ozone treatment, the ozone generated in the equipment can provide bleaching effect. Commercially available ozone equipment is operating like a washing machine, but without much use of water for the colour fading process. In dry ice blasting, the working principle is like sand blasting using abrasive materials. However, in this case, dry ice is used for the blasting. The advantage of using dry ice is that after blasting, the residual material is carbon dioxide gas without any secondary contaminants. In coming years, denim and jeans washings may involve only such dry treatments or water free treatments.

In the future, consumers may also desire to see washed denim garments having durable colours in diversified material types, and more environmentally friendly processes employed for denim garment washing. Thus the scope of the washing applications can be further broadened to cover more fibre types and colourants.

## 11.7 Conclusion

Denim fabric has first appeared in the late eighteenth century. It is a cotton twill fabric and the weft passes under two or more warp yarns. Denim was traditionally coloured blue with the indigo dye with ring dyed effect. Through the years, denim has evolved and has become one of the most fashionable items in the fashion and textile industry. It can provide durability and different appearance effects for the garment and fashion products. Various washing effects have been introduced to make the denim garments and jeans attractive to consumers. Denim washing machines also play an important role and, depending on the market requirements, these machines can develop uniform colour fading or appearance effects in a short time. In the future, new sustainable types of denim washing techniques may be developed; however, some problems still need to be addressed, such as colour consistency, piece-to-batch reproducibility, yellowing and staining.

# Sources of further information

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# Biotechnological washing of denim jeans

12

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# 12.1 Introduction

Enzymes are used in a wide range of processes in the textile industry such as desizing, scouring, bleach clean-up, denim washing, biopolishing, etc. The normal washing of denim is intended to reduce the stiffness of the fabric and to improve its softness and wear comfort. However, in modern denim washing, the main aim of the process is to improve the visual appearance of the garments, giving them more aesthetically pleasing looks. It is with this goal in mind that laundries are producing fashionable finishes on jeans.

Denim – which derives from *serge de Nimes* – is a coarse cotton fabric which was manufactured in Provence, France, in the past century. The designation denim fabric is used for fabrics in the market containing a dyed warp yarn and a white cotton weft yarn. The warp yarn may be dyed with a sulphur, pigment or reactive dyes. However, indigo dyed blue denim is most prevalent. Usually the warp yarn is dyed on continuous dyeing machines in the form of a warp or cable. After the sizing and weaving processes, the denim fabric is finished.

Earlier, garment processing was limited only to the washing of blue and black jeans. Nowadays much more extensive treatments of garments are possible in laundries, for example dyeing, permanent wrinkles, special effects, etc. Denim fashion was the start of today's garment finishing, but to this day, jeans washing is still the largest part of this industry sector. Ecological aspects of denim processing are increasingly at the forefront of brands and retailers, and will become an even more important target to aim toward in the future.

It is well known that denim washing processes have a high impact in terms of environment and sustainable requirements. In a number of cases, some or all of these drawbacks can be virtually reduced or eliminated by using enzymes. Sustainable processes that decrease water consumption, energy, time and harmful substances will become more and more important for the worldwide denim community as well as for the laundries around the world, and this is where biotechnological techniques can help in decisive ways.

# 12.2 Types of industrial enzymes

Enzymes are biological catalysts in the form of proteins that catalyse chemical reactions in the cells of living organisms. As such, they have evolved – along with cells – under the conditions found on our planet, to satisfy the metabolic requirements of an extensive range of cell types. In general, these metabolic requirements can be defined as:

- · Chemical reactions must take place under the conditions of the habitat of the organism.
- Specific action by each enzyme.
- Very high reaction rates.
- Numerous enzymes for different tasks.

#### 12.2.1 Reactions under mild conditions

This in particular means that there will be enzymes functioning at mild temperatures, pH, etc., as well as enzymes adapted to harsher conditions, such as extreme cold (in arctic or high altitude organisms), extreme heat (e.g. in organisms living in hot springs) or extreme pH values (e.g. in organisms in soda lakes). As an example of enzymes working under mild conditions, consider a chemical reaction observed in many organisms, the hydrolysis of maltose to glucose, which takes place at pH 7.0:

Maltose + 
$$H_2O \rightarrow 2$$
 glucose

For this reaction to proceed non enzymatically, heat has to be added to the maltose solution to increase the internal energy of the maltose and water molecules, thereby increasing their collision rates and the likelihood of their reacting together. The heat is supplied to overcome a barrier called 'activation energy' so that the chemical reaction can be initiated.

As an alternative, the enzyme maltase may enable the same reaction at  $25 \,^{\circ}$ C by lowering the activation energy barrier. It does this by capturing the chemical reactants – called substrates – and bringing them into intimate contact at active sites where they interact to form one or more products. As the enzyme itself remains unchanged by the reaction, it continues to catalyse further reactions until an appropriate constraint is placed upon it.

#### 12.2.2 Highly specific action

To avoid metabolic chaos and create harmony in a cell teeming with innumerable different chemical reactions, the activity of a particular enzyme must be highly specific, both in the reaction catalysed and the substrates it binds. Some enzymes may bind substrates that only differ slightly, whereas others are completely specific to just one particular substrate. An enzyme usually catalyses only one specific chemical reaction, or a number of closely related reactions.

#### 12.2.3 High reaction rates

The cells and tissues of living organisms have to respond quickly to the demands put on them. Activities such as growth, maintenance and repair and extracting energy from food, have to be carried out efficiently and continuously. Again, enzymes rise to the challenge. Enzymes may accelerate reactions by factors of a million, or even more. Carbonic anhydrase, which catalyses the hydration of carbon dioxide to speed up its transfer in aqueous environments like the blood, is one of the fastest enzymes known. Each molecule of the enzyme can hydrate 100,000 molecules of carbon dioxide per second. This is 10 million times faster than the non enzyme catalysed reaction.

#### 12.2.4 Enzymes for different tasks

Because enzymes are highly specific in the reactions they catalyse, an abundant supply of enzymes must be present in cells to carry out all the different chemical transformations required. Most enzymes help break down large molecules into smaller ones and release energy from their substrates. To date, scientists have identified more than 10,000 different enzymes. Because there are so many, a logical method of nomenclature has been developed to ensure that each one can be clearly defined and identified. Although enzymes are usually identified using short trivial names, they also have longer systematic names. Furthermore, each type of enzyme has a four part Enzyme Commission (EC) classification number based on the standard enzyme nomenclature system maintained by the International Union of Biochemistry and Molecular Biology and the International Union of Pure and Applied Chemistry.

Most enzymes catalyse the transfer of electrons, atoms or functional groups. And depending on the types of reactions catalysed, they are divided into six main classes, which in turn are split into groups and subclasses. For example, the enzyme that catalyses the conversion of milk sugar (lactose) to galactose and glucose has the trivial name lactase, the systematic name, beta-D-galactoside galactohydrolase, and the classification number EC 3.2.1.23. Table 12.1 lists the different types of industrial enzymes and some examples of each type, whereas Table 12.2 shows the reaction profile of these enzymes.

## 12.2.5 Enzyme activity

Activity means the speed of the reaction being catalysed and it depends on:

- Enzyme concentration.
- Substrate concentration (saturation).
- Temperature (faster at higher temperature).
- pH.
- Cofactor.
- Inhibition.

# 12.3 Enzymes for jeans washing

The most important enzymes for jeans washing process include amylases, cellulases and laccases.

| Types           | Examples  |
|-----------------|---|
| Oxidoreductases | Catalases, glucose oxidases, laccases   |
| Transferases    | Fructosyltransferases, glucosyltransferases   |
| Hydrolases      | Amylases, cellulases, lipases, mannanases, pectinases, phytases, proteases, pullulanases, xylanases |
| Lyases          | Pectate lyases, alpha acetolactate, decarboxylases  |
| Isomerases      | Glucose isomerases  |
| Ligases         | Not used at present   |

# Table 12.1 Classification of main industrial enzymes

# Table 12.2 Enzyme classes and types of reactions

| Class of enzyme | Reaction profile   |
|-----------------|--|
| Oxidoreductases | Oxidation reactions involve the transfer of electrons from one<br>molecule to another. In biological systems, it is usually<br>observed as the removal of hydrogen from the substrate.<br>Typical enzymes in this class are called dehydrogenases. For<br>example, alcohol dehydrogenase catalyses reactions of the type<br>R-CH <sub>2</sub> OH + A R-CHO + H <sub>2</sub> A, where A is an acceptor molecule.<br>If A is oxygen, the relevant enzymes are called oxidases or<br>laccases; if A is hydrogen peroxide, the relevant enzymes are<br>called peroxidases. |
| Transferases    | This class of enzyme catalyses the transfer of groups of atoms from<br>one molecule to another. Aminotransferases or transaminases<br>promote the transfer of an amino group from an amino acid to an<br>alpha-oxoacid.  |
| Hydrolases      | Hydrolases catalyse hydrolysis, the cleavage of substrates by water.<br>The reactions include the cleavage of peptide bonds in proteins,<br>glycosidic bonds in carbohydrates and ester bonds in lipids. In<br>general, larger molecules are broken down to smaller fragments<br>by hydrolases.  |
| Lyases          | Lyases catalyse the addition of groups to double bonds or the for-<br>mation of double bonds through the removal of groups. Thus<br>bonds are cleaved using a principle different from hydrolysis.<br>Pectate lyases, for example, split the glycosidic linkages by<br>beta elimination.   |
| Isomerases      | Isomerases catalyse the transfer of groups from one position to<br>another in the same molecule. In other words, these enzymes<br>change the structure of a substrate by rearranging its atoms.  |
| Ligases         | Ligases join molecules together with covalent bonds. These enzymes<br>participate in biosynthetic reactions in which new groups of bonds<br>are formed. Such reactions require the input of energy in the form<br>of cofactors such as adenosine triphosphate.   |

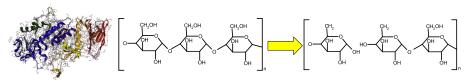


Figure 12.1 Action of amylase on amylose starch.

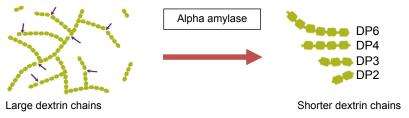


Figure 12.2 Action of amylase on large dextrins.

# 12.3.1 Amylases for desizing

Industrially important amylases are made from the *Bacillus* species and *Asper-gillus* species. Usually, amylases are the most common way used to remove starch sizes. Native starch is only slowly degraded by amylases. Gelatinisation and swelling are needed to make the starch susceptible to enzymatic breakdown. These proteins are specific to the hydrolysis of starch. They work by cleaving the 1,4 beta-glucosidic linkage in the starch polymer and converting to a smaller water soluble fragment. Figure 12.1 shows the action of amylase enzyme on amylose starch. Alpha amylase randomly cleaves large dextrins to form a mixture of smaller dextrin chains (polymers of glucose). Figure 12.2 shows the action of amylase on large dextrins.

# 12.3.2 Sizing agents for denim

## 12.3.2.1 Warp sizing

- To have a proper weave process, sizing agents are absolutely necessary.
- Sizing agents are applied to warp yarns by immersion during slashing. The weight of dry size deposited on yarns is referred to as add on and is calculated as a dry weight percentage.
- At this stage, warp yarns may have already been scoured and dyed on an indigo dye range and treated with a rebeaming agent.
- · Sized yarns are dried and wound onto a warp beam for placement on the loom.
- Only warp yarns are sized because stresses experienced by warp yarns during weaving are greater than for weft yarns. Warp sizing effectiveness is measured in the ability to protect yarns from breakage due to stretching, strain and abrasion.
- · Reduction of end breaks is one measure of mill efficiency and is directly related to sizing.
- Higher standards for easy removal of size have been set as mills and finishing plants work together.

#### 12.3.2.2 Sizing bath components

Today, one of the biggest problems in jeans wash treatment is the lack of information regarding the raw material, especially because the finishing operation rarely knows the composition of size to be removed.

Synthetic sizes are very sensitive to high pH values and can react by coagulating and become extremely difficult to remove. Sizes are classified by water soluble and water insoluble sizes—each class requires different methods of removal. List of possible components are:

- Starches.
- Modified starches.
- Carboxymethylcellulose (CMC).
- Plasticisers (film formers).
- Lubricants.
- Fixing agents.
- Polyvinyl alcohol.
- Waxes.
- Defoamers.
- Surfactants.

Approximately 5–15% size or weight of warp yarns is applied. Of this, typically more than 75% is soluble in hot water. Both size penetration and size encapsulation of a yarn are important. Size penetration provides a smooth coating. Hairy yarns in weaving are undesirable. Sizing baths are typically unique to a fabric mill, and a mill may have developed several formulations to meet particular processing needs. But in general, the starch component is present in the majority of sizing processes for denim fabrics.

#### 12.3.2.3 Starch

Starch is a film forming material with a high degree of adhesion for cotton and other polar fibres. Similar stress/strain and flex behaviour to cellulosic make starch an excellent choice as a sizing agent. Economics, and ease of use, are additional features making starch sizing attractive.

Starch is a natural polymer based on glucose found in plants. Polymer chains may be branched (amylopectin) or unbranched (amylose). The degree of polymerisation range for amylopectin is 6000 and the degree of polymerisation range for amylose is 1000. Table 12.3 shows the amylose and amylopectin contents in different starch sources.

Many commercial starches have been modified by acidification, oxidation or other processes to alter properties such as water solubility and gel viscosity. For efficient starch removal, water temperature must be raised above the gelatinisation point (i.e. the temperature at which a starch begins to swell and form a slurry). The gelatinisation temperature varies according to the ratio of amylose to amylopectin, but is usually  $60 \,^{\circ}\text{C}$ – $70 \,^{\circ}\text{C}$ . Gelatinised starch is more susceptible to decomposition by amylase enzymes, removal by surfactants and oxidation.

| Starch source  | Amylose (%) | Amylopectin (%) |
|----------------|-------------|-----------------|
| Corn           | 27          | 73              |
| Sago           | 26          | 74              |
| Sago<br>Potato | 22          | 78              |
| Wheat          | 19          | 81              |
| Tapioca        | 17          | 83              |
| Rice           | 14          | 86              |

Table 12.3 Amylose and amylopectin in different starch sources

At the present time, is well known that the most used process for the elimination of the starch is enzymatic desizing with amylases. In addition to the advantages already mentioned, another decisive factor is that the use of enzymes has a smaller ecological impact when compared with other procedures and its effectiveness is much greater compared with detergents that could be considered acceptable from an environmental point of view.

## 12.3.2.4 Enzymatic desizing

Proper desizing is essential to obtaining the required look or finish. Poor desizing will often result in a poorly finished garment; therefore, it is crucial to carry out the correct desizing process. Should this process not be thoroughly carried out, further problems will occur in the subsequent finishing steps, for instance, crease marks, white lines, streaks or backstaining formation, because amylases also prevent swollen starch from adhering to the surface of denim fabrics, especially in the rear and white parts (pockets) that may otherwise act as a glue for particulate indigo spots (backstaining). Figure 12.3 shows examples of streaky finishing due to improper desizing. The damage is visible on the finished garment and is irreparable.

When desizing using amylase, the garment finisher should be aware of the optimum pH and temperature ranges for the enzyme being used. Amylase enzymes are available which operate at low  $(30 \degree \text{C}-50 \degree \text{C})$ , medium  $(50 \degree \text{C}-90 \degree \text{C})$  and high  $(80 \degree \text{C}-110 \degree \text{C})$  temperature ranges. Low temperature amylase enzymes are most typically used in denim garment processes. Amylase enzymes typically operate at pH 5.5–7.5. Some still exhibit as much as 90% activity at pH 10. Figure 12.4 shows some examples of temperature and pH profiles of different amylases.

## 12.3.2.5 Desizing recipe guidelines

Table 12.4 shows the desizing recipe guidelines for both front loader and belly washing machines. These recipes show some application conditions for desizing processes with amylases in combination with some chemicals that can be used for an effective desizing.



Figure 12.3 Streaky finishing resulting from improper desizing.

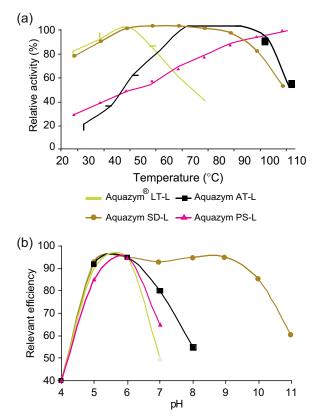


Figure 12.4 Temperature and pH profiles of amylases.

| Front loader washing machine   | Belly washer machine   |
|--|--|
| <ul> <li>Product dosage:</li> <li>1. 0.5–1.0% o.w.f amylase (Aquazym<sup>®</sup> series)</li> <li>2. 0.5–1.0% o.w.f wetting dispersing agent</li> <li>3. 1.0–2.0% o.w.f lubricant (optional)</li> <li>Time: 20 min</li> <li>Temperature: 40 °C–50 °C</li> <li>pH: 6.5–8.0</li> <li>LR: 1:3, 1:5</li> <li>After treatment:</li> </ul> | <ul> <li>Product dosage:</li> <li>1. 0.5–1.0% o.w.f amylase (Aquazym<sup>®</sup> series)</li> <li>2. 0.5–1.0% o.w.f wetting dispersing agent</li> <li>3. 1.0–2.0% o.w.f lubricant (optional)</li> <li>Time: 20 min</li> <li>Temperature: 40 °C–50 °C</li> <li>pH: 6.5–8.0</li> <li>LR: 1:15, 1:20</li> <li>After treatment:</li> </ul> |
| Rinse: 20 °C, 3 min, LR 1:5  | Rinse: 20 °C, 3 min, LR 1:20   |

#### Table 12.4 Desizing recipe for front loader and belly machines

## 12.3.3 Cellulases for denim abrasion

The group of enzymes used for abrasion of denim fabrics is the so called cellulases. As mentioned previously, enzymes, in general, are proteins which are catalysts to different reactions in nature, where cellulases catalyse the hydrolysis of specific bonds in cellulose. They perform a specific catalytic action on the 1.4-beta-glucosidic bonds of the cellulose molecule. Because the enzyme is only a catalyst and is not consumed by the reaction, it is able to move to another position and initiate the hydrolysis of another bond. Furthermore, a small amount of enzyme is able to reduce a larger quantity of substrate because the enzyme keeps repeating its action.

In nature, cellulases are produced mainly by various fungal and bacterial species to enable the microorganism to live from cellulose containing material, such as wood and plants. Microorganisms produce mixtures of several cellulase types which, even though they all degrade cellulose, are rather different in the way they act. In this way, complex materials containing different cellulose structures can be efficiently degraded. Fungal cellulases are the most important from an industrial perspective. Generally, they are divided into several classes based on investigations into the Trichoderma species:

- Endo-glucanases (EGs) (several kinds) only attack soluble cellulose. They randomly cleave the long cellulose chain into shorter polymers.
- Cellobiohydrolases (CBHs) convert the crystalline cellulose to soluble. They degrade the cellulose chain from one end, thereby producing cellobiose (two glucose molecules linked together).
- Cellobioases degrade the cellobiose into glucose.
- · Beta-glucanases attack large fragments and convert to small chains.

As an example, a typical commercial Trichoderma cellulase product contains six different endo-cellulases, three cellobiohydrolases and one cellobiase. Individually, each family of activity is converting/degrading an insoluble piece of cellulose, for example cotton fibre, into a sugar (food source for a microbe).

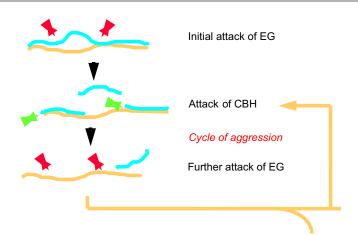


Figure 12.5 Cycle of aggression of endo-glucanase and cellobiohydrolase.

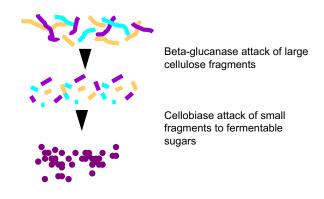
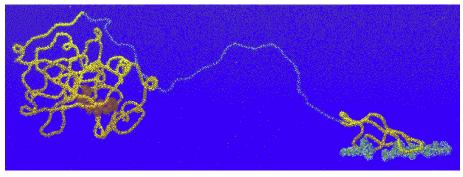


Figure 12.6 Cycle of aggression of beta-glucanase and cellobiase.

The main process consists of a combined action of EGs and CBHs, where the initial EG attack creates a few large, soluble fragments which are the binding sites for the CBH; the CBH converts the crystalline cellulose to soluble form and produces little free sugars. Figure 12.5 shows the cycle of aggression of endo-glucanase and cellobiohydrolase attacks.

To complete the process of cellulose breakdown, beta-glucanase converts the large, soluble cellulose fragments into small ones and the cellobiases hydrolyse those fragments into fermentable sugars. Figure 12.6 shows the cycle of aggression of beta-glucanase and cellobiase attacks.

Furthermore, some cellulase types do not work on the insoluble form of cellulose found in cotton material, but only on soluble cellulose derivatives, like CMC. This is important because CMC is often used in cellulase activity measurements and by that – it is possible (to some extent) to recognise the cellulose composition and therefore, to predict its application.



 Catalytic core
 Hydrophilic linker
 Cellulose binding domain (CBD)

 Figure 12.7
 Typical cellulase enzyme with binding domain.

EGs and CBHs have been shown to consist of three parts: a cellulose binding domain that attaches the enzyme to the cellulose surface, a core that catalyses the cleavage and a linker that connects the two regions. Figure 12.7 shows a typical cellulase enzyme with binding domain.

In the textile industry, cellulases are used to modify cellulosic material such as cotton, viscose, linen or lyocell, and it is the cellulase effect on these substrates that is of interest. In other words, considering the specificities of these fibres, such as content of pure 1-4-beta-glucosidic bonds, ratio between soluble and insoluble cellulosic parts, affinity to enzymatic attack, etc., it is possible to predict the action of a given cellulase composition onto a given fibre or to design such a cellulase composition.

To obtain the desired effect, the right enzymatic product should be chosen. This choice depends on the fibre type and many other parameters, such as fabric strength and weight, available machinery, fabric, etc. In general, any of the products that follow could be used for biowashing of a given cellulosic fabric. However, the recommended products in the different cases should be considered as a first choice.

The abrasion phenomenon in denim articles is produced by the following main factors:

- · Enzymatic modification of cotton fibres.
- Mechanical abrasion from: garments, machinery and abrasives materials like pumice stones, perlite, cellular glass, etc.

The enzymatic modification happens when:

- The cellulase molecules bind strongly to exposed cellulose.
- · The cellulases hydrolyse the cellulose surface where the indigo dye resides.
- · When the surface becomes too weak, the abrasive forces break or tear off fibrils with indigo.
- · Where the fibre surface is damaged, a new attack rapidly takes place creating white parts.

The biostoning mechanism is depicted in the Figure 12.8.

The main advantages of the use of cellulase enzymes for jeans wash processes are outlined as follows:

- Environmental benefits.
- · Reliable process.

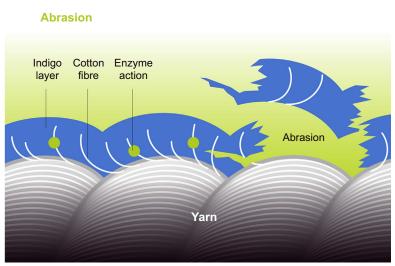


Figure 12.8 Biostoning mechanism.

- Better quality/less damaged jeans.
- · Reduced handling of stones and consequently better work conditions.
- · Longer life of machinery/less wear.
- Less sludge generation.

# 12.3.4 Key parameters for cellulases

# 12.3.4.1 pH control

Cellulase enzymes have a specific pH and temperature at which they have maximum activity. Controlling the pH is extremely important and should be accomplished by use of a true buffer chemical and not by adjusting the water with an acid or alkali. A buffer is a combination of chemicals that will maintain a desired pH range, even after the addition of acid or base to the system. Figure 12.9 shows examples of different pH profiles of neutral and acid cellulases.

# 12.3.4.2 Temperature

Each cellulase enzyme also has a specific temperature range at which it provides maximum activity. Figure 12.10 shows examples of temperature profiles of different cellulase enzymes which also shows the temperature ranges for maximum activity.

# 12.3.4.3 Dosage

The correct dosage versus cellulase activity is important to avoiding strength problems or damage in the articles. Not all cellulases have the same activity and the formulations can be very different.

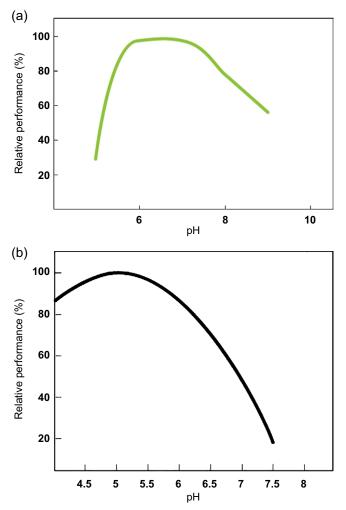


Figure 12.9 pH profiles of neutral and acid cellulases.

#### 12.3.4.4 Time

Enzymatic treatment time is a crucial parameter. Two important factors that play a decisive role in conjunction with time are mechanical action and the enzyme activity.

#### 12.3.4.5 Mechanical action

Modern cellulases are sensitive to mechanical action and completely different performances can be obtained using the same enzyme, same dosage, same time and same temperature, in a different washing machine (front loaders with much higher mechanical action or belly washer with less mechanical action. All of these factors should be considered when designing the right washing protocol. Figure 12.11 shows a typical front loader machine, whereas Figure 12.12 shows a typical belly washer machine.

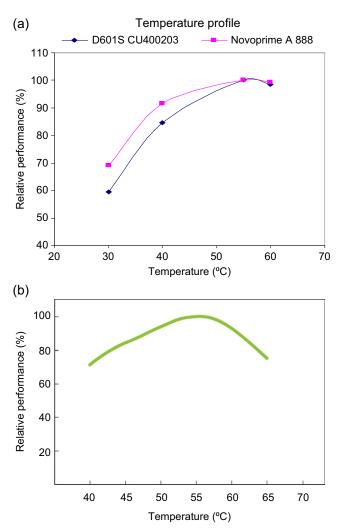


Figure 12.10 Temperature profiles of different cellulases.

#### 12.3.4.6 Biowash recipe guidelines

Table 12.5 shows the biowash recipe guidelines for front loader and belly washing machines. These recipes show some application conditions for the biowash process with cellulases in combination with some chemicals that can be used for effective performance.

## 12.3.5 Laccases for denim bleaching

Laccases are a group of oxidative enzymes whose exploitation as biocatalysts in organic synthesis has been neglected in the past, probably because they were not commercially available. The search for new, efficient and environmentally benign processes for the textile industries has increased interest in these essentially green catalysts which work with air and produce water as the only by-product, making them



Figure 12.11 Typical front loader machine.



Figure 12.12 Typical belly washer machine.

more generally available to the scientific community. Consequently, a significant number of reports have been published in the past decade that have focused on the biochemical properties of these proteins and/or on their applications in technological and bioremediation processes in addition to their use in chemical reactions.

Laccases (EC 1.10.3.2, *p*-diphenol:dioxygen oxidoreductase) belong to the so-called blue-copper family of oxidases. The reactions catalysed by laccases are proceeded by the monoelectronic oxidation of a suitable substrate molecule (phenols and aromatic or aliphatic amines) to the corresponding reactive radical. The redox process takes place with the assistance of a cluster of four copper atoms that form the catalytic core of the enzyme. The overall outcome of the catalytic cycle is the reduction of one

| Front loader washing machine  | Belly washer machine  |
|---|---|
| <ul> <li>Product dosage</li> <li>1. 0.5-2.0% o.w.f cellulase (a)<br/>(Denimax, Valumax<sup>®</sup> series)</li> <li>2. 0.5-1.0% o.w.f wetting dispersing agent<br/>a. Dependent on enzyme activity profile<br/>Time: 30-60 min (b)</li> <li>b. Dependent on abrasion level needed<br/>Temperature: 40 °C-55 °C (c)</li> <li>c. Dependent on programmer temperature</li> </ul> | <ul> <li>Product dosage</li> <li>1. 0.5–2.0% o.w.f cellulase (a)<br/>(Denimax, Valumax<sup>®</sup> series)</li> <li>2. 0.5–1.0% o.w.f wetting dispersing agent</li> <li>a. Dependent on enzyme activity profile<br/>Time: 30–60 min (b)</li> <li>b. It depends on the abrasion level<br/>needed</li> <li>Tormereture: 40%C, 55%C (a)</li> </ul> |
| c. Dependent on enzyme temperature profile  | Temperature: 40 °C–55 °C (c)<br>c. Dependent on enzyme temperature<br>profile   |
| pH: 6.5–7.5 for neutral process with neutral enzymes or   | pH: 6.5–7.5 for neutral process with neutral enzymes or   |
| pH: 5.0–5.5 for acid process with acid<br>enzymes<br>LR: 1:3, 1:5   | pH: 5.0–5.5 for acid process with acid<br>enzymes<br>LR: 1:15, 1:20   |
| After treatment:<br>Rinse×2: 20 °C, 3 min, LR 1:5<br>Washing optional   | After treatment:<br>Rinse×2: 20 °C, 3 min, LR 1:20<br>Washing optional  |

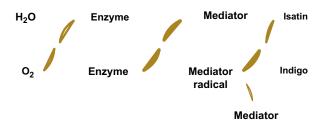


Figure 12.13 Mediator transferring electrons from indigo to laccase.

molecule of oxygen to two molecules of water and the concomitant oxidation of four substrate molecules to produce four radicals.

Frequently, however, the substrates of interest cannot be oxidised directly by laccases, either because they are too large to penetrate into the enzyme active site or because they have a particularly high redox potential. By mimicking nature, it is possible to overcome this limitation with the addition of so-called chemical mediators, which are suitable compounds that act as intermediate substrates for the laccase, whose oxidised radical forms are able to interact with the bulky or high redox-potential substrate targets. Figure 12.13 shows how a mediator is transferring electrons from indigo to the laccase enzyme.

#### 12.3.6 Industrial applications of laccases

At present, the main technological applications of laccases are in the textile industry, in processes related to decolourisation of indigo. In most of these applications,

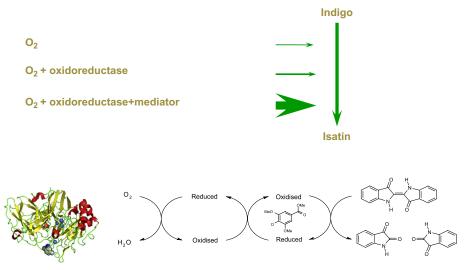


Figure 12.14 Indigo decolourisation mechanism.

laccases are used together with a chemical mediator (Laccase-Mediator System). In the Laccase-Mediator System process specifically for indigo oxidation on denim garments, the dye chromophore is split to yield two molecules of the uncoloured isatin. The system currently comprises a granular formulation of recombinant laccase which is applied with the mediator, the methyl ester of syringic acid. Figure 12.14 shows the indigo decolourisation mechanism by laccases.

The use of laccase in the jeans wash process is now more linked to fashion demand than the replacement of sodium hypochlorite for the bleaching process. Sodium hypochlorite has certain advantages, such as being cheap and the reaction takes place at room temperature, but it is also a harsh chemical and adds a yellow colour to the fabrics if not neutralised properly. Being a strong oxidising agent, it also attacks cotton and reduces its strength which is not desirable in lightweight denim. In addition, it cannot be used for elastane containing garments. Furthermore, the hypochlorite process is environmentally very harmful. For that reason, laccases today are an ecological alternative for the denim bleaching process and customised formulations of laccase are routinely used to target specific bleaching processes or finishing looks as:

- Indigo discolouration in different levels.
- · Vintage effect.
- Backstaining clean-up.
- Grey cast.
- Permanent colour effect/colour cast.

Figure 12.15 shows the typical finished looks with laccase treatment (right side).

#### 12.3.7 Key parameters for laccases

As with all enzymes, the performance of laccases is associated to a specific range of pH, temperature, dosage and time. In this case, the mechanical action is not as relevant



Figure 12.15 Typical finished looks with laccase treatment (right side).

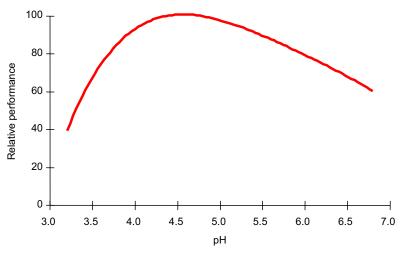


Figure 12.16 pH profile of typical commercial laccase.

as hydrolases such as amylases or cellulases. Figure 12.16 shows the pH profile of a typical commercial laccase, whereas Figure 12.17 shows the temperature profile. The dosage performance profile of a typical commercial laccase is shown in Figure 12.18, whereas Figure 12.19 shows the time performance profile.

#### 12.3.8 Laccase recipe guidelines

Table 12.6 shows the laccase recipe guidelines for front loader and belly washing machines. These recipes also show some application conditions for finishing treatments with laccase.

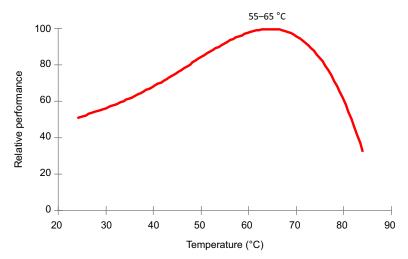


Figure 12.17 Temperature profile of typical commercial laccase.

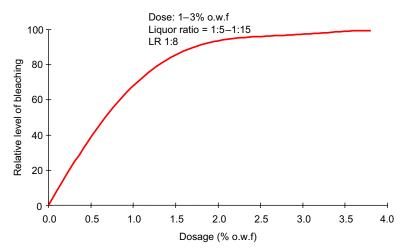


Figure 12.18 Dosage profile of typical commercial laccase.

# 12.4 Biotechniques and process recipes

The basic biotechniques and process recipes (washing protocol) for denim jeans washing include desizing, neutral biowash, acid biowash, neutral bioblast, acid bioblast, biobleach and cast change. Figure 12.20 shows the principal enzymatic washing steps for denim jeans. The exact procedure will vary depending on the targeted fashion look, so that any combination of steps may be used to obtain a specific finish.

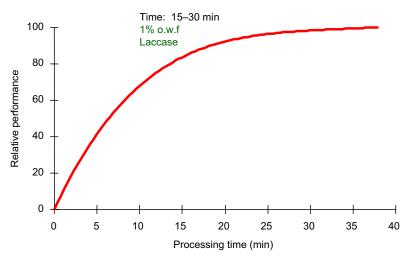


Figure 12.19 Time profile of typical commercial laccase.

Table 12.6 Laccase recipe for front loader and belly machines

| Front loader washing machine            | Belly washer machine                    |
|---|---|
| Product dosage:                         | Product dosage:                         |
| 1. 0–3.0% o.w.f laccase (a)             | 1. 0–3.0% o.w.f laccase (a)             |
| (Denilite <sup>®</sup> series)          | (Denilite <sup>®</sup> series)          |
| a. Dependent on enzyme activity profile | a. Dependent on enzyme activity profile |
| and effect needed                       | and effect needed                       |
| Time: 15–20 min                         | Time: 15–20 min                         |
| Temperature: 60 °C–65 °C                | Temperature: 60 °C–65 °C                |
| pH: 4.5–5.0                             | pH: 4.5–5.0                             |
| LR: 1:3, 1:5                            | LR: 1:15, 1:20                          |
| After treatment:                        | After treatment:                        |
| Rinse×2: 20 °C, 3 min, LR 1:5           | Rinse×2: 20°C, 3 min, LR 1:20           |
| Washing optional                        | Washing optional                        |

This section focusses on the enzyme application process recipes for all the major steps of the jeans washing process. It also includes the portfolios of different enzymes and their performance, guidelines and processing parameters, and the general instructions as offered by Novozymes.

### 12.4.1 Enzymatic desizing

- Load garments flat into machine.
- Fill the machine with water and heat to 50 °C. The cylinder does not turn while filling. Liquor ratio (water L/fabric kg): 6:1–10:1.

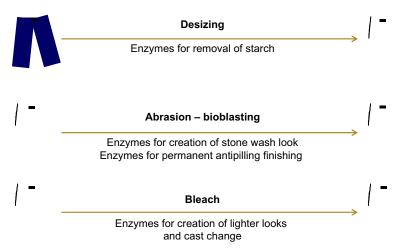


Figure 12.20 Principal enzymatic washing steps.

 Table 12.7
 Portfolio of amylase enzymes

| Enzymes                     | L/S | Activity    | Temperature °C | рН       | Benefits   |
|-----------------------------|-----|-------------|----------------|----------|--|
| BAN<br>240L                 | L   | 240 KN6U/g  | 30-60          | 5.5–6.5  | Complete removal of<br>all types of starch<br>based size, GOTS<br>approved |
| Aquazym<br>Ultra<br>1200 N  | L   | 1200 NAU/g  | 50–90          | 6.0–7.5  | Efficiency across<br>a wide range of<br>temperature                        |
| Aquazym<br>Prime<br>12000 L | L   | 12000 NDU/g | 20-85          | 5.0–10.0 | High concentration<br>and very robust in<br>terms of pH and<br>temperature |

- Turn steam off and add:
  - Recipe 1
    - AQUAZYM<sup>®</sup> (formulated version) 1.0–2.0% (o.w.f).
    - Dispersing agent (nonionic) 0.5–1.0% (o.w.f).
    - pH = 7-8.
- Run for 15 min and drain.
- Rinse: Liquor ratio 10:1 at room temperature for 2 min and drain.

Table 12.7 shows the portfolio of amylase enzymes.

### 12.4.2 Neutral biowash (option 1)

- Fill the machine with water and heat at to 40 °C (low temperature). Liquor ratio (water L/fabric kg): 6:1–10:1.
- Turn steam off and add:
  - Recipe 2a
    - Denimax/Novoprime (formulated version) 1.0-2.0% (o.w.f).
    - Dispersing agent (nonionic) 0.5–1.0% (o.w.f).
    - pH=6.5–7.5.
    - If required, add pumice stones (garments to stone ratio 1:1–3:1).
- Run for 45–70 min and drain.
- Rinse: Liquor ratio 10:1 at room temperature for 2 min and drain.

## 12.4.3 Neutral biowash (option 2)

- Fill the machine with water and heat at to 55 °C (high temperature). Liquor ratio (water L/fabric kg): 6:1–10:1.
- Turn steam off and add:
  - Recipe 2b
    - Denimax/Novoprime (formulated version) 1.0-2.0% (o.w.f).
    - Dispersing agent (nonionic) 0.5–1.0% (o.w.f).
    - pH=6.5–7.5.
- If required, add pumice stones (garments to stone ratio 1:1–3:1).
- Run for 45–70 min and drain.
- Rinse: Liquor ratio 10:1 at room temperature for 2 min and drain.

# 12.4.4 Acid biowash (option 3)

- Fill the machine with water and heat to 55 °C (high temperature). Liquor ratio (water L/fabric kg): 6:1–10:1.
- Turn steam off and add:
  - Recipe 2c
    - Denimax/Novoprime (formulated version) 1.0–2.0% (o.w.f).
    - Dispersing agent (nonionic) 0.5–1.0% (o.w.f).
    - pH=5.0–5.5.
- If required add pumice stones (garments to stone ratio 1:1–3:1).
- Run for 45–70 min and drain.
- Rinse: Liquor ratio 10:1 at room temperature for 2 min and drain.

# 12.4.5 Neutral bioblast (option 4)

- Fill the machine with water and heat to 50 °C (medium temperature). Liquor ratio (water L/fabric kg): 6:1–10:1.
  - Turn steam off and add:
    - Recipe 2d

.

- Cellusoft (formulated version) 1.0–2.0% (o.w.f).
- Dispersing agent (nonionic) 0.5–1.0% (o.w.f).
- pH=6.5–7.0.

- Run for 20–30 min and drain.
- Rinse: Liquor ratio 10:1 at room temperature for 2 min and drain.

### 12.4.6 Acid bioblast (option 5)

- Fill the machine with water and heat to 55 °C (high temperature). Liquor ratio (water L/fabric kg): 6:1–10:1.
- Turn steam off and add:
  - Recipe 2e
    - Cellusoft (formulated version) 1.0–2.0% (o.w.f).
    - Dispersing agent (nonionic) 0.5–1.0% (o.w.f).
    - pH=5.0–5.5.
- Run for 20–30 min and drain.
- Rinse: Liquor ratio 10:1 at room temperature for 2 min and drain.

Table 12.8 shows the portfolio of cellulase enzymes.

### 12.4.7 Bleaching with grey cast (option 1)

The pumice stones should be first removed from the washing bath for the clean-up and for achieving the bleached look with a grey cast (vintage look).

- Fill the machine with water and heat to 65 °C. Liquor ratio (water L/fabric kg): 6:1-10:1.
- Turn steam off and add:
  - Recipe 3a
    - Novoprime Base 268 and F 258 (formulated version) 1.0-3% (o.w.f).
    - pH=4.5–5.5 (check and adjust in case).
    - (\*) If required to meet desired shade repeat steps 1 and 2.
- Run for 15 min and drain.
- Rinse: Liquor ratio 10:1 at room temperature for 2 min and drain.

Table 12.9 shows the portfolio of laccase enzymes.

### 12.4.8 Chlorine bleach for light cast (option 2)

The pumice stones should be first removed from the washing bath.

- Fill the machine with water and heat to 50 °C. Liquor ratio (water L/fabric kg): 6:1-10:1.
- Turn steam off and add:
  - Recipe 3b
    - Chlorine bleach (15% active) for dosage (see Table 12.10).
    - pH 10.5–11.0.
- Run for 15 min and keep the pH between 10.5 and 11.0. Drain. (\*) If required to meet desired shade repeat steps 1 and 2.
- Rinse: Liquor ratio 10:1 at 50 °C for 2 min.
- Refill machine (Liquor ratio 10:1) with water and heat to 50 °C and add:
  - Recipe 3c
    - Sodium meta-bisulphite (30% active) for dosage (see Table 12.10)

| Enzymes             | L/S | Activity      | Temperature °C | pН      | Benefits  |
|---------------------|-----|---------------|----------------|---------|---|
| Novoprime A 328     | s   | 1600 DAU/g    | 50-55          | 6.0–7.5 | Multicomponent, GOTS approved   |
| Novoprime A 378     | S   | 4500 ECU/g    | 45-55          | 6.0–7.5 | High colour contrast finish   |
| Novoprime A 379     | L   | 4500 ECU/g    | 45-55          | 6.0–7.5 | High colour contrast finish, liquid form  |
| Novoprime A 388     | S   | 3150ECU/g     | 45–55          | 6.0–7.5 | Medium contrast finish and very good antibackstaining<br>properties   |
| Novoprime A 868     | S   | 20,000 ECU/g  | 30–50          | 5.5–7.0 | Suitable in broad pH and temperature, recommended for cold process  |
| Novoprime A 888     | S   | 8200 CCU/g    | 30–50          | 5.5–7.0 | For cold process with excellent antibackstaining proprieties  |
| Novoprime A 966     | S   | 5000 ECU/g    | 50-55          | 5.0-6.5 | Cost-effective solutions  |
| Novoprime A 800     | S   | 7900 ECU/g    | 40–55          | 6.0–7.5 | Broad pH and temperature, can be used under different<br>conditions, excellent antibackstaining proprieties |
| Cellusoft CR Conc   | L   | 15,000 ECU/g  | 45–55          | 5.5–7.0 | High concentrate liquid version, suitable for abrasion and bioblasting, optimum colour retention            |
| Denimax Core 6400 S | S   | 6400 CNU-CA/g | 40–55          | 6.0–7.5 | One bath wash   |

# Table 12.8 Portfolio of cellulase enzymes

| Enzymes               | L/S | Activity   | Temperature °C | рН      | Benefits   |
|-----------------------|-----|------------|----------------|---------|--|
| Novoprime<br>Base 268 | S   | 800 LAMU/g | 55-65          | 4.5–5.5 | Chemical free bleach-<br>ing effect, grey<br>shade change, cre-<br>ation of new looks, |
| Novoprime<br>F 258    | S   |            | 55–65          | 4.5–5.5 | vintage design look  |

 Table 12.9
 Portfolio of laccase enzymes

Table 12.10 Different bleaching dosages

| Product                      | Light bleach | Medium bleach | Strong bleach |
|------------------------------|--------------|---------------|---------------|
| Sodium hypochlorite (g/L)    | 4.0          | 10.0          | 18.0          |
| Active chlorine (g/L)        | 1.2          | 3.0           | 5.4           |
| Sodium meta-bisulphite (g/L) | 0.5          | 2.0           | 4.0           |

- Run for 5 min and drain.
- Rinse: Liquor ratio 10:1 at room temperature for 2 min.

Table 12.10 shows the different bleaching dosages of sodium hypochlorite and sodium meta-bisulphite.

### 12.4.9 Softening

The pumice stones should be first removed from the washing bath.

- Fill machine (liquor ratio 6:1) at a temperature and pH recommended by softener supplier.
- Add softener and/or silicon emulsion, and/or ozone protector, following supplier recommendation.

# 12.5 Factors affecting washing effectiveness

The most important factors affecting washing effectiveness include the denim fabrics, dyeing processes, washing machines, enzymes, auxiliaries, backstaining, etc. The entire denim community knows that a garment that has been through a proper washing treatment will have a higher commercial value than a garment that has been inadequately washed. Although the laundry process can seem simple, there are many factors that come into play, among them those that can contribute in a decisive way in the final result.

# 12.5.1 Fabrics

One should consider that the behaviour of each fabric type can be totally different in the expected results. In the point of view of the washing treatment, it is important to establish a classification of the different fabrics with respect to the construction and the processes associated with dyeing.

# 12.5.2 Overview of denim fabrics

- The fabric used to make genuine denim jeans is strong cotton twill (weave) with a 3/1 diagonal rib. In traditional denim fabrics, the warp is dyed with indigo and the weft is not dyed.
- Originally known as 'serge de Nimes' (after the town where it was first produced). Denim is now manufactured by specialised mills all over the world.

# 12.5.3 Fabric weights

- The weight of the denim fabric. For example women's wear versus men's wear.
- Strength.
  - · Lighter fabrics will be weaker because of lighter warp and filling yarns.
- Appearance
  - Lighter fabrics have a finer look.
  - Heavier fabrics have a coarser appearance.

Table 12.11 shows the weights of different types of denim fabrics.

# 12.5.4 Fibre content

- 100% cotton
  - Used for most nonstretch denim applications.
  - Comfortable.
  - Authentic look.
  - · Good wicking properties.
  - Cost.
- Blends
  - Cotton can be blended with other fibres to achieve a particular outcome (e.g. strength or stretch).
  - Cotton/polyester (stretch and nonstretch).
  - Cotton/nylon.

### Table 12.11 Weights of different denim fabrics

| Heavy weight  | 12–16 oz/sq yd* |
|---------------|-----------------|
| Medium weight | 8–12 oz/sq yd*  |
| Light weight  | 4–8 oz/sq yd*   |

\*1 oz=28.35 g, 1 yard=0.945 m.

### 12.5.5 Fabric construction

- Weave types:
- Twills: 3/1 RHT, 3/1 LHT, 2/1 RHT, 2/1 LHT.
- Non directional: 3/1 BT, plain weave.
- Spun: ring spun, open end, jet spun.
- Nonspun yarns: 3/150/34 textured polyester 600 denier nylon.

### 12.5.6 Open end versus ring spun

- Open end: PROS
  - Cost efficient as a result of fewer processes, open end has lower cost than other spinning types.
  - Higher efficiency translates into better quality (less breaks and piece ups).
  - · Uniform and consistent.
  - Great flexibility.
- Open end: CONS
  - · Lower tensile/tear strength in fabric form than ring spun and fine vortex spun yarns.
  - Yarn is very uniform and therefore is not as soft as ring spun and jet spun.
  - Lacks the softness of ring spun.
- Ring spun: PROS
  - Greater strength than open end yarns.
  - Better flexibility.
  - More character in the fabrics.
  - Softer feel than open end yarns.
- · Ring spun: CONS
  - Cost: yarn is more expensive than other spinning methods because of the additional steps needed to produce yarn.
  - Quality problems with the yarn due to increased processing may lead to increased defect in some fabrics.

# 12.5.7 Denim dyeing

- Dye types:
  - Indigo and sulphur are most common
  - Indigo primarily blue Dips – refers to the number of times the strands of yarns are run (dipped into) into dye boxes.
  - Sulphur wide colour range.
  - Combinations (indigo-sulphur in top or bottom) adding cast to the jeans.

Table 12.12 shows the different denim segments based on their colour.

| Blue denim   | 80% | Indigo              |
|--------------|-----|---------------------|
| Black denim  | 17% | Sulphur black       |
| Colour denim | 3%  | Various dye classes |

### Table 12.12 Denim segments by colour

### 12.5.8 Washing machines

One of the decisive factors in the washing treatment is the mechanical effect that is proportionate to the type of available washer. As stated previously, the mechanical effect has a great impact on the result of the abrasion or bioblasting effect, especially in the performance of the cellulase enzymes. On the other hand, the mechanical effect is directly bound to other process parameters, such as time, temperature, chemical dose, etc. It is obvious that the higher the mechanical effect, the lower the times, dosages and temperatures should be. In the same way, the lower the mechanical effect, the more important it is to take this into consideration before designing the washing protocol. It is also important to mention that at the present time, other types of equipment for washing or finishing processes using other technologies such as laser or ozone are available to the finisher. The characteristics of the two main washing systems used nowadays for jeans washing are outlined in the following section.

### 12.5.8.1 Vertical drum/front loader

- Sophisticated.
- · High abrasion effect.
- High degree of automation/control.
- High productivity ratio (up to 750 kilo capacity).
- · More common in Europe/North Africa/Americas.

#### 12.5.8.2 Barrel/belly washer

- · Simple.
- Low abrasion effect.
- Lower degree of sophistication.
- · Less aggressive action.
- · Less productivity ratio.
- More common in Asia (China).

### 12.5.9 Enzymes

This section focusses only on cellulases because they are the most important and decisive elements in the jeans washing process. Choosing the correct enzymes in the first place is important to determining the factors that have to be taken into consideration.

From the garment point of view:

- Abrasion level.
- Colour shade.
- · Backstaining.
- Contrast.
- Handle/softness.
- Strength retention.

From the process point of view:

- Cost.
- Robustness.
- Easy to use.

The purpose of cellulase formulation is to provide the customer with an easyto-use product which maintains a processing pH suitable for the cellulase, whilst ensuring proper wetting and low backstaining. A typical formulated product contains one or more cellulase products, buffer salts, surfactants and other auxiliaries to adjust the physical properties. The following important points should be considered.

Performance related parameters:

- · Choice of product.
- · Buffer requirements.
- · Dispersing agent.
- Wetting agent.
- Product strength.

Product stability and reliability:

- Enzymatic stability.
- Product stability (hygroscopicity, flowability).
- Microbial stability.
- Homogeneity.

Customer parameters:

- Fabric type and quality.
- · Process equipment/stones.
- Process conditions.
- Water quality.

It is important to have a technology which can be adapted to achieve a range of different abrasion levels, abrasion patterns and handles, for use as a fashion tool. On the other hand, cellulase enzymes are a processing aid which needs to deliver:

- Abrasion or bioblasting without extensive loss of tear or tensile strength.
- A certain level of forgiveness to minimise the risk of overtreatment.
- · Robustness with respect to process conditions.

To achieve the desired combination of processing attributes and the final look of the denim, the appropriate enzyme must be chosen. When choosing cellulase products for the washing process, the following must be taken into consideration:

- Enzyme concentration and level of aggressiveness: Different products will reach different levels of abrasion at the same % o.w.f. dosages due to variation in aggressiveness.
- Sensitivity to mechanical action:

Multicomponent enzymes are generally less sensitive to differences in mechanical action, whereas monocomponent enzymes will typically show better performance in high mechanical action systems. At low liquor ratios, monocomponent enzymes are very effective on their own. At higher liquor ratios, a multicomponent enzyme or a blend of monocomponent and multicomponent is the better choice. When using a mono-component, increasing cycle time is recommended to effectively increase abrasion levels.

- Operating conditions: pH and temperature: Enzymes which operate in broad conditions of pH and temperature ranges are easily adjusted and will maximise the level of abrasion achieved at a given dosage.
- Formulation compatibility: All selected enzymes must be compatible with the surfactant, buffer system (external or internal) and auxiliaries chosen for the process.

#### 12.5.10 Auxiliaries

Apart from enzymes, other auxiliaries are used in the washing process with the objectives of improving:

- Process control: buffers.
- · Process efficiency: neutralisers of bleaching process.
- · Quality: antibackstaining, detergents, wetting agents, lubricants, anticorrosion.
- · Fashion handle: softeners, silicones, resins, fluorocarbons.
- Fashion look: cast changers, dyes, pigments, etc.
- · Fashion concepts: wellness and delivering systems.

The most important auxiliary products that can further improve the basic enzyme treatment (washing performances) are discussed further.

### 12.5.11 Buffer system

Nowadays, almost all enzymatic preparations contain an adequate buffer system to operate at the maximum efficiency range of each particular enzyme. However, because of cost reasons, some enzymes preparations only contain fillers and very little dispersing agent. In any case, a good buffer system (external or internal) is important for adjusting control of the pH in the abrasion cycle. Typical mixtures of weak acids and bases and their salts can be applied. The choice depends on the desired pH, price, etc.

Optimal buffer capacity will be obtained within 0.5 pH units of the pKa (pKa =  $-\log Ka$ , where Ka is the dissociation constant expressing the acidity of the acid; a strong acid will possess a high Ka.) The pH may vary depending on temperature (especially amine containing buffers) and ionic strength. A typical end user strength product will contain 30–40% buffer salt, depending on the desired pH, water quality, liquor ratio and fabric type. Residual alkalinity from the fabric normally makes acidic pH control more difficult and requires higher buffer concentrations.

Figure 12.21 shows the pH evolution during the combined process (desizing and abrasion in one step) and the differences of performance in terms of pH control between different formulations. The buffer systems can be used as a starting point and additional adjustment to meet local conditions should be expected.

#### 12.5.12 Antiredeposition agents

Surfactants provide some remarkable benefits in denim finishing. Antiredeposition (dispersing) agents reduce backstaining and improve contrast. Wetting agents increase

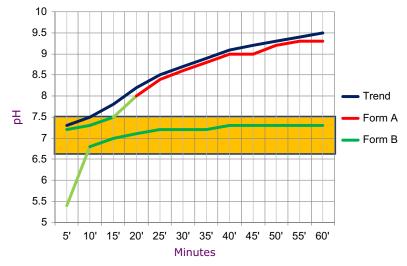


Figure 12.21 pH evolution during the combined process.

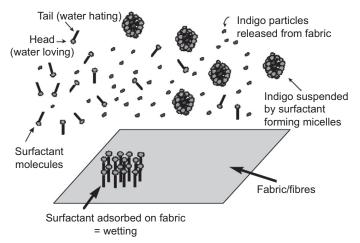


Figure 12.22 Action of surfactants in denim washing.

cellulase performance by facilitating optimal contact between the cellulase and the cotton fabric. Surfactants are surface active compounds which consist of two parts: a hydrophobic tail and a hydrophilic head group (they are amphipathic). This unique structure results in a tendency to adsorb at surfaces and interfaces, thereby lowering surface tension. Surfactants self-assemble into structures called micelles which are very important for dispersing properties. A certain concentration is necessary for the micelles to form, normally denoted as the critical micelle concentration. The action of surfactants in denim processing is shown in Figure 12.22. Traditionally, surfactants are classified on the basis of the polar head group:

- Nonionics (zero charge).
- Anionic (negative charge).

- Cationic (positive charge).
- · Amphoteric (negative and positive charge).

Nonionic surfactants are widely used in denim finishing. The head group often consists of a polyether, especially oxyethylene or oxypropylene. An alcohol ethoxylate consists of a number (n) of polar ethoxy groups linked together ( $-OCH_2-CH_2-$ )n. The number 'n' is called the degree of ethoxylation. In ethoxylate propoxylate types, the head will consist of a mixture of ethoxy and propoxy groups ( $-O-CH_2-CH_2-$ )n, +( $-O-CHCH_3-CH_2-$ )m.

A special feature of polyether based surfactant solutions is that they become cloudy above a certain temperature. This temperature is called the cloud point. Surfactants often work most efficiently at temperatures close to their cloud point. Surfactant solutions should be stored well below the cloud point to avoid phase separation. The size of the lipophilic tail by comparison with the hydrophilic head group is very important for the properties of a surfactant. If the hydrophilic head dominates a surfactant, it will prefer to stay in solution and thus be a good dispersing agent. If dominated by its lipophilic tail, it will adsorb to surfaces and be a good wetting agent. This characteristic can be quantified based on the chemical structure of a surfactant and is denoted by the hydrophilic lipophilic balance, or HLB. HLB values can be found in data sheets from most surfactant suppliers.

By changing the size or the structure of the head or tail group, the properties of the surfactant change. When the degree of ethoxylation is increased, the hydrophilic part increases. In addition, a range of associated characteristics also changes, as summarised as follows:

- HLB increases.
- Cloud point increases.
- · Dispersing ability increases.
- · Wetting ability decreases.
- · Water solubility increases.
- · Foaming increases (until approximately 13 EO, then falls again).
- · Melting point increases.

Modifying the tail results in the opposite changes in surfactant characteristics:

• A longer or more bulky (branched) tail will lower the HLB, enhance the wetting properties, reduce the dispersion properties and decrease the foaming tendency.

The following very general guidelines can be applied when choosing a nonionic surfactant:

- HLB 9-11: good wetting agent, for example alcohol ethoxylate C12-14 (EO)n, n=4-7.
- HLB 11–14: exhibits good wetting and dispersing properties, for example C13.
- Alcohol ethoxylate (branched) C13 (EO)n, n=7–10.
- HLB >14: good dispersing agent.

A combination of two or more surfactants often improves performance. If working with a solid formulation, the physical form of the surfactant may constitute a problem. Most surfactants of interest are liquids or pastes at room temperature. Many

| Surfactants and polymers         | Cellulase performance  |
|----------------------------------|--|
| Nonionic surfactants             | Generally compatible with all nonionic surfactants, espe-<br>cially ethoxylates. High foaming surfactants should be<br>avoided or a defoamer should be used.   |
| Anionic surfactants              | Noncompatible and they may cause the enzyme to dena-<br>ture, especially if used alone. The use in combination<br>with a very low concentration of nonionic surfactant<br>may be beneficial. Avoid high foaming surfactants. |
| Cationic surfactants (softeners) | May be compatible, however, surface coverage may<br>prevent cellulase adsorption and hydrolysis.   |
| Amphoteric surfactants           | Compatible   |
| Polymers                         | Generally compatible with most polymers used (polyeth-<br>ylene, polyvinylpyrrolidone).<br>Note that some polymers will adsorb to cotton fabric and<br>prevent cellulase action by surface coverage.                         |

#### Table 12.13 Effect of surfactants and polymers on cellulase

surfactants are essentially water soluble, but their rate of dissolution may differ. Slow dissolving surfactants tend to form a gel like, sticky substance upon contact with water which can be a problem in some dosing systems. The addition of a buffer salt, mixed into the product, will usually minimise this problem.

Compatibility is a very important point as some surfactants can have a negative influence on cellulase performance. This is typically related to one of the following three phenomena:

- · Inactivation of the enzyme from denaturation (protein unfolding).
- Surface coverage which impedes the cellulase action.
- · Foaming which lowers the mechanical action and traps the enzyme in the foam phase.

Table 12.13 shows the effect of various surfactants and polymers on the performance of cellulase enzymes. It also provides some general guidelines for compatibility with different surfactants and polymer classes. However, washing trials are highly recommended in the product selection phase.

### 12.6 Backstaining phenomenon

Backstaining or redeposition is when indigo released during stone washing, stains back onto the denim material (recolouration) of the blue threads and causes blue colouration of the white threads and pockets of the denim garment. It is without doubt one of the main issues of the washing process. Back staining reduces the contrast between the dark blue and white parts of the fabric. Backstaining is a term which refers to the amount of stain that accumulates on the natural undyed filling yarns as result of a wet process step. Cellulase enzymes create the abraded effect on denim by removing small pieces of the cotton yarns by an enzymatic chemical reaction.

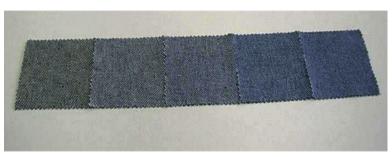


Figure 12.23 Backstaining on denim fabrics.



Figure 12.24 Backstaining on pockets (left).

Once the piece of cotton is removed along with the colour, the enzyme can reattach the colour back on the warp and fill yarns via a binding site on the enzyme molecule. This results in staining of the cotton and often masks the actual amount of colour removed. Backstaining is undesirable in denim washing and some poor quality articles are directly linked to these problems because:

- Redeposition of loose indigo, or indigo dyed short fibres, removed during desizing, stone washing or enzyme washing.
- Redeposited indigo, reduces the contrast between warp and undyed weft.
- Redeposited indigo stains pockets and labels.
- Redeposited indigo is more prone to ozone and yellowing.

Figure 12.23 shows the backstaining on denim fabrics, whereas Figure 12.24 shows the backstaining on pockets (left side). Figure 12.25 shows the influence of pH on the backstaining. The degree of back staining depends on:

- The cellulase type and composition:
  - Acid cellulases because the pH influence during the treatment causes more backstaining than neutral cellulases. Formulations that do not contain dispersing systems perform more poorly.

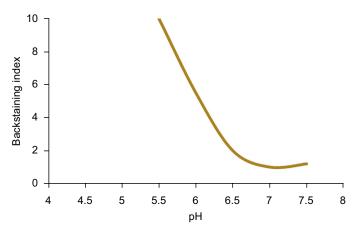


Figure 12.25 Influence of pH on backstaining.

- Type and concentration of surfactants:
  - Nonionic surfactants in a combination with PE polymers display the best results for maintaining the indigo in dispersion and consequently improve antibackstaining performance. Polyester polymers were first introduced in garment washes market in 1997. The polyester polymers revolutionised the wash industry in allowing laundries to control, and in some cases, completely eliminate backstaining. The products work equally well in prevention of staining of both polyester and cotton fibres in all washing steps (desizing, abrasion and after treatments).
- · Processing factors:
  - pH, time, temperature, liquor ratio, mechanical effect and after treatments (rinses).
- Type of fabric (denim and pockets):
  - Today many denim fabrics are treated with fixing agents to avoid an excess of indigo colour loss during the washing process. Nevertheless, some fabrics present a great loss of indigo during the washing treatment and it is very difficult to keep the indigo particles in suspension. Furthermore, in the case of pockets, we can observe that the fabrics composed of 100% cotton cause more problems than polyester/cotton blends.

### 12.7 Troubleshooting guidelines

In earlier days, garment processing was limited to the washing of blue and black denim. Nowadays, much more extensive treatments of garments are possible in laundries (e.g. dyeing, permanent wrinkles, special effects). Denim fashion was the start of today's garment finishing, but to this day jeans washing is still the largest part of this industry sector.

The target of normal garment washing is to provide good handling and softness and to improve the wearing comfort of the previously stiff fabric. However, in jeans washing, the main target of the process is to improve the visual appearance of the garments, giving them more aesthetically pleasing looks. It is with this aim in mind that the laundries produce fashionable finishes such as stone wash, ice wash, used look, etc. They can however, face some or all of the problems listed here.

Appearance issues:

- · Unevenness.
- Crease marks, streaks and spots.
- Reduced tensile and tear strength.
- Staining on white parts.
- Poor handling.
- Shrinkage too high.
- Corrosion of metal parts.
- Poor contrast between warp and weft.
- Colour changes of indigo dyed garments caused by air pollution.

The laundry, usually the last stage in the jeans production chain, can face difficulties created by previous mistakes. Therefore, cooperation throughout each step of jeans manufacturing is required to avoid problems. Good cooperation between fabric producers, garment manufacturers, laundries and chemical suppliers is essential to obtain the desired results. In this respect, the following guidelines are presented from a practical point of view:

- · Washing protocol guidelines.
- Troubleshooting guide.
- A–Z index for garments.

Table 12.14 shows the general washing protocol guidelines. Table 12.15 provides the troubleshooting guidelines in jeans washing, and Table 12.16 provides the commonly used A–Z index for denim garment processing.

### 12.8 Sustainable developments in washing

Sustainability is great concern in the jeans washing industry and in this respect a combined process which can reduce water consumption, energy, time and harmful substances was developed by Novozymes, and is termed Denimax Core<sup>®</sup>. In the standard process, desizing or prewash and abrasion are carried out in two separate steps and large amounts of water and heat are used during processing and it may involve several rinsing steps. Figure 12.26 shows the standard washing steps for desizing and abrasion processes.

With the new enzyme Denimax Core process, desizing or prewash and abrasion can be combined in one bath, and heat and electricity can be saved because less water needs to be used and heated and less electricity is needed for water pumping and stirring. Figure 12.27 shows the Denimax Core washing steps for desizing and abrasion process. The amounts of energy and water that can be saved vary from factory to factory depending on process setup, liquor ratio, heat and electricity sources as well as energy and water management.

# Table 12.14Washing protocol guidelines

| General inform                                    | ation      |          |           |             |               |               |
|---|------------|----------|-----------|-------------|---------------|---------------|
| Trial date:                                       | Run no.:   |          | Name      | of pe       | erson:        |               |
| Name of laundry:                                  |            |          |           |             |               |               |
| Washing machine: (make and capacity):             |            |          |           |             |               |               |
| Denim: yes or n                                   | 0          |          |           |             |               |               |
| Garment brand:                                    |            |          |           |             | Weigh         | t/ (kgs):     |
| Pocket composit<br>(cotton/polyester              |            |          |           |             |               |               |
| Fabric compositi                                  | on:        |          |           |             |               |               |
| Total weight of w<br>(kgs):                       | vashload   | ls t     | oackstai  | ning        | a conce       | ern?          |
| Desired level of                                  | abrasion ( | high, me | edium, Ic | ow):        |               |               |
| Desired effect:                                   |            |          |           |             |               |               |
| Is strength loss important (y/n):                 |            | Target   | tensile:  |             |               | Tear:         |
| Current prepara                                   | ation proc | edures   |           |             |               |               |
| Type of desize (                                  | (amylase,  | caustic, | etc.):    |             | Amour         | nt (g):       |
| pH: Tem   | р (°С):    |          |           | Сус         | cle time      | (min):        |
| Are any abrasive perlite, other):                 | es used (p | umice,   |           |             | Amount (kgs): |               |
| Current enzyme                                    | e procedu  | res      |           |             |               |               |
| Cellulase produc                                  | ct name:   |          |           |             | Amour         | nt (g):       |
| Are any abrasives used (pumice, perlite, other)?: |            |          |           | Amour       | nt (kgs):     |               |
| Is any acid of buffer added (acetic, etc.):       |            |          |           |             | Amount (g):   |               |
| Are any surfactants added (identity)?:            |            |          |           | Amount (g): |               |               |
| a)  |            |          |           | Amount (g): |               |               |
| b)  |            |          |           | Amour       | nt (g):       |               |
| c)  |            |          |           |             |               |               |
| pH: Temp (°C                                      | :)         | Cycle    | time (m   | nin):       |               | Liquor ratio: |

| Additional procedures (clean-up, so wrinkle free) | ftening     | , bleachi   | ng,               |  |
|---|-------------|-------------|-------------------|--|
| Clean-up – Are any surfactants added              |             | Amount (g): |                   |  |
| (identity)  | Amount (g): |             |                   |  |
| a)  |             | Amount      | (g):              |  |
| b)  |             |             |                   |  |
| c)  |             |             |                   |  |
| Cycle time Temp (°C):<br>(min)                    |             | Number      | of rinses:        |  |
| Bleach (chlorine, peroxide,<br>laccase, etc.)     | Amour       | nt (g):     | Cycle time (min): |  |
| Resin treatment used?                             | Amount      |             | Catalyst?         |  |
| Type?   |             |             |                   |  |
| Softener used?                                    |             |             |                   |  |
| Procedures for trial (desize – soften             | ing)        |             |                   |  |
| Product to test                                   |             | Amount      | (g):              |  |
|   |             |             |                   |  |
| Abrasives (pumice perlite, other)                 |             | Amount      | (kgs):            |  |
| Type of pH controller (buffer or acid)            |             | Amount (g): |                   |  |
| Type of surfactants added (identity)              |             | Amount (g): |                   |  |
| a)  |             | Amount (g): |                   |  |
| ~,  |             | Amount      |                   |  |
| b)  |             | Amount      | (9).              |  |
| c)  |             |             |                   |  |

| Actual pH:                                      |              |              |        | Actual temp:          |
|---|--------------|--------------|--------|-----------------------|
| Cycle time (min):                               |              |              |        | Liquor ratio:         |
|   |              |              |        |                       |
|   |              |              |        |                       |
| Trial data                                      | a            |              |        |                       |
| Time<br>(min)                                   | Temp<br>(°C) | pН           |        | Observations          |
|   |              |              |        |                       |
|   |              |              |        |                       |
|   |              |              |        |                       |
|   |              |              |        |                       |
|   |              |              |        |                       |
|   |              |              |        |                       |
|   |              |              |        |                       |
|   |              |              |        |                       |
|   |              |              |        |                       |
|   |              |              |        |                       |
|   |              |              |        |                       |
| Results r                                       | elative to   | o standa     | rd     |                       |
| Abrasion  | (similar, to | oo little, t | too m  | uch, etc.):           |
| Colour (si                                      | imilar, ligh | nter, dark   | er, et | c):                   |
|   |              |              |        | gher, lower, etc.):   |
| Backstain                                       | ning on po   | ckets (si    | milar, | higher, lower, etc.): |
|   |              |              |        | her, lower, etc.):    |
| Cast on p                                       |              |              |        |                       |
| Cast on pockets (similar, bluer, greyer, etc.): |              |              |        |                       |
| Cast on tags (similar, bluer, greyer, etc.):    |              |              |        |                       |
| Physical strength loss:                         |              |              |        |                       |
| Softness:                                       |              |              |        |                       |

| Comments             |  |  |  |  |
|----------------------|--|--|--|--|
|                      |  |  |  |  |
|                      |  |  |  |  |
|                      |  |  |  |  |
|                      |  |  |  |  |
|                      |  |  |  |  |
| Recommendatio        | ons and conclusions                                      |  |  |  |
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|                      |  |  |  |  |
|                      |  |  |  |  |
|                      |  |  |  |  |
|                      |  |  |  |  |
| Troubleshooting      | g guide  |  |  |  |
| Streaks/lines        | Check lubricant and amylase dose                         |  |  |  |
|                      | Check temperature and machine speed                      |  |  |  |
|                      | Are synthetic sizes used (PVA)? – Try higher temperature |  |  |  |
|                      |  |  |  |  |
| Abrasion too<br>low  | Check pH and temperature for enzyme                      |  |  |  |
|                      | Check enzyme usage level                                 |  |  |  |
|                      | Check foam level   |  |  |  |
|                      | Check process parameters (pH, temp, LR, time, etc.)      |  |  |  |
|                      |  |  |  |  |
| Abrasion too<br>high | Check enzyme dosage                                      |  |  |  |
|                      | Check abrasive dosage if present                         |  |  |  |
|                      | Was time correct?  |  |  |  |
|                      |  |  |  |  |

| Backstaining    | Check enzyme dosage, check abrasion level                       |  |  |
|-----------------|---|--|--|
|                 | Check pH and temperature of abrasion bath                       |  |  |
|                 | Check clean-up chemistry  |  |  |
|                 | Does backstaining get worse with softening?                     |  |  |
|                 | Was foaming too high?   |  |  |
|                 | Possible reduction in temperature                               |  |  |
| Strength loss   | Check dosage level of enzyme and abrasives                      |  |  |
|                 | Reduce time and/or dosage if needed                             |  |  |
| Shade too light | Check bleach/peroxide/laccase concentrations, temp and time     |  |  |
|                 |   |  |  |
| Shade too dark  | Check bleach level, temperature and pH                          |  |  |
|                 | If laccase – test temperature and pH                            |  |  |
|                 | If peroxide – check dosage and temperature. Is stabiliser used? |  |  |

### 12.8.1 Water savings

Combining desizing or prewash and abrasion with Denimax Core can save two of four baths and therefore reduce water consumption by 50%, that is,  $2 \times 10 = 20 \text{ m}^3$  water per ton of denim fabric, if the liquor ratio is 10.

### 12.8.2 Heat savings

Energy savings achieved by combining desizing or prewash and abrasion are primarily driven by heat savings. When the combined denim jeans wash process is introduced, one heated bath (50-60 °C) is avoided. Given an ambient water temperature of 20 °C and a liquor ratio of 10, the heat saving can be calculated.

### 12.8.3 Greenhouse gas reduction

Greenhouse gas savings achieved by combining desizing or prewash and abrasion are mainly driven by heat saving and have been roughly estimated.

| Symptoms                             | Possible causes  |
|--------------------------------------|--|
| White lines                          | Packing (not opening)  |
|                                      | Poor desizing  |
|                                      | Overloading  |
|                                      | Water level too low/high   |
|                                      | pH too low/high  |
|                                      | Temperature too low/high   |
| Crow's feet                          | Overloading  |
|                                      | Poor stone quality   |
|                                      | Poor desizing  |
| Uneven wash                          | Turning of sleeves in jackets  |
|                                      | Overloading  |
|                                      | Manufacturing error  |
|                                      | Mixing fabrics   |
| Backstaining                         | Poor dye suspension  |
| -                                    | Too much loose dye   |
|                                      | Lack of rinses   |
|                                      | Water level too low  |
|                                      | pH too low   |
|                                      | Temperature too high   |
| Blue pockets                         | Same as above  |
| Crocking                             | Same as above  |
| Hard jeans                           | Poor desizing  |
|                                      | Poor softening   |
|                                      | Over drying  |
| Abrasion                             | Over dosage of enzymes/stones  |
| <ul> <li>Too much</li> </ul>         | Wash process too long  |
| Abrasion                             | Not enough mechanical action   |
| <ul> <li>Lack of abrasion</li> </ul> | pH out of control (enzymes)  |
|                                      | Activity of enzymes  |
|                                      | Presence of resins/pigments in fabric coatings                       |
| Staining                             | Alkali, chlorine, softener   |
| Poor colour                          | Chemical residues: alkali (brown cast), chlorine (yellow-green cast) |
|                                      | Low pH on bleaching (greenish cast)                                  |
| Marbling                             | Use of large rocks   |
|                                      | Improper water level   |
| Holes in pocket                      | Stones trapped in pockets  |
| Yellow cast                          | Bleach residue   |
|                                      | Low pH bleaching   |
| Rusty rivets and                     | Stone abrasion   |
| buttons                              | Alkali attack  |
| Elastane missing                     | Inadequate chlorine treatment  |

 Table 12.15
 Troubleshooting guidelines

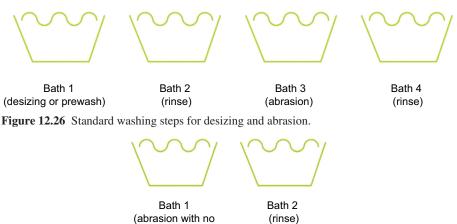
### Table 12.16 A–Z index for denim garment processing

| Amylase          | Enzyme used for enzymatic desizing containing starch.   |
|------------------|---|
| Backstaining     | Indigo pigments which are removed during processes which stain back   |
|                  | onto the garment: pockets and weft yarns turn blue which is usually not required.   |
| Bioblasting      | Treatment of hairy cotton garments with enzymes to decrease pilling.  |
| Blue denim       | Woven fabric with indigo dyed warp yarn. The weft yarn remains white.   |
| Black denim      | Woven fabric with sulphur dyed black warp yarn. The weft yarn remains white.  |
| Bleaching        | Decolouration and removing of natural pigments and impurities to increase the white level of the garment.   |
| Blend            | Garments which are mixed with minimum two different raw materials.  |
| Cellulase        | Enzyme used for abrasion and bioblasting treatments. Depending on their application, neutral or acid cellulases can be used.  |
| Desizing         | This is usually the first treatment step to prepare the garments for the subsequent finishing processes. During this process the size which was applied for the weaving process is removed. |
| Dispersing agent | Chemical which is used in the wet processes of jeans to prevent backstaining.   |
| Enzyme wash      | Enzymatic treatment of garments to achieve abrasion. This process should imitate a used look on garments.   |
| Garment dyeing   | Dyeing of readymade garments. Mainly reactive and direct dyes are used.   |
| Garment bioblast | Treatment of garments with a short washing step. Garment washes are carried out if no effects and no colour changes are required.   |
| Laccase          | Enzyme which is used for enzymatic bleaching of indigo denim fabric.  |
| Ozone machine    | System based on ozone delivery that can achieve bleaching effects.  |
| Ozone            | Radical of oxygen which causes yellowing on garments and jeans, especially during storage in store.   |
| Organic cotton   | Cotton which is organically cultivated and not treated with toxic chemicals.  |
| Pigments         | Water insoluble colourants which are used for low cost colourations.  |
| Stone wash       | Treatment of jeans with pumice stones and enzymes which produce a worn out look.  |
| Shrinking        | Process where garments gets smaller caused by wet and hot processes.  |
| Vintage          | The worn out look which jeans get over a long wearing time or imi-<br>tated by the laundries.   |
| Yellowing        | Degradation of indigo dyestuff by radicals: mainly oxygen.  |

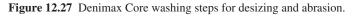
Table 12.17 shows the potential consumption savings with Denimax Core process.

### 12.8.4 Comparison of washing protocols

A comparison of the conventional standard washing protocol against that of Denimax Core is discussed further, where some practical examples under bulk conditions are considered.



prewash)



### Table 12.17 Potential savings with Denimax Core

Heat: 3400 MJ Electricity: 18 kWh Water: 30 tonnes Auxiliaries: 20 kg Data per ton fabric Reference: Novozymes environmental assessment of Denimax Core with reference to Life Cycle Assessment of 'Elemental Textiles'

- Garment manufacturer with own washing plant.
- Current production: 5000–7000 pieces per day.
- Brands: own brand.
- Machine: Tonello front load.

### 12.8.5 Standard protocol

Desizing: (60 °C × 10 min) Water: 1000 L Desizing enzyme: 2 kg Cold rinse (2 min): water 1000 L Abrasion (40 °C × 50 min) Water: 700 L Neutral granulate: 1.5 kg Cold rinse (2 min): water 1000 L Finishing

### 12.8.6 Denimax Core process

Biowash: (40 °C × 50 min) Water: 1000 L

|                       | Standard process  | Denimax Core process      |
|-----------------------|---|---------------------------|
| No. of steps          | 5   | 3                         |
| Time (min)            | 64  | 53                        |
| Water (L)             | 3700  | 1700                      |
| Steam                 | For desizing $60 ^{\circ}\text{C} \times 15 \text{min}$ | No steam                  |
| Chemicals and enzymes | Desizing enzyme: 2 kg                                   | Desizing enzyme: 0kg      |
|                       | Neutral granulate: 1.5 kg                               | Denimax Core 1380s: 1.2kg |

#### Table 12.18 Comparison of standard and Denimax Core processes

Summary of benefits to customers: Time saving: productivity increase by ~20% Water saving: 2000 L water less Energy saving Cost



Figure 12.28 Denimax Core (left) comparison with standard process (right).

Adjust pH to 6–6.5 Denimax Core 1380S: 1.2 kg Cold rinse (2min): water 1000L Finishing

Table 12.18 provides a comparison of standard process with Denimax Core process. A savings calculator provided by Novozymes, shows in detail, the real cost savings for each specific process. Figure 12.28 compares the Denimax Core process (left) with standard abrasion process (right). The Denimax Core process thus saves time, energy and water, and it reduces the consumption by up to:

- 50% water.
- 50% heat.
- 15% for electricity.

#### 12.9 Future trends

Enzymes are capable of replacing the stone washing and chemical bleaching process in denim jeans washing and can develop the desired looks in a more environmentally friendly way. As early as the 1970s, amylases were used to desize denim to eliminate the need for harsh alkali chemicals in the desizing step. In the 1980s, stone washing and bleaching were introduced for denim to achieve increased comfort and new fashionable looks. But these processes have eventually resulted in huge effluent problems. Later in the decade, cellulases were used to achieve abrasion effects whilst eliminating some of the disadvantages of stones. Cellulases are also used for the specific treatment of antipilling in denim fabrics (bioblasting). As of today, enzymes are available commercially as an alternative to chemical bleaching where the laccase uses a mediator radical to oxidise indigo to soluble degradation products.

In the future, the environmentally conscious consumers will demand more sustainable processes for jeans washing. The industry is also responding to this demand and continues to develop more sustainable processes involving enzymes, laser, ozone, etc. In general, some of the main hurdles for the complete industrial implementation of enzymes are their low stability, low compatibility with other chemical agents, longer processing time and their relatively high cost. In this context, the future will witness the development of robust enzymes with increased efficiency, either by genetic engineering or by using mixed enzymatic systems. The enzyme immobilisation could also rise up as an essential methodology to ensure the reuse of enzymes and thus reducing the process costs. Thus, most of the conventional processes involving chemicals in denim garment washing will possibly be replaced with bioprocesses or by other dry techniques, reducing considerably the environmental footprint.

# 12.10 Conclusion

Nowadays, enzymes are available commercially for substituting chemicals and stones in the denim washing and finishing processes. Biotechnology and precisely enzymes can play an important role in denim garment washing for reducing its environmental impact. The application of enzymes is now well known to the majority of finishers and laundries and the big brands and retailers are also very much aware of their sustainability aspects. The continuous research on new enzymes and formulations are going hand in hand with the innovation and sustainability strategies of leading fashion brands and laundries. Thus there will be more and more applications for enzymes in denim and garment processing and the further optimisation of existing enzymatic formulations or combined processes will hold the key for efficient and sustainable jeans production.

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# Reduced water washing of denim garments



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## 13.1 Introduction

The denim jeans industry is unique in that the cut and sew process is not the final stage of manufacturing. The washing or finishing stage has developed into a major industry in itself and is primarily designed to bring a particular unique aesthetic to the final garment. The washing of a denim garment brings with it major added value but also has the potential to cause environmental or human damage. Industrial washing of jeans started in the late 1970s/early 1980s and, even though thousands of pairs of jeans are produced every day, jeans finishing has been largely an artisanal process with little regard for water or chemical excesses.

The pioneers of the industrialisation of jeans finishing at that time are now the denim gurus of today. François Girbaud, one of the most iconic industry figures, is on record as saying that he has had 'an environmental awakening' and that he does not want to make jeans using traditional methods anymore. He also said that one cannot continue to waste water, which is going to become a very scarce resource (Denim Freaks, 2012). This declaration of François Girbaud illustrates the beginning of a new revolution in the mass production of jeans. In 2010, Levi's launched its 'Water <Less' jeans collection and claimed to reduce the water consumption in the line (Levis Strauss & Co., 2012). 'Low impact denim' by Jack and Jones (Jack and Jones, 2014), H2Ø from Springfield (Joe Madrazo, 2012) or the conscious denim collection by H&M (2013a) are a few more examples of the efforts to reduce water consumption in the jeans manufacturing supply chain.

A recent denim Life Cycle Assessment (LCA) analysis (Levi Strauss & Co., 2009; Ademe, 2011) reveals that more than 3000L of water are used during the full product life cycle of a pair of jeans. According to this analysis, the most important water consumption happens during the domestic washing and cotton growing stages, respectively, and only 3% of the cradle to grave water consumption comes from the manufacturing process. Although the contributions of garment finishing look small in comparison, one might be astonished when looking at the numbers involved.

Annual global jeans production is estimated in 5000 million units and, considering that the average amount of water required to finish one pair is 70L, this means that 350 million m<sup>3</sup> are consumed in jeans manufacturing. This is twice the water supply needs of all inhabitants of one of the most populated cities of Europe, Madrid (Spain) (Instituto Nacional de Estadística, 2013; Europa Press, 2009). Table 13.1 shows the total water consumption in jeans production.

| Table 13.1 W | Vater consumpti | ion in jeans | production |
|--------------|-----------------|--------------|------------|
|--------------|-----------------|--------------|------------|

| Average water consumption per jeans produced<br>Estimated annual production of jeans | 70 L<br>5000 million pairs |  |
|--|----------------------------|--|
| Total water consumption in jeans production  | 350 million m <sup>3</sup> |  |

It is easy to understand, after analysing these data, why denim finishing using less water is becoming a priority for many brands and retailers. New technologies such as laser and ozone, together with new thinking about ways jeans are washed, are making it possible. The adoption of these reduced water finishes is a sign of the radical transformation happening within the garment finishing industry, which is changing from an artisanal, labour intensive industry towards an industry based on knowledge and technology that feels more responsible for the environment and for workers.

## 13.2 Techniques for reducing water in denim washing

#### 13.2.1 Definition of reduced water techniques

Generally speaking, reduced water finishing processes are those that obtain a defined look and handle using the minimum quantity of water. To quantify this minimum amount of water is a difficult task. Different working methods have been applied to find out acceptable levels of water consumption to finish a pair of jeans. Most of the research refers to the definition of the average water consumption in garment processing. Knowing these data, it should be possible to set limits at which a process can be considered as a minimum or reduced water finish. But, according to Nike Inc. (2010), garment treatments are a Pandora's box. Every treatment is different and the combinations of dry and wet processes are infinite; moreover, to obtain the same look, the process might be different if different fabric qualities are used. This complexity makes it very difficult to define standards and that is why every garment style needs to be assessed individually. This is also why every brand and retailer is defining its own threshold for reduced water denim washes.

Jack & Jones have carried out an indepth LCA which has allowed them to define the average water consumption for their five best selling jeans, which accounts for 40% of their total production. The LCA research concludes that the average water consumption of finishing a pair of Jack & Jones jeans is 36L per garment. By introducing new technologies and innovative thinking in their production, they were able to save >40% water and, additionally, important savings on energy consumption. The company defines jeans as 'low impact denim' when they are finished with less than 22L of water. Levi Strauss & Co. also published the results of an LCA (Levi Strauss & Co., 2009) it conducted. According to the information in its Website, Levi's analysis led them to conclude that the average consumption of water in the finishing



**Figure 13.1** Reduced water finished garments. © Jeanologia 2014.

stage is 42L per garment. In its 2010 Water < Less campaign, Levi's talked about water savings from 28% up to 96%. Figure 13.1 shows some examples of reduced water garments.

The quest to develop best practise in denim washing is not only the concern of brands and retailers. Other sectors of the industry are also driving initiatives to promote environmental awareness within industrial laundries. As an example of this, in 2011, Jeanologia launched its Environmental Impact Measuring (EIM) tool (Jeanologia s.l., 2012). With regards to water, EIM classifies a low impact process as consuming less than 35 L of water per garment.

#### 13.2.2 Reduced water finishing techniques

There has been significant technical evolution in the production of denim fabrics in the past several years. Denim mills have attempted to develop fabrics with laundry requirements in mind: 'easier to wash' fabrics. However, many laundries have failed to adapt to this; as a result, washing formulas today are no different from the washing formulas used 10 years ago.

H&M explains on its webpage that water savings of upto 30% can be achieved solely through process optimisation (H&M, 2013b). Therefore by questioning the conventional finishing and understanding why certain processes are carried out and taking into consideration the improvements in denim fabrics, the company found that a change in the mentality of the garment washing industry can lead to important savings, not just in water, but also in energy, chemicals and toxic waste. Moreover, the available technologies such as laser, ozone and Jeanologia e-flow contribute greatly to the reduction of the environmental footprint of a laundry.

The ongoing research of denim mills and chemical suppliers are playing an important role in the implementation of these technologies. Mills are working to define best dyestuff categories and dyeing procedures that react positively to laser and ozone



**Figure 13.2** Laser marking process. © Jeanologia 2014.

treatments. Enzyme producers are working on the combination of multiple wash cycles into a single wet cycle process.

The successful reduction of water use by the denim finishing plants is the result of a combination of changes in the mentality and the integration of the new technologies into the conventional processes. But, as mentioned previously, there are numerous concepts to consider and, as such, results can be different when some of these concepts are combined. For a better understanding of how each of the technologies can influence water consumption, a detailed description is given in the following sections. The biggest advantage in water footprint reduction comes from the combination of these technologies and its integration into the finishing routes.

#### 13.2.2.1 Laser technology

The energy provided by a laser beam has two effects on indigo dyed fabrics (Bosman, 2007). On one side, the thermal effect of the laser sublimates indigo dyestuff, bleaching to a certain extent those areas of contact. From another side, this thermal effect is burning the surface of the fabric, eliminating coloured fibres and revealing the undyed yarn/fibre below. Figure 13.2 shows the laser marking process of denim jeans.



**Figure 13.3** Laser effects after marking and after rinsing. © Jeanologia 2014.

The superficial burning of the fibres explains why after a laser marking, instead of a white area, a brown layer is found (this is then removed in a subsequent rinsing). Figure 13.3 shows the laser effects after the marking and also after the rinsing. The dyeing process of denim yarns can include additional dyestuffs to indigo, such as sulphur dyes (commonly sulphur black). Each dye has its own molecular structure and so reaction to the thermal effect of the laser will be different for each dyestuff.

The use of laser in the laundry is in fact not new. It was actually used in textile applications as far back as the late 1990s. Initially, laser treatments were seen more as a tool to create new and novel effects in denim garments, such as local printing, tattoo images, etc. But it was Jeanologia, after the launch of its first laser machine which discovered the real benefit for the use of laser in the denim finishing industry. The company took the risk and provided all the necessary resources to develop laser as a leading technology to replace manual finishing tasks such as whiskering, sand blasting and other artisanal techniques. Long years of research and a whole team of textile laser application expertise, distinguish the latest Jeanologia Twin HS laser machine from the first Jeanologia Marcatex machine. Figure 13.4 shows the Jeanologia Twin HS laser machine. Practical improvements include a marking area, increased machine power and greater productivity but probably more importantly tailor-made software, design expertise and constant customer support is what has set this product apart from the competitors.

## 13.2.2.2 Ozone technology

Amongst all the available new denim washing technologies, ozone is the one that has the greatest impact on water reduction. Ozone is a strong oxidising agent which decomposes indigo and other dyestuffs. The oxidising characteristic of ozone is used



**Figure 13.4** Twin HS laser machine. © Jeanologia 2014.

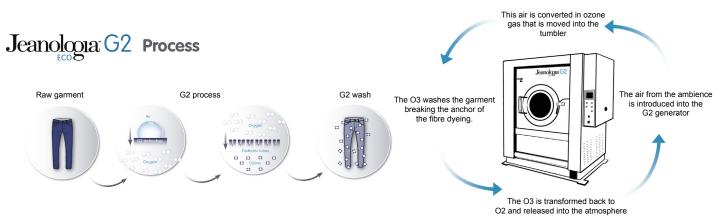
to fade down denim jeans, thus replacing enzymes, pumice stones or hypochlorite bleaching processes. The eco-certified G2 technology from Jeanologia has been a key technology for water reduction processes. Figure 13.5 shows the G2 processing scheme.

Ozone technology is a real revolution in the washing industry, not only for denim jeans but for other textile items such as T-shirts, shirts, chinos and casual wear in general. The ozone based technology named G2 technology is based on a natural system of provision of oxygen. The machine takes air from the atmosphere, filters the air and stores pure oxygen. This oxygen is transformed, through a photovoltaic excitement into ozone gas. The gas is introduced into a sealed tumbler where the degradation of the indigo takes place. Once the cycle is finished, the ozone is transformed back into oxygen and this oxygen is exhausted back to the atmosphere. The fade down of the denim jeans through ozone is consequently a clean process.

The most efficient bleaching effect is obtained when the fabric is ozonated at 60% wet pickup (Özdemir et al., 2008). This offers the option of treating indigo garments in two different states: dry or wet. When ozonisation of the garments is carried out in dry conditions, there is no evidence of bleaching; however, all indigo backstaining (redeposition of discharged indigo) is easily removed. When ozonisation of wet garments is done, indigo is bleached out. Using longer cycles or a higher concentration of ozone increases the degree of bleaching.

Through direct practical experience of commercial production, it has been proven that treating denim garments in the G2 machine makes is possible to eliminate indigo backstaining without the need for water or chemicals. Figure 13.6 shows the ozone cleaning of pockets. The direct benefits are (Jeanologia s.l., 2012):

- Increase in the white-blue contrast.
- Clean up of pockets, labels, etc.
- Enhancement of abraded areas, increasing the whiteness of these areas and so avoiding the need of using potassium permanganate.
- Enhancement of high-low effects.



**Figure 13.5** G2 processing scheme. © Jeanologia 2014.



**Figure 13.6** Ozone cleaning of pockets. © Jeanologia 2014.

The wet ozonisation of the garments can lead to:

- Substitution of abrasion processes (enzyme washes).
- Bleach down effects (substitution of traditional bleaching processes) without affecting fabric strength.
- Special effects.

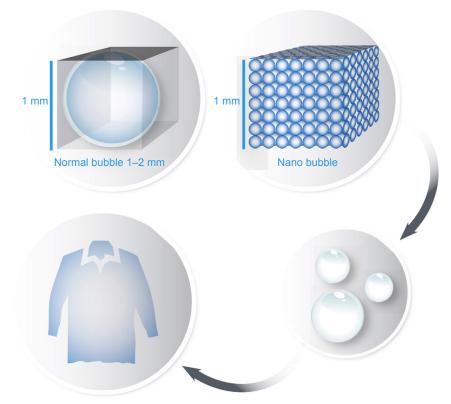
When treating wet denim garments with G2, high colour degradation takes place. The oxidation by-products of indigo are isatin, anthranilic acid and a complex of these two products which is yellow in colour (Özdemir et al., 2008). This is the reason behind yellowing resulting from atmospheric ozone fading. When fading is high, rinsing with water is necessary to remove the yellowing.

## 13.2.2.3 Nano bubble technology

A new technology based on nano bubbles developed and patented by Jeanologia is known as e-flow. The e-flow 'breaks up' the surface of the garment, achieving soft hand feel and controlling shrinkage. A minimal quantity of water is needed and there is zero discharge from the process. Air from the atmosphere is introduced into an electroflow reactor and subjected to an electromechanical shock creating nano bubbles and a flow of wet air. Figure 13.7 shows the e-flow process scheme.

The nano bubble mix is then transported into a rotating tumbler containing the denim garments, and when it comes into contact with them produces a soft and natural hand feel. The garments are then dried in the same tumbler. When treating indigo dyed garments with this technology, some indigo cross contamination may occur that can be eliminated by a dry ozone treatment.

As an example of the use of this technology is the sample denim garment shown in Figure 13.8. This aesthetic has been achieved with less than 1 L of water. Such jeans are known as 'new raw' jeans. The new raw garments look raw but they have important benefits for the end user. The e-flow process produces a preshrinkage of the fabric, avoiding high shrinkage during home laundry. It also gives a softer



**Figure 13.7** e-flow process scheme. © Jeanologia 2014.

hand feel and so the garments are comfortable to wear and even the rub fastness properties are slightly improved.

## 13.2.2.4 New enzyme formulations

Apart from the previously mentioned machine technologies, some other techniques and products are also used in reducing water usage in denim washing. Enzymes have been used in denim processing for a many years now. New enzyme formulations in combination with different processing steps have now become an area of research in several textile applications. In denim processing, the use of alpha amylase enzymes in desizing and cellulase enzymes to substitute the abrasion processes made with pumices stones are very well established within the finishing plants. The new generation of enzymes allows the combination of both desizing and abrasion processes in the same bath, thus reducing the need for both washing baths and rinses. Despite the benefits of processes combination, denim finishers seem to be reluctant to adopt this approach. The reason for that can be found in the fact that fewer process steps and fewer rinses lead to a higher indigo backstaining and consequently to a contrast reduction. Nevertheless, postozone treatment will remove the backstaining and create excellent results.



**Figure 13.8** New raw garment. © Jeanologia 2014.

# 13.2.2.5 Crosslinking agents

The use of glyoxal resins in denim finishing is relatively new, but their application has become a basic process because of the multiple properties that they confer to garments when applied as first finishing step. Crosslinking agents have a direct effect into fabric strength because there is a substantial change in the fibre structure. When controlling this strength loss, this characteristic can be used to embrittle, break and consequently remove fibres from the surface through dry mechanical action. This abrasion is effectively produced by dry pumice stones thus no water is required to obtain the valuable high and lows and increasing white and blue contrast in seams and fabric panel.

# 13.3 Industrial application scenarios

The three industrial application cases described in this section are taken from actual production scenarios. The garments have been finished combining the previously described reduced water technologies. To be able to quantify savings in water and energy, as well as the impact reduction to the environment and workers health, a conventional processing route is compared against the new alternative that uses laser and ozone technologies.

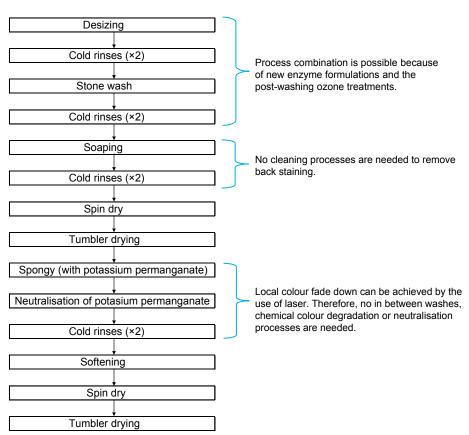


**Figure 13.9** Finished garment without backstaining. © Jeanologia 2014.

#### 13.3.1 Prevention of backstaining

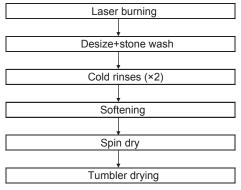
One of the major headaches in the denim laundry is indigo backstaining (Anon.). Backstaining reduces the white-blue contrast and gives an evenly distributed bluish colour all over the garment including local abraded areas, pockets, labels and other trims. Higher liquor ratios in washing, intermediate rinses, dispersing agents and specific steps such as soaping are different measures taken by the laundry specialists to prevent indigo backstaining. Contrast on local abraded areas is also often masked because of the indigo backstaining. In this case, techniques such as spraying potassium permanganate are adopted to achieve the desired effect. The garment to be reproduced, conventional processing route and the alternative route using new technologies are shown in Figures 13.9–13.11, respectively.

Backstaining is not a problem when ozone technology is used, so any actions carried out in the past to prevent it are not necessary anymore. It is possible to combine the desizing and stone wash processing steps, using the new generation of enzymes, to reduce the



#### Water: 91 L/garment produced

**Figure 13.10** Conventional processing route. © Jeanologia 2014.



Water: 24 L/garment produced

**Figure 13.11** Alternative processing route. © Jeanologia 2014.

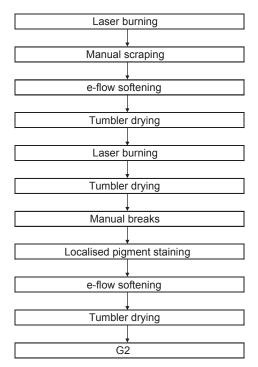


**Figure 13.12** Finished garment with whiskers. © Jeanologia 2014.

number of rinses to just one, and to eliminate the soaping operations, by adding a dry ozonisation stage at the end of the finishing processes. The local colour reduction, achieved by using a sponge soaked in a potassium permanganate solution, can be replaced by a laser marking. Both actions not only lead to a reduction of 75% in water consumption but also to a better quality product and consistent effect through the whole production.

# 13.3.2 Recreation of whisker and natural ageing

By employing the laser, it is possible to recreate the whisker and local used areas which are typical of the natural ageing of a raw pair of jeans. Softening with the e-flow induces shrinkage in the garment, so that shrinkage will not happen during home laundry and it will be softer and consequently more comfortable to wear. The resultant ash resulting from the laser marking is eliminated by humidification of the fabric during micronisation and the garment to garment surface friction. Micronisation is the action of transferring the micro bubbles created by e-flow to the surface of the garments. However, humidity and surface abrasion can result in increased indigo backstaining which can be completely removed during a dry ozonisation process. The garment to be reproduced and the processing route using new technologies are shown in Figures 13.12 and 13.13, respectively.



Water: 1.3 L/garment produced

Figure 13.13 Processing route. © Jeanologia 2014.

## 13.3.3 Three dimensional effect using crosslinking agents

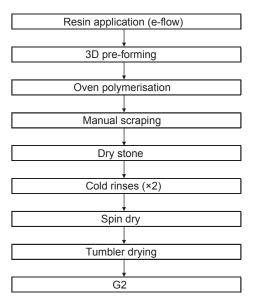
To achieve a permanent three dimensional (3D) effect in certain areas of a garment, the application of crosslinking agents in combination with acrylic resins is a common practise. The use of the e-flow technology to apply the resin solution will have important benefits in terms of water and chemical wastage in comparison with the conventional garment application systems. The dry stone process employed after fixation of the 3D effects and local colour fade down to imitate worn jeans, increase warp and weft contrast and produces high and low seam contrast. Rinses are necessary after the dry stone to remove the powdered pumice stones. The dry ozonisation of the garments will clean up any indigo backstaining so the contrast will be higher. The garment to be reproduced and the processing route using new technologies are shown in Figures 13.14 and 13.15, respectively.

# 13.4 Factors affecting process effectiveness

In practise, the details of a denim garment finishing route are established through a test error system. As mentioned previously, a garment finishing process is made up of a combination of different operations or processing steps. The combinations will vary depending on the required look, required hand and the fabric characteristics. Machine



**Figure 13.14** Finished garment with a three dimensional effect. © Jeanologia 2014.



Water: 8.6 L/garment produced

**Figure 13.15** Processing route. © Jeanologia 2014.

type also plays an important role and differences can occur even between the same types of machine from different manufacturers. Therefore it is always necessary to run a control or confirmation bulk test before embarking on a bulk production run. Reduced water finishes are no exception and it is important to assess different process steps, different machines and different fabric qualities both at sample pilot stage and in bulk scale-up.

The industrial application scenario of the prevention of backstaining can be considered as a reference to analyse and explain the factors that can affect the effectiveness of washing when using the reduced water techniques (Figure 13.11). Laser burning intensity is the first parameter that needs to be determined. Control of burning is done through marking intensity. If marking intensity is too low, the local effect will not be visible after the washing. If the marking intensity is too high, significant strength loss, or even total fabric destruction might occur.

To establish the laser intensity, a test is carried out at a range of different intensities using the correct design on the correct fabric base. The selection of the best marking intensity for a particular fabric is decided on by visual evaluation of the washed sample and manual verification to confirm that the fabric is not damaged. Figure 13.16 shows the fabric study for determining the best laser marking intensity.

There are multiple variables to control during the desizing and abrasion stages. These include liquor ratio (the quantity of water per garment produced), quality and quantity of the chemicals used and washing time and washing temperature. All these variables will depend on the type of machine and loading capacity of the machine. During ozonisation, the most important variables to take into consideration are the gas concentration at a defined gas flow and the processing time. Variations on the gas concentration will lead to inconsistencies in colour, especially between different production batches. With ozone, it is important to ensure that it is used in a safe manner and that no ozone is released into the working atmosphere.

## 13.5 Testing the effectiveness of washing

Advantages of reduced water finishes are not only related to environmental concerns. Caring for the environment in the laundry processes has also economic



**Figure 13.16** Determination of best laser marking intensity. © Jeanologia 2014.

advantages for the garment finishing plant. The cost reduction comes from the lower water usage, lower effluent discharge, less energy use and a reduction in the type and quantity of chemicals used. The cost effectiveness of these processes results in a quick return of investment on these particular technologies. Furthermore, in most of the cases, garments processed with this concept are more durable because fabric strength losses are minimised compared with conventional processing.

For testing the effectiveness of washing using reduced water techniques, it is important to examine the garment and to ensure that the appearance, hand feel and product performance (fastness) meets specifications. It is also necessary to determine whether the water consumption in the finishing process is below established limits for the reduced water processes. As stated previously, different limits have been set by different brands and retailers.

To measure the washing effectiveness, Jeanologia has developed an EIM tool that assesses the environmental impact of the garment finishing processes. It is the first of its kind and is specifically designed for the garment finishing industry. The software assesses the environmental impact of garment laundry processes categorising the impacts under four individual headings: water consumption, energy consumption, chemical impacts and impact on worker health. Moreover, it allows the user to compare different processes and assess their subsequent results. It provides valuable information to determine if process modifications and integrated technologies used for a particular denim processing route have led to the desired objective of water reduction.

The software benchmarks the impacts in each category against a predefined environmental threshold. First of all, it classifies each individual category and, second, the entire process into either low, medium or high impact. The results are presented in an easy to understand colour coded display. Figure 13.17 shows the EIM comparison of two different processing routes.

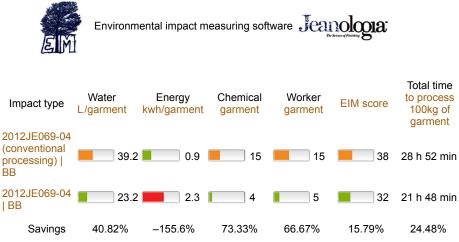


Figure 13.17 EIM comparison of two different processing routes. © Jeanologia 2014.

#### 13.6 Future trends

The current demand for water, energy and chemical footprint reduction in manufacturing of any product and particularly the demand to reduce water usage and wastage have led to the development of new ways of finishing garments minimising the quantities of water used. At present, this dive towards adopting reduced water finishes can sometimes be misunderstood and may, in some cases be considered as a fashion trend.

In reality, however, to be able to offer the consumer a desirable product that meets the specifications while also using minimal quantities of water is the present and the future of the denim finishing industry. Not only water but many other external factors are accelerating the need to adopt new production models. The growing labour cost even in countries with high production capacities, the application of stricter environmental legislation by governments all over the world, non governmental organisations pressing brands and retailers to sign up to environmental and social commitments are just a few reasons driving the need for this rapid transformation in the denim washing industry.

The garment washing industry of today, which is artisanal and labour intensive is moving to an industry based on knowledge and technology. In the future, it is important for the industry to show that it cares about the environment and its workers. The rise of the conscious consumer is driving the market in new ways and although it is still very important how denim products look, in future, how a product is made will be of growing importance in the decision to purchase.

## 13.7 Conclusion

The washing of denim garments to give them self identity and therefore add value for the final consumer has historically been a water intensive process. The newly available laundry technologies provide the possibility of offering fashion jeans produced with minimal quantities of water. The main technologies that make this possible are laser, ozone and e-flow, together with new enzyme formulations and crosslinking agents. The individual integration of these technologies into the conventional finishing processes will ensure jeans can be produced with less water. The best results in terms of the least water used are obtained when combining the three technologies.

The measurement of these improvements and savings, via the use of software index tools, provides the proof that water footprinting reduction is possible and profitable. The current garment finishing industry is traditional, conservative and resistant to change. Water footprinting is only the first environmental step in transforming an industry into one that cares about the people and about the planet, thus ensuring the permanence and credibility of this industry.

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# Finishing of jeans and quality control



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# 14.1 Introduction

Originally denim is a stiff fabric with an unpleasant dark blue colour. The blue coloured indigo denim changes the colour and fade during wearing and after the washing treatments. Different looks and varying hues can be achieved on the same raw denim fabric by applying different dry and wet processes. For the consumers, colour is the most important aspect of denim garments. Together with the colour, hand and surface trends are extremely important, which determines countless variations in processing techniques. Dry and wet processes can be applied in different combinations to obtain the desired effect and colour. These processes include scraping, stone and enzyme washing, damaging, sanding, brushing, overdying, coating, tinting, fraying, printing, embroidery and other special finishing techniques.

Denim is linked with the lifestyle of people, and it is possible to create infinite and unique styles on jeans such as wrinkles, fades, threadbare knees, vintage and retro styles, worn out selvedges, hems, embellishments and prints on different areas or all over the product (Synder, 2008; Paul and Pardeshi, 2003). By combining different treatments, uneven colours, contrast appearance, worn out effect, shiny effect, creases providing a permanent three dimensional (3D) effect, as well as whisker and honeycomb effects can be obtained on denim jeans.

Special final finishing can be applied to enhance the hand and functionality of the denim garments. These finishes include silicone lubrication oils, crease resistant, cosmetic and antibacterial finishes, among others. Final trimming and pressing processes are also very important for the marketability of the finished denim garments. After the treatments, mechanical and chemical damages may occur depending on the application processes. Major quality problems are strength losses, shading between the panels, yellowing, excessive abrasive damages, chemical defects, needle damages and dimensional stability. Some of the finishing treatments and an efficient quality control can reduce or make up many of these defects.

# 14.2 Dry and wet finishing processes

Different processing techniques are applied to change the colour, hand and feel of denim jeans and garments. Nowadays, these garments are processed to have a

desirable worn out or vintage look as well as a soft handle, by applying combinations of different treatments. In general, these treatments can be classified as dry processes and wet processes.

## 14.2.1 Dry processes

There are both mechanical and chemical dry processes. Dry processes are scraping, grinding, rupture (manual and machine damage), sanding, brushing, tagging, laser fading, resin, iron creases, flat press and sand blasting. Generally dry processes are applied before wet processes (Suglobal Tekstil, 2013). The principle of the mechanical processes is to abrade or tear the products by using different abrasive equipments or knives in order to give the jeans a worn out effect, abraded look or used look. A mechanical damaging process is applied to the denim garments before permanganate spraying. After wet processes, these damages to the garments will increase.

## 14.2.1.1 Sanding

The aim of sanding is to remove locally the indigo dyestuff from specific parts of the garment by using metal emeries or sandpapers of different numbers ranging from 40 to 600 (from coarser to finer scraping), for different effects and for different fabric weights. The sandpaper abrasion creates an obsolete image on the denim garment. On the garments, the abradable parts are the regions that are exposed to friction during daily life such as some parts of the knee, front pocket, hip pockets and hip regions. Scraping is done on inflated vertical or horizontal rubber mannequins) are dressed with untreated jeans and the workers sand thighs and crotches or desired parts manually. Sandpapers that are used for sanding of denim products are used in different forms. Sandpaper wrapped around a soft sponge or on fine wooden stick material is used for different scraping purposes. Scraping must be equally applied on both legs of the jeans. Manual scraping process is shown in Figure 14.1. Diamond paper, glass



**Figure 14.1** Manual scraping of jeans. Picture: Suglobal Tekstil.

paper and different grades of sandpaper create different colour contrasts on the jeans, increasing the attractiveness of the final product (Suglobal Tekstil, 2013).

# 14.2.1.2 Sand blasting

The sand blasting technique is based on blasting an abrasive material in granular, powdered or other form through a nozzle at very high speed and pressure onto specific areas of the garment surface to give the desired abraded look. A straighter surface and less effect can be obtained with the sand blasting process than with the sanding process, and sand blasting can be done in less time. For this reason, it is more advantageous in terms of costs. However, silicon grains that are located in the sand can cause silicosis disease. The sand blasting process is now prohibited in most countries because of its negative effect on human health (Suglobal Tekstil, 2013; Paul and Naik, 1997a; Paul and Pardeshi, 2003).

# 14.2.1.3 Brushing

A variety of effects can be achieved by using different types of brushes. Carbonium brushing is used to give a shiny effect on the garment surface. Several other types of brushing equipments are also used to give different effects on the garments (Suglobal Tekstil, 2013).

# 14.2.1.4 Grinding

Grinding, also called destroyed effect, is a method to tear the pocket edges, bottom hem edges, fly and knees to obtain unique destructions on the garments by using different abrasive methods. Depending on the desired effect, different knives and pen grinding tools are used to achieve a worn out effect. Figure 14.2 shows pen type stone tools, and Figure 14.3 shows grinding apparatus working with pressurised air. This apparatus is touched to the warp yarn for pilling or partial damage to the warp yarns. Ripping, pilling and cuts are also created by using sharp edged tools, blades and knives. Generally, warp yarns are cut by the knife, and white weft is left to create



**Figure 14.2** Pen type stone tools for grinding. Picture: Suglobal Tekstil.



**Figure 14.3** Grinding apparatus working with pressurised air. Picture: Suglobal Tekstil.

a worn out look. To obtain holes, both of the yarns can also be destroyed, depending on the unique design of the jeans. The worn out effect at the bottom of the hems are obtained by a pen grinding apparatus (Suglobal Tekstil, 2013).

# 14.2.1.5 Whiskers

Whiskers are worn out lines generated by natural wearing around the hip to crotch area and at the back of knees, and they are formed in different strengths and shapes depending on the design of the garment. A specific shape or design is drawn with the help of a sharp edge of sandpaper manually or by using moulds. To obtain whiskers, the products dressed in mould and trace of mould under the product will be drawn with sandpaper to produce different types of whiskers. Furthermore, the whiskers can be drawn by laser, machine sanding, etc. Pattern shape and strength of whiskers must be similar in both legs of the jeans (Suglobal Tekstil, 2013).

# 14.2.1.6 Tagging

This process is done by tagging small plastic tag pins to hold small gathers of fabric around pockets, hips, seams and bottom hems to get strong contrast due to less exposure of the folded parts to mechanical rubbing and chemicals. Figure 14.4 shows the tag pins on the waistband and on the pocket of the jeans. After washing, the tags are snipped and colour contrasts and 3D effects are obtained in these areas. Variations are provided by using different lengths of tag pins. Using thick tags leaves large holes on the fabric surface after the washing processes, on the other hand, finer tags may break off during washing and the contrast appearance may not be achieved. Figure 14.5 shows combinations of different dry processes on jeans (Suglobal Tekstil, 2013).

# 14.2.1.7 Laser fading

Laser fading is another popular dry process in denim processing, and transfer of different images to denim garments is possible by using laser beams. After the intensity of the laser reaches a specific level, the lights are sent to denim surface to engrave the



**Figure 14.4** Tag pins on waistband and pocket of jeans. Picture: Suglobal Tekstil.



**Figure 14.5** Combinations of different dry processes on jeans. Picture: Suglobal Tekstil.

required pattern on the garment. The indigo dyestuff is burned and is removed during the washing process. It is possible to form whisker shapes, lines, different images and pictures on denim garments with the same quality for the whole batch. The intensity and duration of exposure determines the final effect on the fabric. The laser intensity must be chosen correctly not to damage the garments (Tarhan and Sariisik, 2009).

#### 14.2.1.8 Resin applications

Resin application is a process that is applied to denim garments to give dry and lustre appearance, to improve the rubbing fastness, to give 3D effects, to provide stiff and firm handle and to reduce pilling. Generally, resin application is the first step of dry processes. This process can be applied on denim garments in different ways including by spraying the resin solution or dipping the garment in resin solution. Different resin solutions give denim garments different effects. After resin application, jeans must be cured in ovens at the right temperatures and time to get the perfect result. Resin can be applied on jeans manually with a brush and with a sponge for partial applications. After resin application, the jeans are manually folded to obtain whole garment crush, partial crush or special streaky effects. The crushes or creases are formed on the high, hip and back knee or over the ankle to get 3D effects with different methods. After crushing or creasing, the jeans should be dried manually with a hot press and then must be cured in an oven at right temperature (AATCC, 2004).

Aluminium flex pipes are widely used for crushing and creasing jeans legs. After placing these flex pipes inside the legs, operators can manually form different creases on the jeans. Then the creased jeans are cured for permanent creasing effects. Figure 14.6 shows the creases on the back of legs and over the ankle of jeans. Other techniques



**Figure 14.6** Creases on back of legs and over ankle. Picture: Suglobal Tekstil.

use shaping presses or frames similar to a grill to form a 3D crease effect (Suglobal Tekstil, 2013). Resin reduces the tearing strength of the material and must be tested before applying on different types and weights of the fabrics. Moreover, if the resin is applied to elastic denim products, the elasticity of the fabric may be damaged, and for this reason the fabrics must be tested before applying resin.

## 14.2.1.9 3D crush effects

There is a big demand in the market for 3D crushed effects on jeans. There are various types of 3D making equipments such as wire crinklers, crushing machines, aluminium flex pipes, shaping presses and grill frames. These methods can be applied to jeans after resin application for permanent 3D effects. Nowadays resins are used not only to produce ironing free products but also to make permanent wrinkles and creases to look natural vintage during the use (Suglobal Tekstil, 2013).

## 14.2.2 Wet processes

Wet processes are desizing, stone washing, enzyme washing, bleaching, tinting, overdyeing, softening and all other chemical finishing processes. There are countless variations in processing techniques and application steps. Figure 14.7 shows the flow chart of all these basic treatments.

## 14.2.2.1 Stone washing

Stone washing is a basic process that can be used alone or combined with other processes to obtain warp specific effects. Indigo dye does not penetrate deep into the fibre, and by using stones, the dyed surface fibre is removed by abrasion of the stones on the fibres. The stones and denim are spun together in large industrial washing machines to achieve an aged and worn out appearance due to abrasion. This process removes the surface bound indigo dye locally and reveals the white interior of the yarn, enhances the hand of products and creates a bright appearance. Pumice stones of varied sizes create different fades. Many variations can be achieved by changing the amount of liquor ratio, number of stones, size and shape of stones, cycle time, chemical addition and garment load. Thereafter, the fabric undergoes various cleaning, rinsing, softening and drying processes (Paul and Naik, 1997a; AATCC, 2004; Bajaj and Agarwal, 1999; Paul and Pardeshi, 2003).

## 14.2.2.2 Enzyme washing

Enzyme washing is an alternative method and has almost replaced stone washing. In denim fabrics, due to enzymatic abrasion, dye is released from yarns, giving contrasts in the blue colour. The fibrillation produced during ageing process is a result of the action of cellulases and mechanical action. The pumice stones damage the washer drum and reduce the fabric strength due to abrasion in the stone washing process. The application of cellulases prevents damage to the machine and garments, eliminates the time for disposal of used stones, increases the loading amount of garments in the washing drum and improves the quality of wastewater. Moreover, the use of cellulases

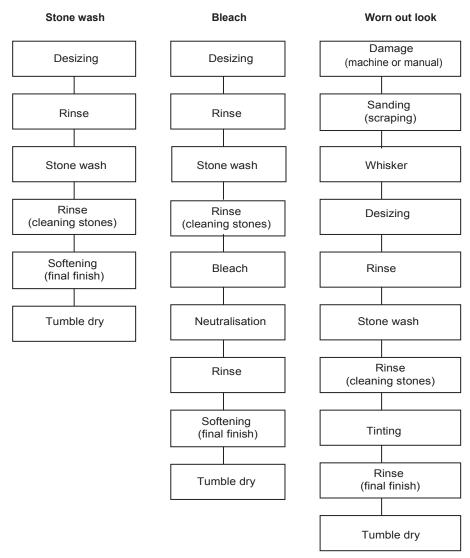


Figure 14.7 Flow chart of basic treatments.

results in a softer fabric hand, and strength loss is lower when compared with stone washing (Cavaco-Paulo and Gubitz, 2003). However, due to the increased time and other considerations, the current trend is to use combinations of stone and cellulase to achieve the worn out look more quickly (AATCC, 2004).

## 14.2.2.3 Bleaching

Bleaching of denim garments means lightening the colour of the indigo dyed garment. Sodium hypochlorite, calcium hypochlorite, hydrogen peroxide and potassium permanganate are applied to jeans for bleaching. Bleaching is a separate process, which can be applied instead of stone washing or sometimes together with stone washing. The bleaching process must be followed by the neutralisation process in order to avoid yellowing problems. To ensure colour uniformity after bleaching, denim fabrics should be carefully sorted before bleaching (Paul and Naik, 1997a; AATCC, 2004).

#### 14.2.2.4 Acid washing

Acid washing is soaking the volcanic or pumice stones in sodium hypochloride, potassium permanganate or bleach solutions and then tumbling similar to stone but washing with less water to obtain lighter colours. The well known frost, ice or white washed jeans are obtained with these application techniques (Suglobal Tekstil, 2013). Acid washed indigo dyed denim has a tendency to yellow after wet processing and for this reason this wash also must be followed by a neutralisation process (Paul and Naik, 1997a; AATCC, 2004; Bajaj and Agarwal, 1999; Paul and Pardeshi, 2003). Figure 14.8 shows three different combinations of dry and wet processes to obtain vintage and worn out effects. The appearance, hand, damage, colour and look of the jeans are completely different after these three washing combinations.

## 14.2.2.5 Tinting and overdyeing

With an increase in demand for tinted and overdyed looks on garments, the garment processor is using an additional dyeing process to dye the garment partially or completely. Tinting and overdyeing of denim garments are usually carried out after the washing processes, in order to give the final denim a dirty, worn out and vintage look. During tinting, jeans are dyed partially by using direct dyestuffs. Overdyeing is dyeing the whole garment mainly with reactive dyestuffs or metal complex dyestuffs (AATCC, 2004; Bajaj and Agarwal, 1999).

#### 14.2.2.6 Spray applications

Spraying is different from the exhaustion method by applying the chemical only to the surface and to the desired parts of the denim garment. Air pressurised hand guns are used to spray the chemical on the surface of garments, which are placed on inflated vertical mannequins. Different chemicals are sprayed for different purposes. Instead of manual spraying, spray robot machines are now widely used in the laundries. The robot sprays chemical in right position and in right amount on all of the jeans in the batch, and therefore same effects will be obtained after the washing procedure. This standardises the spraying process to ensure standard quality (AATCC, 2004; Suglobal Tekstil, 2013). Potassium permanganate is used to partially create contrast and a variety of effects. It is applied especially on sanded parts of the garment to increase the contrast. After this process, they are neutralised, rinsed, softened and dried.

Polyurethanes are sprayed for coating purposes, to obtain a leather like look and to increase the durability of the garments. Microsilicones and fatty acids are used as spraying chemicals to obtain an extremely soft handle. In the overdyeing of one colour over another, pigments are sprayed to colour only the outside of the garment. Resins are also applied by the spraying technique to make the folds permanent in desired parts of the jeans, to give 3D crease effects, to obtain easy care products, etc.

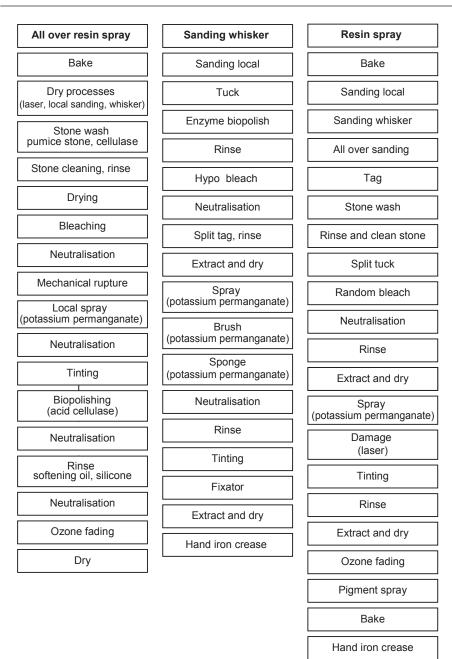


Figure 14.8 Combination of dry and wet processes for different effects.

#### 14.2.2.7 Ozone fading

Ozone fading is carried out in closed chamber by using ozone gas. After ozone fading and bleaching, there is no loss of strength on the jeans. It is a simple and 'green' process because steam and water are not used, and therefore ozone technology significantly reduces the laundry's water, chemical and energy consumption and wastewater processing. Moreover, bleaching and fading can be done in washing machines with ozone dissolved in water. This method is also environmentally friendly because after laundering, ozonised water can easily be deozonised by UV radiation. Ozone technology is applied to jeans to obtain an aged effect and retrostyle, unique yellow cast for true vintage looks or grey cast for a retro look. It is also used for cleaning backstaining without detergents and eliminates yellowing from bleached jeans (AATCC, 2004; Bajaj and Agarwal, 1999).

## 14.3 Printing techniques

The printing of denim garments is mainly carried out on garment screen printing machines after cutting the panels of garments before sewing. Garments or garment components are placed on a palate and printed with screens loaded onto a rotating carousel. The printing process is followed by a fixation process to fix the pigments with binders. Prints are applied mainly to the hip pockets, side seams, pocket inside and back side of trousers. Depending on the design of the garment, prints can also be applied to the whole garment, as shown in Figure 14.9.

Discharge printing, flock printing and varak printing are the common methods used in jeans printing. Discharge patterns are produced by destruction of the original dye in the printed areas. Indigo dye can be destroyed by oxidation or reduction. There are also high fashion printing techniques applicable on denim jeans based on novel pigments with metallic effects, phosphorescent colours, optically variable pigments, thermochromic pigments and photochromic pigments. Embossing is another technique, which allows engraving a simple pattern, as well as to obtain 3D patterns on denim fabrics. To produce a pattern, the fabric is passed through a calendar in which a heated metal bowl engraved with the pattern works against a relatively soft bowl.

Apart from the conventional printing techniques, inkjet printing of denim jeans is becoming more popular. In fact, inkjet printing of jeans has already become quite significant, slowly replacing screen printing. Its versatility has led to the development of innovative fashion designs, changing the way textile and fashion designers interact with denim fabrics, and stimulating their creativity within a digital frame.

Denim garments can also be printed by laser engraving, as shown in Figure 14.10. It is one of the easiest printing applications for denim garments, resulting in unlimited patterns. The main advantages of laser methods over conventional printing techniques are similar to those offered by inkjet printing in the simulation of traditional finishing effects and the reproduction of any type of images, colour fading and 3D effects with reduced water and energy use.



**Figure 14.9** Prints applied on whole garment. Picture: Suglobal Tekstil.

# 14.4 Finishing of denim fabrics

A proper finishing process is essential for the performance and the appearance of denim fabric. After weaving, the denim fabric should be mechanically and chemically treated to give it a soft and pleasant handle and correct dimensional stability, both in the warp and the weft to prevent shrinkage in subsequent washing. The finishing process can comprise various stages such as brushing, singeing, impregnating, stretching, drying and shrinking (Paul and Naik, 1997b). Brushing and singeing eliminate impurities and help to even the surface of denim fabric. Impregnation and stretching regulate the hand and rigidity of the fabric, while compressive shrinking ensures its dimensional stability. The standard width denim fabrics are then sent for making up. In this process, the fabric is cut into the desired width according to the size required.

In addition to these process stages and depending on the required result, further chemical processing can take place such as desizing, overdyeing, coating, retro dyeing, pigment dyeing, reverse dyeing, non uniform dyeing or multicoloured dyeing. The purpose of chemical finishing is to change or improve the aspect and hand feel of the fabric to stiff, soft or drapey, and to gain unique functional properties such as oil or water repellence, wrinkle resistance or flame resistance and also to improve the sewability. Some of the major finishing processes for denim fabrics are discussed in this section.



**Figure 14.10** Laser engraving of different patterns. Picture: Suglobal Tekstil.

# 14.4.1 Singeing

Singeing is a process that uses a gas flame to burn off the fluff or tiny hairs on the surface of denim fabric. This process burns away surface material that makes the fabric look fuzzy. It is carried out to obtain a cleaner and smoother appearance of denim fabrics. This process enhances the colour, and the fabric wettability is also increased (Paul and Naik, 1997b).

# 14.4.2 Preshrinking

Progressive shrinkage is a common problem with garments manufactured from denim. In particular, heavy weight twill denim construction is dimensionally unstable after weaving, which requires very high compression at preshrinking or sanforizing. Fabric that does not undergo the sanforizing process and is considered raw is likely to shrink up to 10-15% on the initial wash and continue to shrink up until the third wash, and sanforizing aims to reduce the shrinkage to 1-2% (Paul and Naik, 1997b). The cause of progressive shrinkage may be the excessive swelling of the yarn during the washing cycle.

The sanforizing process involves stretching of the fabric before it is washed, and it helps to prevent further shrinkage. Thus sanforizing is a crucial process to set the relevant parameters to adjust the dimensional stability of warp, weft and skew of fabrics, so that the fabric will not shrink during garment production or wear.

# 14.4.3 Calendering

Calendering is a processes in which denim fabric is passed between rollers or calenders, usually under controlled heat and pressure, to produce a variety of surface textures or effects in fabric such as compactness, smoothness, glazing, etc. The process involves passing the denim through a calender in which a highly polished, usually heated, steel bowl rotates at a higher speed than the softer bowl against which it works, thus producing a glaze on the face of the fabric that is in contact with the steel bowl.

# 14.4.4 Mercerising

Mercerisation is an industrial process involving sodium hydroxide for cotton yarns or fabrics to increase the lustre and dyeability. But the mercerisation of denim is usually carried out after the denim is woven, and so it is different from the more common method of mercerising cotton yarn. Mercerisation of denim may be used for achieving ring dyeing, thus keeping the dye on the surface of the yarns or fabrics and to prevent dyes from fully penetrating the fibres. In addition to increasing the fabric lustre, it also improves its strength. As it significantly increases the cost and lead times of denim production, at present, it is a relatively rare process.

# 14.4.5 Softening

Due to the removal of impurities such as wax, paraffin and oil after pretreatment processes, denim fabric loses its natural hand feel and therefore it is necessary to regain its softness. Softeners improve abrasion resistance, increase tearing strength and diminish the risk of stitching thread and needle breakage during garment sewing. A wide range of softeners is used in the aftertreatment of denim fabrics. The major softener types are cationic, anionic, nonionic, silicones and special softeners (Paul and Naik, 1997b).

# 14.4.6 Foam finishing

Foam finishing of denim fabric is an environmentally friendly and energy saving finishing and shrinking method for meeting the highest quality demands. In this method, the required finishing agents are added to the foam, where the moisture content is minimum. The foam is usually laid on a rubber conveyor, evenly across the width of the conveyor by an oscillating feed pipe system, and a doctor blade ensures a uniform layer of foam across the width. Foam finishing can result in an 80% savings in water and energy compared with the traditional denim finishing methods.

# 14.4.7 Overdyeing

Traditional indigo dyed denim fabric can be overdyed as part of a finishing process. Overdyeing can take place between desizing and the addition of softeners. The best results, however, are achieved after stone washing and subsequent bleaching. The preparation requirements for overdyeing are the same as for any other dyeing process (Paul and Naik, 1997b).

#### 14.4.8 Resin applications

Resin is a chemical solution that fills into the amorphous area of a fibre, penetrates thorougly by drying and curing and polymerises inside the fibres. The resin amount, fixation temperature, pH and process time are the critical parameters of a proper resin application on denim fabric. A post curing can activate the resin after garment production (Schindler and Hauser, 2004).

#### 14.4.9 Coating

Coating is a simple process for covering the surface or back of denim fabric with chemicals or dyestuffs in order to gain or improve various surface properties such as waxy, oily, glossy, paper, leather, silicone, etc. Coating materials can be waxes, rubbers, latex, plastic films, resins, polyurethanes, binders or metal powders. Today several coating layers are applied to denim fabrics to obtain different effects after washing. Knife coating, screen coating and foam coating are the common coating methods (AATCC, 2004).

## 14.5 Functional finishing of denim jeans

With the market expanding at a fast pace, denim washing techniques are being combined with fabric construction variations and surface finishing techniques. The results obtained from garment washing represent a combined effect of colour dissolution, destruction of the dyed colour and mechanical abrasion. To improve the handle of the jeans, garment washing processes are usually finalised by a softening treatment. For further colour effects, the materials after washing can be optically brightened or top dyed before the softening treatment (Paul and Naik, 1997a).

Apart from the normal washing and finishing treatments, which add style and fashion effects to the denim jeans, different functional finishes can be applied in order to confer technical properties to denim. Micoencapsulation techniques and nanotechnology are offering different possibilities that were not possible to achieve with normal finishing chemicals. The application of nanotechnology to denim creates an expanded array of functional properties, enabling denim to be used for making novel technical materials and non-apparel products. Another important development is the plasma enhanced chemical vapour deposition technique. It is a finishing process that can be used to deposit thin solid polymeric films from a gas state to a solid state on denim to achieve the desired functional properties (Paul, 2014).

Various functional finishes for water, oil and soil repellent treatments, crinkle look, silky look, application of aroma wellness and cosmetic microencapsulation finishes are the latest applications for jeans. There is also a demand for odour resistant, antibacterial, insect repellent and flame retardant finishes. In a study using nanoclay, old look, soft handle, flame retardant and antibacterial properties on denim garments have been analysed. It was found that it is possible to obtain denim wash effect without using enzymes and the desized denim can be washed using nanoclay. Desirable hand, air permeability, wrinkle resistance and abrasion resistance properties were obtained, as well as a used look appearance with good antibacterial activity (Maryan et al., 2013; Vijayalakshmi and Ramachandran, 2013).

Thus many fashionable and multifunctional effects can be created simultaneously on denim jeans by using different chemical finishing agents. A wide variety of functional finishes are now applied on denim jeans for improving their comfort and performance properties (Schindler and Hauser, 2004; Paul, 2014). Some of these functional finishes are discussed in detail in this section.

#### 14.5.1 Cosmetic effects

Denim garments can act as delivery systems of bioactive compounds as they are in contact with the skin. Hence, they can be used for cosmetic purposes as they can provide a controlled slow release of the active cosmetic or medical ingredients to be absorbed through the skin (Paul, 2014). Denim based cosmetotextiles are normally created by microencapsulating substances such as aloe vera, vitamin E, various plant oils, menthol, caffeine, retinol, ceramides or minerals from seaweed, crabshell or seawater and attaching them to garments after the wet processes are finished. When the cosmetic denim garment is worn, the microcapsules gradually transfer the active ingredients to the skin, where they are opened by movement, pressure or the effect of the skin's natural warmth and enzymes. The cosmetic ingredients are intended for moisturising, nourishing, firming or smoothening the skin and for reducing the appearance of cellulite, or for cooling and reviving the area where the cosmetic denim is worn. Anticellulite and moisturising ingredients are popular applications of microencapsuated finishing agents for jeans (Schindler and Hauser, 2004).

#### 14.5.2 Odour resistance

Unpleasant odours have a negative impact on denim garments and their aesthetic properties, and so there is a need for odour resistant finishing. The main principle of odour resistant finishing is the hindrance and delay of adsorption and desorption of unpleasant smelling substances. Odour resistant denim garments have the function of containing unpleasant odours like tobacco. Among other possibilities, cyclodex-trins incorporated into denim can absorb or remove odour. The odour molecules, being hydrophobic, become trapped in the cavities of the cyclodextrins and are removed during laundering.

#### 14.5.3 Softening

The addition of chemicals and softeners to garments as a top finish after washing processes has multiple effects such as to provide better hand, to improve wash and wear properties or to add different functional properties to the garments. Softeners may give the proper hand but may have an adverse affect on the shade and fastness properties. When choosing the softener, different factors such as yellowing, fastness properties, shade change, absorbency, shear stability and ionic compatibility must be considered. Typical finishes used in denim garment final finishing are cationic fatty acids, silicone oils, micro silicone emulsions and nonionic anionic blends. Final finishing provides washed garments softness, hand and added value (AATCC, 2004).

## 14.5.4 Moisture management

Moisture management finishes improve the ability of denim garments to absorb humidity from the skin, transport it to their outer surface and release it into the surrounding air. In a way, moisture management finishes increase the moisture holding power of the fibres. The new generation of novel softening agents that form a part of the moisture management finishes are capable of greatly improving denim garment performance.

# 14.5.5 Thermal regulation

In recent years, new materials and new finishing processes for thermal regulation functions of textiles have been extensively studied, which can be applied to denim jeans. Microcapsules containing phase change materials (PCMs) use chemicals such as nonadecane and other medium chain length alkanes in their core. When the ambient temperature increases above their melting point, the microencapsulated chemical melts and latent heat is absorbed, thereby interrupting the increase in temperature of denim garments. Once the ambient temperature falls, the PCMs solidify and latent heat is released, providing a heating effect.

# 14.5.6 Hydrophobicity

Water repellent finishes are now becoming more important for denim garments, and traditionally these finishes are based on fluorinated compounds. These compounds are normally applied on denim by conventional padding and exhaustion processes. A variety of new generation chemicals and processes, including nanomaterials and plasma techniques, are also available for developing hydrophobic surfaces on denim garments.

# 14.5.7 Soil release

The soil release finish applied on denim does not prevent initial soiling, but it does enable deposited dirt to be removed easily in laundering. Soil release finishes attract water to the surface of fibres during laundering and help in removing the soils. Thus they permit relatively easy removal of soils with ordinary laundering. Meantime, stain and soil resistant finishes prevent soil and stains from being attracted to fabrics. Such finishes may be resistant to both oil borne and water borne soils and stains.

# 14.5.8 Easy care

For textiles such as denim, which are made of cotton, the attainment of easy care, durable press or wrinkle free finishes is sometimes desired for easy maintenance.

Easy care is the property associated with an improved maintenance of cellulose based textiles, especially with respect to wrinkling and thus ironing. Easy care finishes like citric acid, 1,2,3,4 butanetetracarboxylic acid, etc. can be applied on denim garments by various techniques such as padding, exhaustion and spraying.

## 14.5.9 Self cleaning

The self cleaning action of the surface of the lotus leaf has given rise to the so called 'lotus effect', which is being utilised to produce superhydrophobic finishes on denim garments. Another interesting approach in self cleaning is the nanocoating of denim garments with nanoparticles of anatase form of titanium dioxide, which can effectively decolourise stains in the presence of water, oxygen and solar radiation. Starting from the concept of superhydrophobicity, the scope of self cleaning surfaces on denim has now further extended to photocatalytic as well as superhydrophilic effects.

## 14.5.10 Ultraviolet protection

Textiles in general may not be able to provide effective ultraviolet (UV) light protection, and they should be treated with UV blocking agents to ensure that the fabrics deflect the harmful UV rays, and such finishing treatments are relevant for outdoor and light weight denim garments. Several UV blocking agents are being developed to add or to improve the UV protection function of the denim garments. There are both organic and inorganic UV blockers. Compared with organic UV absorbers, inorganic blockers are now preferred due to their properties such as non toxicity, chemical stability under UV radiation, etc. In recent years, innovative nanotechnology based textile finishing techniques are gaining importance to develop more efficient and cost effective UV protective textiles.

## 14.5.11 Antimicrobial protection

Denim garments provide an excellent medium for the growth of microbes under humid climates. The growth of microbes negatively affects the denim garments as well as the wearer. Hence, antimicrobial finishes should be applied to the denim to prevent the growth of microbes and also to protect the denim garments from strength and colour loss, unpleasant odour and quality deterioration. A number of antimicrobial finishes are now on the market that can destroy bacteria and enable denim garments to remain fresh for longer.

## 14.5.12 Mosquito repellency

Mosquito repellent denim garments can protect the wearers from the bite of mosquitoes, thereby offering safety from mosquito borne diseases such as malaria, dengue, etc., which are serious public health problems in tropical regions. Among the various insect repellent chemicals, DEET is extensively used and has the ability to repel insects and mosquitoes effectively, whereas permethrin is widely used in textile applications (Paul, 2014). In recent years, the potential of various insect repellents derived from natural sources has also been explored on denim garments (Sumithra and Raaja, 2012).

#### 14.5.13 Flame retardancy

Flame retardant treatments are usually applied to combustible fabrics to prevent these textiles from bursting into flame. Such finishes can be applied to denim fabrics intended for automotive and home interior applications, as well as for the garments for personal protection and safety purposes. A wide variety of halogen free flame retardant chemicals based on phosphorus, silicone and nitrogen compounds are now available. Ideally, the best flame retardant system for denim garments should char the fibre, releasing no toxic smoke or gases and prevent afterglow (Paul, 2014).

# 14.6 Final operations and inspection

After the washing and finishing procedures are completed and the garments are dried, they are sent to the final trimming and pressing department. Figure 14.11 shows the process flow of final operations in this department before packaging the jeans. These operations include pressing, trimming, inspection, measurement control, labelling, ticketing and packaging. The inspection process includes checking the shading between the panels, the evenness of fabric colour, defects and measurements. Generally, metal zippers, buttons, snaps, studs and rivets are used on denim garments, which may be produced from copper, iron, chromium, zinc, nickel, etc. Normally, buttons, rivets and labels are attached to the garments once the washing and final finishing processes are completed.

Figure 14.12 shows rivet setting on jeans. Zippers are attached during sewing operations, but the other metal trimmings are attached after wet processing is completed due to the risk of corrosion and other chemical damages. Selection of zipper type, button type, labels and other trimmings for the jeans is related to the design, but as in the case of other denim garments, zippers and other metallic trimmings (studs, buttons, rivets, etc.) must be checked for potential problems after washing processes. Metal trimmings may present a problem in the washing liquor by catalysing oxidative bleaching agents and create holes, stains or fabric damage. Furthermore, corrosive damage may occur on the trimmings, and rust stain on the fabrics is also a common problem. These problems can be avoided by using coated metal zippers. The leather labels used at the back and the other labels on the garment may also be damaged during wet processing and final finishing. Depending on the customer requirements, these labels may also be sewn after wet processing or if a washed appearance is required, they can be washed separately and sewn later to the garment (AATCC, 2004).

After many treatments and tumble drying processes, undesirable wrinkles occur on denim garments. Different presses are used to eliminate undesirable wrinkles, to give a final shape, and to set the final measurements of the garments. The means of pressing are heat, steam and pressure. The use of an iron and pressing table may require considerable skill of the operator. Programmable steam presses ensure that all of the garments in a batch receive the same, satisfactory cycle of steam, pressure and vacuum (Tyler, 2008).

First the pressing process is applied to open the side seams of the jeans, as shown in Figure 14.13. The two legs of the jeans are placed on the bed buck for pressing the legs, the long side seams of the jeans are smoothened with a steam

#### Final operations

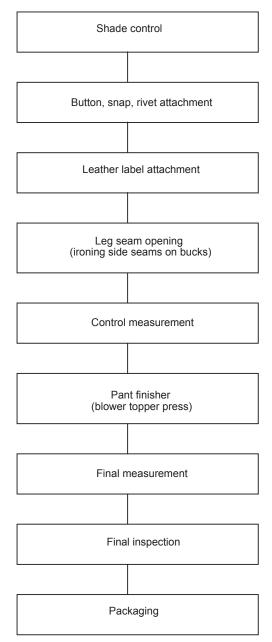
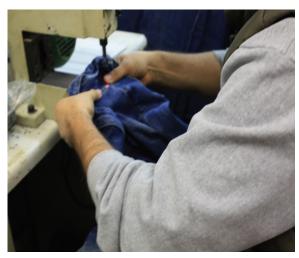


Figure 14.11 Process flow of final operations.



**Figure 14.12** Rivet setting on jeans. Picture: Suglobal Tekstil.



Figure 14.13 Pressing process applied to open side seams. Picture: Suglobal Tekstil.

iron, and then vacuum is applied to dry and fix the shape. The next process is to press the jeans completely on the pants finisher (blower topper) as shown in Figure 14.14. The jeans are clamped in a ring at the waist and clamped again at the ankles. Steam followed by hot air is blown through, while maintaining slight downward tension on the legs. The final pressing process involves steaming the waistline area with pants topper. Hem press is used to steam and press the hems of the jeans. After measurements, if necessary, the final touching up operation is done with irons (Tyler, 2008).



Figure 14.14 Complete pressing of jeans on pants finisher. Picture: Suglobal Tekstil.

# 14.6.1 Measurements

Consistency of size measurements is a major concern for buyers and manufacturers. The sizing system and measurement tolerances are usually based on the sizing standard of the companies. Buyers and manufacturers have to set tolerances that apply for each model of jeans and each measurement to avoid and prevent large measurement variations among and between garment styles. Quality audits check measurement on semi completed products and final products, during garment production, after garment production and after wet processes to keep consistency of the measurements (Glock and Kunz, 1995). Garments are rejected when they do not meet the sizing standards of the company. The measurements that are mainly checked during controls of jeans are waist, thigh, knee, bottom hem, inseam, back rise and front rise.

# 14.6.2 Final inspection

Final inspection consists of inspecting finished garments from the point of view of a consumer, where size measurements after pressing, form fitting, colour and shade control and a list of points have to be checked. When checking with this list, the inspector sorts the jeans into three groups as good quality, seconds and those needing repair. Garments that have major and critical defects are sorted as seconds and the garments with minor defects are sent to be repaired. The control list consists of three parts. The first part includes the manufacturing defects related to measurement, appearance and seam defects such as belt loops, hems, zip, rivets, buttons, measurements, twisted legs, front pocket, back pocket, shade of panels, shaded parts, fly area, needle damage, inseam, seat seam, side seam, waist seam, risers and labels.

The second part of the control list is related to fabric defects such as picks, ends, loomstop, slubs, knots, warp dyestreaks, colour soil thread and fabric off shade. The final part of the control list is related to washing and finishing defects such as streaks at seams, streakiness, crease lines, damage, soil, spots of bleach stones, colour out of shade, local abrasion, excessive abrasion, overdye, unsymmetrical effects on the jeans, stones in the pockets and stiffness. After inspecting the batch, the total defects and defect percentage of the batch are calculated for further evaluations. Final inspection can be applied as 100% inspection or acceptance sampling, according to acceptable quality level tables (Mehta, 1992).

# 14.7 Quality control in jeans production

Manufacturers establish quality standards that result in garments of a particular quality depending on the specifications or customer requirements. Each finished product must provide adequate quality and performance to ensure serviceability in use. Consistency is a major factor in determining quality and value (Tyler, 2008; Mehta, 1992). In jeans production, in addition to in-process inspection, quality control may involve inspection of denim fabrics, inspection during garment production and finished goods before and after wet processing. Quality problems are mainly related to denim fabric defects, shade problems, seam defects, dry and wet treatment defects, yellowing, shrinkage and twisting.

## 14.7.1 Denim fabric defects

Denim fabric defects can be classified as yarn defects on both warp and weft, weaving defects and finishing defects. Yarn defects are warp slub, weft slub, foreign fibre, coarse pick, yarn fly and yarn irregularity. Weaving defects are knots, weaving fly, loom stop, stack end, snarl, broken pick, miss pick, tangle, double warp, hole, sizing defect, oilspots, drawing defect and broken warp yarns. In order to check the weaving defects, the woven denim fabric, wound on a fabric roll, is taken out from weaving machines at particular intervals and checked on inspection machines so that any possible weaving fault can be detected. In this quality control exercise, wherever any fault is seen, corrective measures are taken then and there only.

Dyeing and finishing defects are more complex damages than physical damages. Problems often seen are poor fastness, uneven and poor washdown, abrasion or scrub marks in prewashed denim fabrics, uneven shrinkage, stiff hand after dyeing, dye streaks, side to centre shading caused by the loom, poor stabilisation and corrugation in sanforization. It is easy to confuse many causes of unevenness of colour in indigo denim fabrics. It can be created in preparation of the yarn, including inadequate and uneven boil off, bunching of the yarn during dyeing, uneven squeezing in the dyeing and uneven wash off. It may also be due to poor sizing, poor weaving, loom settings or uneven tensions. Most often, it is a combination of many of these factors, and for this reason it is often difficult to discover the reason (Greer and Turner, 1983). The final denim fabric is thoroughly checked for defects such as weaving defects, uneven

dyeing, bleaching and dyeing defects, oil stains or patches. After inspection, the final products are categorised quality wise. The faultless fabrics are sent to the packaging department, while the defective ones are sent for further corrections.

#### 14.7.2 Shade problems

Shade is the most important quality parameter for garment manufacturer and designer. Shading is variation in hue, value or intensity as measured against a standard. In denim fabrics, shading may occur side to side, side to middle or end to end within the same roll and between rolls. Substances such as fats, oils, waxes, optical brighteners, softeners, sizing compounds and finishing chemicals may result in mixed or shaded panels, off shades, spots and stains on the garments, if not properly applied (AATCC, 2004; Mehta, 1992).

The shade of the treated garments is affected by dry and wet processes, but fabric properties are extremely important. Cotton quality, yarn type, weave construction and the processes during denim fabric manufacture such as mercerising, bleaching and brightening influence the shade and tone of the garments. All these parameters or their combinations may result in mixed or shaded panels, off shade or off quality for the garment processor, and some of them cannot be compensated during the finishing of the garment. Figure 14.15 shows shading on the panel of garment directly related to the fabric properties (Suglobal Tekstil, 2013).

Shading between the panels of the garment very often occurs due to the mixing of garment parts after cutting or due to the denim fabric structure and production procedures. Thus the colour and shade of denim fabrics are apparent only after washing processes, and so before spreading the fabrics, shade sorting is an



**Figure 14.15** Shading on the panel of garment. Picture: Suglobal Tekstil.

important step in denim garment production. The right selection of denim fabric can help minimise the cost of treatment and reduce environment related issues (Suglobal Tekstil, 2013).

Before garment production, the materials must be sorted according to their colour. The most important test for sorting is the blanket test. Figure 14.16 shows a blanket test sample. The aim of this test is to minimise the risk of manufacturers with shade variation and mixed panel or parts. A shade blanket is prepared by cutting a full width piece from each roll of fabric and sewing them into a blanket including a control swatch out from a master roll. The garment processor can wash this blanket with the final garment recipe, and after shade evaluation, can decide which fabric rolls should be processed together or sort the fabrics if there is a shade difference within the fabric rolls or between the fabric rolls (Suglobal Tekstil, 2013; Mehta, 1992).

#### 14.7.3 Defects of dry processes

During manual scraping, mechanical damage and different effect problems on the garment are directly related to the experience and skill of the operator. If the abrasion or mechanical damage is not uniform, fading will not be uniform after washing. If strong sanding is applied, holes and pillings may occur on the garment after the washing processes. The sandpaper size is also very important. If the sandpaper has a larger grain, it will damage light weight fabrics. Another problem with sandpaper application is forming crease marks.

If the air pressure inside the mannequins is not sufficient, some small folds occur on the garment, and after sanding, crease marks occur on the folded parts. If the pressure of the mannequin is high, edge seams, fly seams, etc. can be torn. Most of this



**Figure 14.16** Blanket test denim sample. Picture: Suglobal Tekstil.

damage is apparent after completing wet processes. The air pressure must be set optimum inside the inflated mannequins. If the denim fabric is elastic, the sanding process must be more sensitive, because the seams and joints cannot be elastic like the fabric and damage occurs. Strength loss and weight loss increase with the increase in sand blasting pressure, laser intensity, number of washings and duration of washing and finishing (Tarhan and Sariisik, 2009).

The brushing effect will be more intensive by increasing the pressure, the number of passages or by choosing harder brushes. It is important to choose the right brush in order to not damage the fabric. Plastic tags are tagged on some parts of denim products to achieve a strong contrast effect. If a light colour contrast is needed, these tags should be removed before permanganate spray or between stone washings. If the washing cycle is too long, the contrast between the parts of washed denim will be too strong. Moreover, another problem with this process is that the fabric damages near the tagged places after long washing cycles. Grinding process also may strongly damage the hems and other parts, if not properly applied. The manual destruction process is directly related to the skill of the operator, and after washing, excessive damage may occur on the garment parts.

The most important problem of laser processes is incorrect intensity of the laser beam. If it is low, the effect cannot be obtained, and if the laser intensity is high, it can damage the bonds of fibres, causing chemical damage and tearing occurs (Tarhan and Sariisik, 2009). Before production, the intensity of the laser must be tested on the fabrics and calibration of the machines must be checked. After laser application, neutralisation must be carried out.

The problems related to resin applied products are strength loss and tear, and for this reason the physical properties of the selected denim fabric should be very good. Before resin application, the denim fabric must have sufficient strength to withstand 40-50% loss in tensile and tear strength. The application of resin must be homogeneous, otherwise colour differences and stains occur on the garment. The fabric must have excellent absorbency to allow resin to penetrate into the very interior of the fibres, and for this reason a high degree of size removal is essential before resin application. After resin application, the fixing temperature and time in the oven must be set same for all of the batches (AATCC, 2004).

#### 14.7.4 Defects of wet processes

Desizing is the first process of denim washing. If desizing is not good, the hand and the wash effect will not be perfect and there may be streaks and uneven dyeing effects on the garments. Inconsistent and ineffective desizing results in garment streaks and inconsistent garment surface abrasion. The starch film on the garment is often broken or cracked during sewing. During wet processing, the areas of cracked size films abrade quicker than the other parts of the garments, creating streaks on the surface (Paul and Naik, 1997a; AATCC, 2004).

Defects related to stone washing are mechanical damages and creating uneven footprints of stone shapes on the garments. The effect of stone washing mainly depends on the size of the pumice stones. Bigger stones can give the effects easily and quickly but there is a risk of mechanical damage. If the liquid ratio is low, there is also risk of mechanical damage. Cleaning stones is an important step after stone washing. If the garments will undergo bleaching in the next process, stones remaining inside the pockets of the garments will soak the chemicals and cause local bleaching spots on the garments (Paul and Naik, 1997a; AATCC, 2004). Figure 14.17 shows bleaching spots and defects related to wet processes.

Washing quality is also directly related to the clean up procedures used after decolourisation processes. Low tensile and tear strength, yellowing, holes and stains are the main quality problems caused by inadequate clean up procedures. Rinsing and neutralisation are important clean up processes, which must be applied after every chemical washing and finishing processes. Greyness, red or brown spots and blue stains are important chemical defects together with yellowing problem and silicone stains on the garments (AATCC, 2004). Figure 14.18 shows stains and unsymmetrical effects on the legs after wet processing.

Backstaining is another important problem of indigo dyed products. Indigo dyestuff is applied to the yarn in several layers. The outer layers are not perfectly fixed and come off into the dyeing liquor, and can cause backstaining of the pockets or other garment parts. In order to minimise the deposition of indigo dye on the garment parts inside pockets or labels, the pH should be correctly set and optimised rinsing procedures should be followed (AATCC, 2004). It is also suggested that backstaining can



Figure 14.17 Bleaching spots and defects on jeans. Picture: Suglobal Tekstil.



Figure 14.18 Stains and unsymmetrical effects on legs. Picture: Suglobal Tekstil.

be removed with the aid of laccase washing applied after normal washing for a short period of time with low concentration (Tarhan and Sariisik, 2009).

In a study, the effect of sanding, stone washing, enzyme washing and combined washing procedures of denim fabrics on physical and mechanical properties and hand feel has been analysed. It was found that weight loss was high for stone washed and bleached fabrics. Breaking and tear strength values were affected more in the warp direction because of twill fabric construction. Breaking elongation and tear strength values after stone washing and enzyme process were reduced. Subjective hand evaluation results showed that softer and bulkier surfaces were obtained after sanding and stone washing (Sular and Kaplan, 2011).

## 14.7.5 Yellowing problem

#### 14.7.5.1 Reasons for yellowing

The yellowing of denim garments, specifically after bleaching, is a major problem. This yellowing occurs as large patches throughout the garment as well as at the folded edges of the garment. Studies have shown that the yellow formation is due to decomposition products of indigo dye, namely isatin and anthranilic acid. Residual chemicals from the oxidation process can certainly leave a residue behind, especially if the rinsing is inadequate. Yellowing in cotton denim fabrics can also be caused by a number of nonpermanganate related factors such as:

- Excessive oxidation of residual starch and cotton cellulose in scouring and bleaching, resulting in decomposition products that can potentially yellow on exposure to light or oxidative or reductive atmospheric contaminants.
- · Improper removal of the warp sizing present on the denim jeans going into stone washing.
- The use of cationic softeners, which under storage conditions can yellow.
- The use of fluorescent brighteners or whiteners, which have limited light fastness and can yellow on exposure to O<sub>2</sub>, NO<sub>2</sub> or SO<sub>2</sub>.
- Overdrying of the stone washed denim jeans resulting in decomposition products that are more vulnerable to subsequent yellowing on exposure to light and atmospheric pollutants.
- Caustic treatment can cause yellowing of cellulosics, which is a phenomenon in the pulp and paper industry and referred to as alkaline darkening.
- Formation of oxy cellulose as a result of acid processing of cotton or oxidative attack on cotton by permanganate, ozone, UV light, etc. (Paul and Naik, 1997c).

As with all wet processes involving chemicals, a good rinse is always necessary in order to remove any chemicals that can irritate the skin of the consumer, oxidise or photoreact to cause a problem later on. Yellowing does not occur immediately but occurs during storage. A good rinse with soap in the first rinse is always a good idea. It has also been shown in other washing and rinsing studies that several short rinses with fresh water is better than one long rinse for an equal length of time.

The main problem associated with yellowing of acid washed, indigo dyed denim is the loss of the desired blue/white contrast in the finished goods. Yellowing reduces the fashion appeal of the garments and thereby reduces this value to consumers. Noticeably yellowed garments are often rejected by garment manufacturers. Laundries are then faced with having to rewash the garments at a cost that consumes the profit realised by the original wet processing of several garments.

## 14.7.5.2 Treatments to reduce yellowing

Following treatments are recommended to reduce yellowing:

- Rinsing: Thorough rinsing with hot water after cleaning has been suggested as one way to
  minimise the photoyellowing of acid washed denim jeans. The increase in apparent photoyellowing after thorough rinsing may probably be an optical effect due to the removal of
  indigo dye from the jeans during rinsing. The dye had optically compensated for yellowness
  in the unrinsed samples, and this made photoyellowing less apparent.
- HCl treatment: In practice, it is found that the HCl treatment can reduce photoyellowing to a slight extent only.
- Oxidising agents: Treatment with mild oxidising agents, such as hydrogen peroxide, peracetic acid, sodium chlorite and sodium bromate in different formulations, could probably degrade the photoyellowing compounds.

- Reducing agents: Treatment with reducing agents such as hydrogen peroxide, oxalic acid, sodium bisulphite, sodium hydrosulphite and sodium nitrite has better resistance to photoyellowing. Oxalic acid or nitrous acid (sodium nitrite/hydrochloric acid) treatment produces good results. Clearing with nitrous acid also eliminates the fluorescence in acid washed denim. Treatment with nitrous acid and hydroxylamine sulphate can clear acid washed denim practically, by eliminating the photoyellowing.
- Chelating agents: Chelating agents such as EDTA, DTPA, HEDTA, citric acid and oxalic acid are found to be effective in removal of the residual manganese from acid washed denim (Paul and Naik, 1997c).

# 14.7.6 Crease marks

Crease marks are also a common fault that occurs during dyeing, washing and finishing of fabrics and garments. There are different types of crease marks (Suglobal Tekstil, 2013). Mechanical crease marks occur when the machine is overloaded or the liquid ratio is low in the machine or the machine cycle is too low. Crease marks related to the chemical processes may occur if desizing and preparation are not even. If the fabric desizing and preparation processes are not smoothly done, garments cannot be wetted uniformly, thus creating crease marks on the garments (Suglobal Tekstil, 2013; AATCC, 2004).

# 14.7.7 Strength loss

There are many reasons for strength loss, and most of the reasons are directly related to mechanical and chemical washing processes. Pumice or synthetic stone sizes, oxidising agents, enzymes, acids, chemical agents, resin application, sanding and brushing strength, incorrect grinding and destruction and laser intensity are the possible reasons for strength loss. Cellulose fibre can be degraded chemically by action of oxidising or reducing agents and acids. These chemicals attack the structure of the polymer, and so the polymer is destroyed and strength loss occurs (AATCC, 2004). Physical forces such as extreme abrasive processes may also reduce the strength of some parts of the



**Figure 14.19** Tearing close to bar tack stitch. Picture: Suglobal Tekstil.

garment. After resin application, the tearing strength of the fabric reduces and tears may occur close to the bar tacking stitches on the hip pockets and flies. Figure 14.19 shows tearing that occurred close to bar tack stitching above the back pockets. The influence of sanding, brushing, resin treatment, permanganate spray, bleach, stone washing, enzyme washing, combined washing (stone+enzyme) and final finishing procedures on the mechanical properties of denim fabrics has been studied, and it was found that washing processes reduce the mechanical properties especially of the warp yarns of the fabrics. Resin treatment is found the most degrading treatment, which reduces both tearing and breaking strength of denim fabrics (Khedher et al., 2009).

#### 14.7.8 Sewability problems

The most important sewability problem is the mechanical damage that occurs during needle penetration to the fabrics. Needle damage is the partial or complete severance of yarns at the seam line (Tyler, 2008), and the size of the damage increases after washing and finishing procedures. Figure 14.20 shows a product with needle damage along the seam line. The needle is not the only contributing factor to the problem of mechanical damage. A major problem is that combination of the machine speed and the nature of fabric prevents the yarn from moving out of the way of the needle sufficiently to avoid damage. Needle size, inadequate fabric finishing, inappropriate needle points and damaged needle points may cause mechanical damages at the seam line (Tyler, 2008).

Mechanical damage can usually be detected by manually stretching the fabric at the seam line, but for denim fabrics it is more complex situation. Denim jeans are normally produced from raw denim fabric and only after sewing, washing and finishing processes are applied to the sewn garment. For this reason, if needle damage occurs on the garment during sewing, this damage becomes more serious after washing and it cannot be repaired. Skipped stitches, broken stitches, pleated seams, uneven stitch density and seam pucker are other sewing defects (Glock and Kunz, 1995; Mehta, 1992).



**Figure 14.20** Jeans with needle damage along seam line. Picture: Suglobal Tekstil.

## 14.7.9 Spirality and dimensional stability

The tendency of spirality or twist in a woven garment leads to twisted leg, which is considered an important quality problem. Figure 14.21 shows a twisted leg of denim jeans. Skewing and distortion in dry fabric after washing are critical parameters for garment quality (Mehta, 1992). This problem is caused by dimensional changes in the fabric or tension caused during sewing. The main reason is twill construction, which is the main weave type in the production of denim fabrics. The construction of twill weave is unbalanced, which causes movements in the denim fabric, and tension within fabrics creates skewing on the fabrics and twisting of garments. Measurement of skew and distortion must be checked strictly before pattern making during garment production.

The dimensional stability of denim fabrics is an important problem related to fabric production processes (Mehta, 1992). Control of shrinkage between fabric rolls and within fabric rolls is very important. Dimensional stability of the fabrics must be checked strictly before pattern making in order to add necessary tolerances to the garment panels and to avoid size problems after treatments.



**Figure 14.21** Twisted leg of denim jeans. Picture: Suglobal Tekstil.

## 14.8 Future trends

Ecology and fashion will continue to be the driving factors for jeans production and marketing, and in this respect, waterless finishing will be a priority for this industry. The application of plasma and nanofinishes for developing functional properties on denim will also grow in the future. Innovative and ecological washing procedures, sustainable production programs, recycled products, lighter and softer jeans, elastic jeans, functional finishes related to well being and technical properties will be more popular in the future. These functional finishes will include microencapsulated vitamins and special oils for the skin, as well as anticellulite, odour resistant, moisture management, wrinkle free, water/oil repellent, mosquito repellent, antimicrobial, UV protective and flame retardant properties (Prasad, 2007). Thus, in the near future, many fashionable and multifunctional effects will coexist on denim, and this fabric that was only considered for fashion will enter new markets for non-apparel and technical products.

There is also a trend for the production of multicoloured, pigment dyed, combined dyed and finished, non uniform dyed, retro dyed, hydro patterned, laser faded, reverse dyed, special coated, leather like and embossed denim fabrics and for creative washing procedures for these new innovative denim fabrics. There is also an increased trend for high fashion printing techniques based on novel metallic pigments, phosphorescent colours, optically variable pigments, thermochromic pigments and photochromic pigments. Inkjet printing as well as laser engraving will also become more significant in near future.

There is also a great interest in the production of reused denim, which is made up of 50% denim scrap and 50% virgin cotton or lyocell. Soft jeans are very popular in the market for different age groups. Soft jeans, made of cotton and viscose, lyocell, poynosic, cupra or polyester blends, will be more popular in the future due to their soft and comfortable feel (Bajaj and Agarwal, 1999; Bajaj, 2002). It should also be mentioned that for the green manufacturing of denim garments, three types of digital approaches – digital printing, laser scribing and digital jacquard weaving – will provide quick and efficient manufacturing (Wang et al., 2013).

# 14.9 Conclusion

There are countless variations in denim garment processing techniques to achieve fading, excellent handle and unique look. The results obtained after dry and wet processes are a combined effect of mechanical abrasion, colour dissolution and destructive processes. Apart from such processes for achieving special fashion effects, several functional finishes are also applied on denim garments for providing technical and functional properties. Thus many fashionable and multifunctional effects can be simultaneously created on denim jeans by using different chemical finishing agents. However, at the same time, these combined dry and wet processes may cause several defects that reduce the performance, serviceability and marketability of the products. In order to minimise the defects, the choosing of the right denim fabric as well as the right processing parameters in the final finishing is essential.

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# Comfort aspects of denim garments



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# 15.1 Introduction

Denim has turned into the most famous fabric to be generally used to deliver different apparel ranging from trousers to skirts. Over the world, it is getting to be prominent step by step regardless of social standing, sexual orientation or age. Denim is a twill woven fabric, traditionally manufactured from cotton, yet polyester and polypropylene (PP) are additionally used to top off yarn. It is available in multiple shades, however, blue is the most well known colour to be found all around. The warp of denim is coloured while its weft is left uncoloured. It is believed that the word 'denim' originates from French *serge de Nimes*. The renowned Webster's dictionary included the word 'denim' for the first time in 1864, where it was used for a fabric produced using coarse cotton to make clothing.

Levi Strauss was the person who, in the mid nineteenth century, utilised denim to create trousers to be worn during work hours. Later on, utilising metal rivets strengthened it. Today, the most widely recognised name of denim trousers is jeans, which is connected with the clothing worn by American cowboys. On May 20, 1873, Levi Strauss & Co., a privately owned business, got the copyright of their recently designed pair of blue jeans, which was made stronger by putting rivets on it. First and foremost, these sorts of trousers were supplied to the workers working in mines, as they required effectively wearable trousers amid the work.

Attire made by utilising denim is very famous around the world. Industry is utilising denim for making pants, blouses, kids' dresses and sacks. Denim attire is famous because of its light and washing fastness, alongside numerous shades and hues. One of the real qualities of denim is the thermo-physiological comfort of customers while wearing it. This chapter outlines the thermo-physiological comfort properties of denim under dry and wet conditions. The fibre properties are very distinct in the wet state due to the application of diverse chemical auxiliaries in washing. In addition, the effect of the type of weaves has to be examined for the thermo-physiological comfort.

# 15.2 Comfort aspects of denim

Denim is a thick fabric made by coarse yarn. Its weight ranges from 200 to 400 g for every square metre. In the majority of the cases, open-end yarn is utilised for some particular reasons. First, it gives a better look after its washing, in the shape of

garments; second, it gives a ring effect, which improves its look. The warp of denim is normally coloured by indigo or with sulphur and vat colours, like sulphur black and hydron blue. Some different colours are likewise utilised as a part of washing for colour matching and tinting purposes. Traditional denim is manufactured by using 100% cotton yarns. In any case, some companies are additionally utilising polyester for weft yarn as a part of denim assembling.

Denim made of cotton is an overwhelming fabric and it is retentive. Trouble emerges when the wearer feels uneasy because of the high measure of damping amassed in the fabric as a consequence of sweating or higher moisture in the environment. It is basically because of the progressions in thermal conductivity of denim when it has some measure of water in it. One of the conceivable solutions to this issue is an adjustment in the piece of denim and change in the application of chemical auxiliaries during washing. In relation to the thermo-physiological comfort, distinctive researchers and commercial ventures have proposed many suggestions for changes in denim assembling.

Nearly all the garments made by utilising denim fabric are passed through a finishing or washing process in industrial garment washing machines. The reason for denim garment washing is to give a washed/blurred look and bestow smooth hand feels. The most well known procedure is some abrasive washing that gives a specific shade and look. There can also be enzymatic treatment for giving a smooth surface or the application of softeners for a finer feeling. In addition, numerous unique chemical auxiliaries are applied (Tarhan and Sarisik, 2009). Industrial washing might be utilised to attain certain purposes. Mazumder has contemplated the effect of enzymes for completely biodegradable washing and its effect on fabric surface. Change in fabric surface is because of the removal of projecting strands, and this change adjusts the thermal parameters and prompts changes in thermal comfort (Mazumder, 2010).

## 15.3 Thermo-physiological comfort

## 15.3.1 Clothing physiology

Hohenstein Institute, Germany connected clothing comfort science with the Greek philosopher Empedocles (500 BC), who expressed his belief that human skin is breathing. Empedocles suggested that clothing should not depress the respiration and at the same time should not allow toxic elements to penetrate in the body. It shows that clothing comfort always remained a preference of human beings. Nevertheless, clothing comfort became a subject of study in the early twentieth century when man-made fibres were developed and more novel types of clothing were obligatory. Clothing comfort is hard to explain because of a complex and interdependent amalgamation of physical, psychological and sensory perceptions, and it is exceedingly based on subjective evaluation of the individuals (Hohenstein Institute).

Clothing that is in direct contact with the human body interacts continuously with the skin during use. Such interaction between garment and human body stimulate mechanical, visual and thermal sensations, which eventually lead to perception of either comfort or discomfort. Garment design, size and its material assume a pivotal role in keeping the harmony between human body and the exterior environment. It is possible to modify a stream of hotness through the fabric, by transforming its thickness, structure and

arrangement of the filaments. In addition, application of some textile auxiliaries can likewise change the conduct of fabric amid high temperature and mass exchange.

Traditional denim is made of 100% cotton, and it quickly gets to be soggy in a sultry atmosphere and makes discomfort for the wearer in light of the fact that it retains a great deal of water. All things considered, in not many cases, spandex yarn is utilised, which diminishes the cotton's share. Also, a few makers are additionally utilising polyester within the weft to enhance the quality, however, its rate is never more than 40%. Insensitive moisture uptake, though it provides better comfort in case of reasonable moisture, provides a cool and wet feeling. A higher measure of water reduces its thermal resistance and adds to its thermal conductivity, which then turns into a reason for limiting human body heat. Collection of water between the human body and the denim expands the methodology of putting away high temperature that is created by the human body, which gives a chilling feeling. Additionally, dampness increases skin irritation and skin diseases.

Amid the preparatory review, which is focused around perspectives of end clients of denim pieces of clothing, a clearer perception demonstrated that traditional denim made of 100% cotton gets to be altogether moist in a muggy atmosphere and it causes discomfort for the wearer because of the high spongy property of cotton. At the point when there is restricted dampness ingestion, it gives better comfort, however, in the event of more dampness, it gives a cool and damp feeling. This is because of an incred-ible decrease in thermal resistance, which increases thermal conductivity. Also, water raises thermal conductivity higher than natural fibre.

#### 15.3.2 Specifications of conventional denim

One of the classifications of denim is based on the weight, commonly denoted with ounces per square yard. In this chapter, a gram for every square metre (GSM) term is used to portray the weight of denim. The GSM of conventional denim ranges from 200 to 450. Light denim is made by keeping its weight around 200 GSM. Such fabric is utilised to make denim shirts, children clothing and so forth. Such lightweight fabric is not suitable for trousers, normally called jeans. Jeans are a sort of trousers made by utilising denim having 300–450 GSM. Determination of yarn surface relies on the obliged GSM. Table 15.1 shows denim fabric construction, detailing warp and weft characteristics and the GSM range of denim.

| Tex (warp) | Tex (weft) | Ends per cm | Picks per cm | GSM   |  |
|------------|------------|-------------|--------------|-------|--|
| 84         | 98         | 26.0        | 16.5         | 397.2 |  |
| 84         | 84         | 24.4        | 15.7         | 368.8 |  |
| 74         | 74         | 26.8        | 17.3         | 340.4 |  |
| 74         | 59         | 26.0        | 18.9         | 312.1 |  |
| 74         | 49         | 26.8        | 18.1         | 283.7 |  |
| 59         | 49         | 25.6        | 17.3         | 255.3 |  |
| 49         | 49         | 26.8        | 18.1         | 227.0 |  |
| 42         | 42         | 26.8        | 19.7         | 198.6 |  |

 Table 15.1
 Denim fabric construction details

Under ordinary conditions, conventional denim gives finer thermo-physiological comfort, however, if there should be an occurrence of wet air, it loses all its thermo-physiological comfort and gives discomfort to clients. There are three conceivable choices to rectify this problem. First, utilising some synthetic fibre will diminish the cotton content, and lessen the water sponginess and will dry soon. Second, a change in the weaving outline will enhance the drying procedure. Third, some chemical auxiliaries can be applied to enhance the dampness administration properties.

# 15.4 Development of functional denim

Conventional denim is made of 100% cotton, washed thoroughly, and textile auxiliaries are applied to it to make it soft. Blue and black colours are the most common. Researchers are using the term 'functional denim' for a fabric that is made by exploiting following areas (Mangat, 2012):

- Blending of different fibres in spinning.
- · Using different fibres in the warp and weft.
- · Applying different weaving techniques.
- · Application of different textile auxiliaries.

Functional denim is different from conventional denim and is produced for a specific purpose. It may have a different composition of the fibres, distinct structure and application of certain textile auxiliaries. Such changes will alter the behaviour of heat and mass transfer.

As mentioned before, thermo-physiological comfort depends upon the flow of heat and mass transfer. If any change happens in the heat and mass transfer behaviour of the fabric, thermo-physiological comfort will be affected considerably. So under dry and wet conditions, the thermo-physiological comfort of conventional denim will be very different. The objective of this section is to elaborate the characteristics of functional denim fabrics by identifying links between changes in fibre composition, structure, textile auxiliary application and thermal parameters.

#### 15.4.1 Functional denim with blended yarns

Blended yarn means that more than one type of fibres have been used in making the yarn. Such blending of fibres creates changes in effective thermal conductivity due to diversity in thermal conductivity values of different materials. Moreover, their physical structure affects the arrangement and ultimately there is a change in porosity. All such changes lead toward change in thermo-physiological comfort. In this section, the production of functional fabrics using different fibres and the impact of blending on thermo-physiological comfort are discussed.

The literature provides many studies conducted to evaluate the impact of blending on thermo-physiological comfort, but all such studies relate to fabric made by using blended yarn under dry conditions. Studies about the use of denim made by blended yarn in wet conditions are quite rare. Different studies on different types of fabric give evidence of a significant impact of blending on thermal parameters. A study investigated the impact of moisture flow through blended fabrics. The authors believe that moisture flow through a blended material is a complex process that is influenced by many factors (Das et al., 2009).

Clothing keeps the skin dry by taking moisture from the skin and transferring it to the environment. Though hydrophilic fibres can absorb moisture, it causes the reduction in the level of transfer of moisture from skin to the environment, mainly due to the absorbance nature of fibres. Das et al. worked on polyester and viscose for blending and made eight different fabrics. They examined the level of water vapour transmission and absorbency.

A study examined the relationship between the impact of thermal conductivity behaviour of jute/cotton blended knitted fabrics and fabric thickness (Vigneswaran et al., 2010). The authors found that the higher the jute blend proportions, the lower the thermal conductivity. Nevertheless, thermal conductivity was noted to be also negatively related to the fabric thickness, which implies that thermal resistance would be high. The other factors that were identified were air permeability and tightness factor values as influencing the thermal conductivity of jute/cotton blended knitted fabric. A negative correlation was identified between the fabric tightness factor and air permeability. This study supports the idea of blending two distinct fibres in order to have a required thermo-physiological comfort level.

Another study was conducted to examine the impact of porosity, weight, fibre contents and thickness on overall moisture management capability (OMMC) of fleece fabric. For this purpose, 30 different fleece fabrics were developed and tested by using the Moisture Management Tester (MMT). The results indicated that structure is the most important factor in the determination of thermo-physiological comfort. However, the role of different fibres in determining thermo-physiological comfort is found to be significant (Mangat et al., 2012, Hohenstein Institute).

In another study, Rengasamy et al. examined the characteristics of thermophysiological comfort of airjet textured polyester and cotton yarn fabrics. They used two feed yarns differing in filament fineness and the number of filaments in order to produce airjet textured polyester yarns. They observed that thermal conductivity and resistance of fabrics are not influenced by the texturing parameters or by the textured yarn structure (Rengasamy et al., 2009).

Plante et al. carried out a subjective evaluation of fabrics made by using wool, cotton, polyester and a wool/polyester blend with changing the variable of varying moisture level of environment. Based on the observations of 20 people, the researchers found an interrelation between dampness perception and fibre hygroscopicity. Moreover, highly hygroscopic wool gave a dry feeling while hygroscopic polyester gave a less dry feeling at 25% relative humidity (RH). Additionally, the higher RH resulted in less dampness perception (Plante et al., 1995).

Such studies on developing different textiles with blended yarns can form a base to develop functional denim fabrics. Mangat succeeded in developing 180 different types of denim by using polyester, cotton and polypropylene, using 3 common weaving techniques, and 12 different washing methods were used during this process. Researcher carried out different tests and finally concluded that the use of polypropylene as weft yarn in functional denim gives it the highest moisture management capability. Such a material is

able to retain its thermal resistance property for a longer time as compared to conventional denim, under wet conditions (Mangat, 2012). The study reveals the advantages of functional denim over conventional denim. The next section discusses the different parameters of conventional denim and functional denim under both dry and wet conditions.

#### 15.4.2 Functional denim and moisture transfer

Denim effectively serves the purpose of controlling moisture transfer between the human body and the environment. Many studies have been conducted to examine the changes caused by blending and application of textile auxiliaries on thermal parameters. Most of the studies included traditional fabric in the experiments, which is used for suiting and shirts.

Kandjov describes the complexity of moisture flow through a blended material. Moisture could take the shape of vapours and liquids. Therefore, fabric should have the ability to transmit vapours as well as liquid from skin to the environment (Kandjov, 1999). A number of factors are found capable of changing the process. Kandjov believes that clothing should possess the characteristics of good water vapour as well as liquid moisture transmission. It is a pre-requisite for a better thermo-physiological comfort level.

A study tried to understand the impact of fibre composition on moisture transfer. For this purpose, the authors mixed polyester and viscose and developed eight fabrics with different proportions. Further, they used Permetest (Hes, 2008a) to measure the passing of water vapour through the fabric. They applied a vertical wicking tester for the measurement of the liquid water transmission property of the fabrics and arrived at the conclusion that water vapour permeability and absorbency of the material is positively related to the number of hydrophilic fibres (Das et al., 2009).

Mangat conducted a comparative study of conventional denim and functional denim fabrics. AATCC Test Method 195-2009 was used as a criteria to test denim samples on the SDL Atlas Moisture Management Tester. The instrument is used in view of its functionality to give different indices and it helps to quantify the movement of water in different directions in a textile material. Table 15.2 shows the capability OMMC of denim fabrics made of different fibres. It is observed that the OMMC of the denim made by Spun PP is the maximum, which bears upon its performance to keep skin dry under wet conditions (Mangat, 2012). It is also found that the conventional denim made by using 100% cotton has the minimum moisture management capability.

#### 15.4.3 Significance of thermal parameters

Using different weft fibres and keeping the warp constant can alter the fibre composition of functional denim fabrics. Mangat found that the usage of different fibres in weft has a certain impact on denim. Five different fibres have been utilised to develop functional denim fabrics. The split plot techniques are used to examine the level of significance of weft changes on thermal parameters (thermal conductivity, thermal resistance and thermal absorptivity). Figures 15.1–15.3 show the thermal conductivity, thermal resistance and thermal absorptivity, respectively, of conventional denim and different functional denim fabrics under wet conditions (Hes, 2008a).

| Serial<br>no. | Weft                | Wetting<br>time top<br>(s) | Wetting<br>time<br>bottom<br>(s) | Top<br>absorption<br>rate<br>(%/s) | Bottom<br>absorption<br>rate<br>(%/s) | Top max.<br>wetted<br>radius<br>(mm) | Bottom<br>max.<br>wetted<br>radius<br>(mm) | Top<br>spreading<br>speed<br>(mm/s) | Bottom<br>spreading<br>speed<br>(mm/s) | Accumulative<br>one way<br>transport<br>index (%) | ОММС |
|---------------|---------------------|----------------------------|----------------------------------|------------------------------------|---------------------------------------|--------------------------------------|--|-------------------------------------|--|---|------|
| 1             | Spun PP             | 3.88                       | 3.16                             | 31.00                              | 53.03                                 | 20.00                                | 25.00                                      | 4.84                                | 5.34                                   | 414.43  | 0.87 |
| 2             | SBC PP <sup>a</sup> | 4.76                       | 2.99                             | 34.15                              | 49.87                                 | 20.00                                | 25.00                                      | 4.30                                | 4.79                                   | 373.52  | 0.83 |
| 3             | AT PP <sup>b</sup>  | 4.04                       | 3.80                             | 37.89                              | 38.36                                 | 25.00                                | 25.00                                      | 4.47                                | 4.22                                   | 349.06  | 0.77 |
| 4             | Polyester           | 3.48                       | 3.40                             | 30.34                              | 44.93                                 | 20.00                                | 20.00                                      | 3.36                                | 3.48                                   | 280.95  | 0.67 |
| 5             | Cotton              | 4.44                       | 3.08                             | 42.84                              | 43.66                                 | 20.00                                | 20.00                                      | 4.48                                | 4.46                                   | 192.25  | 0.61 |

 Table 15.2 Moisture management capacities of denim fabrics

<sup>a</sup>Stuffer box crimped PP. <sup>b</sup>Air textured PP.

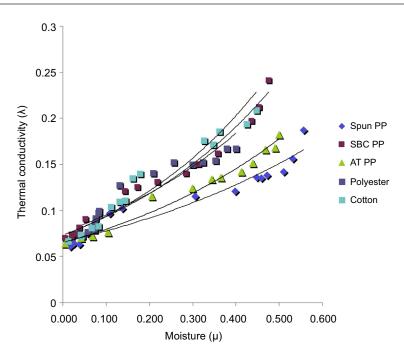


Figure 15.1 Thermal conductivity of conventional and functional fabrics.

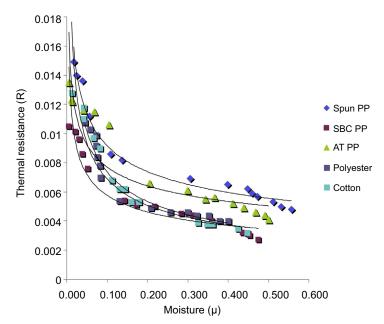


Figure 15.2 Thermal resistance of conventional and functional fabrics.

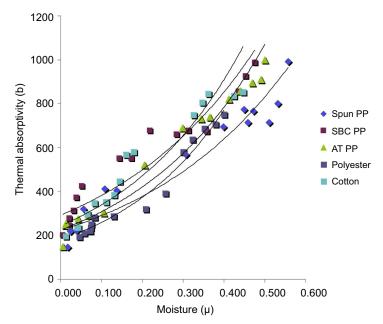


Figure 15.3 Thermal absorptivity of conventional and functional fabrics.

Results indicate that there is a significant impact of fibre composition on thermal parameters. It is mainly due to the significant difference in thermal conductivity and density of polypropylene, cotton and polyester. Density of polypropylene is reported to be 0.9 (gm<sup>-3</sup>) and the density of cotton above 1.4 (gm<sup>-3</sup>). Besides, the difference in thermal conductivity values of cotton, polyester and polypropylene is also very significant, as observed in Figure 15.1 (Mangat, 2012).

According to the above discussion, thermal conductivity plays a significant role in creating thermal resistance, which in turn is important for thermo-physiological comfort of human beings. The significance of the weft variation of thermal parameters has been analyzed with the ANOVA. It was concluded that there was no noteworthy difference in thermal parameters between conventional (100% cotton) and functional denim fabrics composed of polypropylene and polyester under dry conditions. It proves that use of polypropylene and polyester is ineffective in providing extra benefits under normal dry conditions.

As observed in Figure 15.2, the functional denim fabrics made of Spun PP and AT PP keep the thermal resistance property in wet conditions better than conventional denim and also even better than denim fabrics made by using SBC PP and polyester as weft. This means these fabrics can keep the human body warm for a longer time in a wet and cold climate.

As such, the thermal resistance of denim fabrics made by using Spun PP and AT PP is 50% higher than other denim samples. It is primarily due to the higher number of crimps present in AT PP and plentiful in Spun PP due to short fibres. Presence of pores furnishes air pockets, which have much higher thermal resistance as compared

to polymers. This conclusion braces the idea to have less dense fabric for higher thermal resistance. There is a relatively slow decrease of thermal resistance of samples made of Spun PP and AT PP under wet conditions, and so it is evident that these two fabrics will keep the human body warm and will reduce the heat passage between the body heat and the environment.

The next observation studied the relationship between increase in moisture percentage, an increase of thermal conductivity and thermal absorptivity. However, the slope of change indicates great variation, as observed in Figure 15.3. It is obvious that cotton and SBC PP have the steepest slope. It shows that thermal conductivity and thermal absorptivity of denim made by using cotton and SBC PP has higher levels than that of Spun PP and AT PP, where polyester has moderate values for these variables.

An increase in thermal absorptivity increases the cool feeling, which causes discomfort for the user. According to this study, the presence of moisture makes Spun PP and AT PP perform better; in other words, they give a relatively dry contact feeling even in the wet condition. It implies that Spun PP and AT PP can maintain a certain level of thermal comfort under intense conditions.

#### 15.4.4 Weave and thermo-physiological comfort

Textile fabrics are flexible and function as a second skin of human beings with their built in pores. Porosity of the fabric is another main feature, which accounts for its properties. A microscopic observation of fabrics reveals the following facts:

- Area filled with fibres (organic and inorganic).
- Presence of moisture present inside the fibres, between the fibres and between the warp and weft depending upon the humidity in environment.
- Presence of air among voids.

The thermal parameters of a fabric are influenced by of all these features in the order of their arrangement. The level of thermal conductivity of fibres, moisture and air varies. Presence of moisture in fabric plays a crucial role in thermal insulation. The conductive level of water molecules is high as compared to air and polymers. Low porosity of the fabric is caused when its area is filled with polymers, and high porosity implies more spaces in the fabric, which gets filled with moisture and air.

Considering these aspects, denim manufacturing can be carried out in different types of weaving that does not cause any change in fibre composition of denim. However, a change in the direction and arrangements of warp and weft is certain. They also influence tensile strength, but the impact of weave pattern on thermo-physiological comfort cannot be understood without a deep analysis.

Bilisik and Yolacan produced four varieties of denim: conventional, parallel rhombus, hexagonal and octagonal denim. After performing various tests, they concluded that after abrasion, tensile properties of large structural pattern denim fabrics are more affected than the small structural pattern and conventional denim fabric. On the other hand, the weft directional tearing potency of the small structural pattern denim fabric proved to be much higher than that of the conventional denim. It indicated that using different weaves patterns could result in significant change in the tensile related properties of denim. The limitation of this is that it does not provide any information regarding the thermal related properties of denim (Bilisik and Yolacan, 2011).

Karaca studied the effects of fibre cross sectional shape and weave pattern on thermal comfort properties of polyester woven fabrics. They used different cross sectional shaped polyester fibres, and using plain and twill weave developed eight different fabrics. The types of polyester used were round, hollow round, trilobal and hollow trilobal shaped. Their study proved that fabrics consisting of hollow fibres had higher thermal conductivity and thermal absorptivity values, whereas thermal resistance, water vapour and air permeability values were lower than polyester of solid shape. In addition, this study proves that weave has an impact on thermal parameters. The findings indicated that twill fabrics produced from trilobal fibres showed the lowest thermal conductivity and thermal absorptivity, while thermal resistance, water vapour and air permeability were the highest. This study shows that thermo-physiological comfort is affected by blending of distinct fibres, fibres of the same chemistry as well as different shapes (Karaca et al., 2012).

Mangat studied the impact of the weave on thermal conductivity, thermal resistance and thermal absorptivity. Three types of weaves – broken twill, 3/1 twill and herringbone – were used, which helped to produce 180 samples with different yarns and various textile auxiliaries. The results from a comparison test showed the absence of a significant impact on the thermal conductivity, thermal resistance and thermal absorptivity of denim, implying that there is no impact of the type of weave on the thermo-physiological comfort phenomenon (Mangat, 2012).

#### 15.4.5 Role of porosity in comfort

The role of porosity is very effective in thermo-physiological comfort. Porosity is also called the openness of fabric. It is determined by the fineness of yarn, weaving or knitting technology and application of textile auxiliaries. A good number of studies are available in the literature, which focus on finding the impact of porosity on thermal and sensorial parameters of clothing. This part of chapter pertains to discussing in detail the role of porosity or openness of denim in thermal and mechanical comfort.

Haghi explains the porosity as the volume fraction of void spaces. He also further reports that the porosity of hygroscopic fibres continuously changes under wet conditions, whereas this does not happen in case of non-hygroscopic fibres under wet conditions, which is caused by the swelling effect. Haghi also demonstrated that there is a difference between pore and capillary (Haghi, 2003). Water can be retained in textile fabric mainly in three ways:

- · Hydrogen bonding having physical adhesion on the surface of fibres.
- Filling it between yarn spaces.
- Keeping it inside the fibres.

It is well established that there is no chemical reaction between fibres and water. Nevertheless, water presence can cause some possible changes such as swelling. Moreover, in case there is no water, then all spaces are filled with air. It should be noted that air is not fully dried and always has a certain amount of moisture in it. Porosity is a means of letting the heat from inner side of the human body release through convection and channel effect. However, a minor amount may be released though radiation. The literature shows that the main focus of research has been heat dissipation through convection. It is important to note that the heat transfer through convection is of two types – free and forced convection. The element always faced is wind flow, which can range from slow, such as 1-2 m per minute, to a very strong wind. In force convection, heat loss takes place at a higher speed, absorbs more heat from the body and provides a more cooling effect. This is commonly termed the chill effect.

Another impact of porosity is noticed on dye uptake (Çay et al., 2007). It has been observed many times that loose knit fabrics need a smaller amount of dye than dense fabrics. It is evident from the difference in the case of knitted fabric dyeing along with collars. It is mainly caused by the impact of porosity on the flow of air or moisture. Porosity is said to be a function of the geometry of fabric. Fabric geometry depends upon the following factors:

- · Fibre fineness and the number of fibres in a cross section of yarn.
- Type of fibre: filament or staple.
- Surface of fibre.
- Yarn diameter.
- · Yarn compactness.
- Warp and weft per unit length.
- Type of weave or knitting.
- Application of textile auxiliaries.
- Type of mechanical finishes (calendering, etc.).

The air crossing also depends on the type of fabric. The fabric made of staple fibre allows more air to cross than fabric made of filament. It has been reported that the application of different softeners also impacts the airflow as it is a function of porosity, whereas the type of weave does not have a noticeable impact on airflow (Mangat, 2012).

#### 15.4.6 Effect of washing on comfort properties

Starch applied during weaving and the coarse yarns give raw denim rigidity and a very rough look. Normally, it has a solid colour – blue or black. People prefer a soft feeling and less rigidity along with a faded look, and these properties are added during the process of washing. Industrial garment washing machines are used to wash denim garments. Initially, pumice (light weight volcanic stone) was commonly used for denim garment washing. These days, many enzymes are used for denim garment washing. Acids and bleaching agents are also used for a required faded look. The washing process and ingredients can drastically change denim properties after washing.

Khan and Mondal have studied the impact of stone washing and bleaching on denim. During this study, pumice stone and bleaching powder were used at different temperature and pH levels. They found a significant impact on the colour, softness and tensile strength of denim. This change is brought about by the action of chemicals and mechanical rubbing of dyes and cellulose (cotton). Untreated yarn is quite compact, while treated yarn shows roughness and protruding fibres on the surface. This change has a great influence on the porosity of denim. Higher porosity implies that there is sufficient air trapped inside the denim and it provides a smooth surface and decreases rigidity in the warp direction (Khan and Mondal, 2013).

The space for moisture is provided by high porosity under wet conditions, and any amount of moisture can diminish the thermal resistance of denim, as the thermal conductivity of water is 26 times higher than air. So, one can conclude that treated denim possesses pores and space for moisture. The higher the amount of moisture, the more significant will be the impact on thermo-physiological comfort.

Research was conducted to study the nanowashing technique for denim and compared it with the conventional denim washing system. The variables tested were air permeability, rigidity, smoothness and thermal stability. It was found that air permeability of denim treated with nano clay was much less than denim treated with enzymes. The higher air permeability will facilitate transfer of moisture from the surface of the skin to the atmosphere due to difference in moisture concentration in conformity with Fick's law (Khan and Mondal, 2013). Mangat examined the correlation between air permeability and thermo-physiological comfort and found that the higher air permeability of denim leads to evaporation of moisture from the inner side of the fabric (Mangat, 2012). It results in a quick drying process that makes denim become dry in a short time. Thermo-physiological comfort is highly correlated with dryness of denim owing to its higher thermal resistance than that of the wet denim due to low thermal conductivity of air. In view of the above, it can be said that denim treated with nano clay will keep wet under highly wet conditions as well as create a discomfort for users.

### 15.4.7 Effect of coating applications

Coating is a common method in which the fabric is coated or treated with polymers to achieve certain requirements. It may be some organic or inorganic material, and the most common example is the application of flame retardant chemicals, water repellant finishes and silicone emulsions. In this way, it is possible to attain certain functional properties on the fabric.

Tzanov et al. investigated the effect of amino functional silicone on moisture transport properties of fabrics. They used Alambeta and Permetest to measure the moisture transport properties. They find that the application of silicones reduces the water vapour permeability. Nevertheless, silicone treated fabric gives a warmer feeling. In short, the application of textile auxiliaries has the ability to alter the thermophysiological comfort of fabric (Tzanov et al., 1999).

Ruckman et al. investigated the impact of ventilation on thermo-physiological comfort. They compared two garments, which were made of polytetrafluoroethylene (PTFE) and polyurethane (PU) coated fabrics. Their findings showed that clothing having maximum openings limits increase in body temperature during exercise. However, in a resting position, the role of the fabric is dominant (Ruckman et al., 1999).

Ruckman et al. further conclude that ventilation is much demanded at the chest area due to the significant rise of temperature in this body part. Moreover, PTFE coated fabric, which is hydrophilic in nature, gives better thermo-physiological comfort as compared to PU coated fabric. This is primarily due to the passing of air between the human body and the environment.

Thus heat transfer through convection plays a significant role in thermophysiological comfort. Fabric that allows the movement of air from one side to the other prevents the rise of skin temperature, as discussed previously. It is well understood by the work of Hardy, which concludes that heat loss through forced convection is a function of many variables. Hardy proved that the removal of heat from the skin to the environment depends not only on the size of the opening. There are many more factors, which have significant impact on heat transfer. It is important to note that there is no static condition between the human body and the environment. There is a dynamic situation, every time, and user experiences changes in the velocity of air and human body motions. Moreover, there is a continuous change in temperature around users (Hardy, 1968).

Wenying et al. have studied the impact of coating fabric with hydroxyl-terminated polydimethylsiloxane-modified epoxy resin and hybrid aluminum nitride (AlN) particles of various sizes. They found that by adding 50% filler, thermal conductivity was higher, which was not possible with only coating the material. It was primarily due to filling of gaps in the fabric by filler, which provides a channel for heat transfer. The authors conclude that they get a synergistic effect of hybrid fillers giving rise to a better heat conduction capability as opposed to a coating without fillers. At the same time, the coating exhibited excellent high temperature resistance owing to the modified matrix and interaction between filler and matrices. Higher thermal resistance is due to the increase in thickness of fabric due to filling (Wenying et al., 2009).

Rehnby et al. studied the impact of different polymer coatings by varying the amount of coated material. They used knife-over-roll coating in laboratory small-scale equipment and continuously in a pilot plant. They applied polyaniline, polythiophene and polypyrrole mixed with an acrylic binder polymer on polyester fabric. They found that there was a drastic change in thermal conductivity due to coating. In most of the cases, coating is on one side of fabric, and in this way, the user gets fabric having two types of surfaces (Rehnby et al., 2012).

Such coating applications are also suitable for functional denim garments. Abbasi et al. applied polypyrrole on denim made of 100% cotton and polyester/cotton. They tested their thermal conductivity and finally concluded that a thin layer of coating does not change thermal conductivity of fabric significantly. Nevertheless, there is a drastic change in electrical conductivity. It shows that there is not enough space for heat transfer through conduction, whereas for electric conductivity, no large space is required. This study also shows that there might be no correlation between thermal conductivity and electrical conductivity (Abbasi et al., 2012).

So it is clear that in general, coating is one method to alter thermal conductivity and the thermal resistance of fabrics. The most common use of coating is to develop functional clothing, but it is also used to increase thermal conductivity and the reduction in thermal resistance. The most recent development is the application of nanoparticles to alter thermal conductivity and to change the thermo-physiological comfort of denim and other fabrics.

# 15.5 Testing of comfort parameters

#### 15.5.1 Hohenstein skin model

Special instruments are now available for testing the thermo-physiological comfort properties of fabrics and garments. Over the years, Hohenstein Institute, Germany played a crucial role in shaping the clothing physiology and skin sensory assessment of textile products. The Hohenstein skin model is internationally recognised as the primary tool for the measurement of the thermal and vapour resistance of textile materials, both of which are fundamental to thermo-physiological comfort. In order to determine the thermo-physiological quality of textile materials, the Hohenstein skin model simulates the way the skin emits heat and moisture. The measurements supply precise data on thermal insulation and moisture transport resistance, perspiration transport, sweat buffering, drying time, etc.

Using a porous sintered metal plate as a measuring surface, water vapour and fluid water are released in a controlled manner in a climatic chamber, thus simulating perspiration of human skin and different wear situations with different levels of sweat production. Moisture sensors between the measuring surface and the textile to be tested measure the buffer effect of the textile and how much water vapour can be transported from the body within a specific time. This measuring technique supplies more accurate and more detailed results. While the manual evaluation of the measuring data from a series of wear tests could previously take up to 3 months, the modern computer based system can complete this task in a matter of few hours. Measurements using the Hohenstein skin model now form standard tests in the field of clothing physiology worldwide. In Germany, Standard DIN 54101 has defined the measuring method using the Hohenstein skin model since 1991. This was replaced in 1993 by the international standards EN 31092 and ISO 11092 (Hohenstein Institute; Pavlidou and Paul, 2014).

#### 15.5.2 Permetest instrument

Permetest is another fast response measuring instrument (skin model) for the nondestructive determination of water vapour and thermal resistance or permeability of textile fabrics developed by Sensora Instruments, Czech Republic. In this instrument, the full response while measuring the water vapour permeability (resistance) of synthetic fabrics is achieved within 2-3 min, and for dry thermal resistance, the measurement is completed even within 1 min (for the simulated human skin temperature of 35 °C).

It is also possible to measure small size samples, and it is very easy to operate, which allows it to be operated not only in laboratory but also factory conditions. The high sensitivity given by a new concept of measurement makes it possible to distinguish even very small changes of water amount absorbed in the fabric during unsteady state of diffusion and records the heat of absorption and the effects of the fabric's composition and structure. The results are presented in digital form both on the instrument display and on the screen of any modern computer. The instrument provides all kinds of measurements very similar to the ISO Standard 11092 and the results are evaluated by the identical procedure as required in ISO 11092 (Hes, 2008b).

#### 15.5.3 Alambeta instrument

Alambeta, also from Sensora Instruments, can be used for testing the thermal comfort properties of denim and other fabrics. It measures all the thermal parameters of textiles such as thermal resistance, thermal conductivity and thermal absorptivity. The principle of Alambeta depends in the application of an ultra thin heat flow sensor, which is attached to a metal block with constant temperature that differs from the sample temperature. When the measurement starts, the measuring head containing the heat flow sensor drops down and touches the sample, which is located on the instrument base under the measuring head. In this moment, the surface temperature of the sample suddenly changes and the instrument computer registers the heat flow course. Simultaneously, a photoelectric sensor measures the sample thickness. All the data are then processed in the computer according to an original program, which involves a mathematical model characterising the transient temperature field in a thin slab subjected to different boundary conditions.

To simulate the real conditions of warm-cool feeling evaluation, the instrument measuring head is heated to 32 °C, which correspond to the average human skin temperature, while the fabric is kept at room temperature, 22 °C. Similarly, the time constant of the heat flow sensor, which measures directly the heat flow between the automatically moved measuring head and the fabrics, exhibits a similar value (0.07 s) as human skin. Thus, the full signal response is achieved within 0.2 s. The validity of thermal absorptivity as a new warm-cool feeling parameter of fabrics was confirmed by several tests where the results of relative subjective feeling of 100 persons were compared with the values of thermal absorptivity found by means of the Alambeta instrument (Hes et al., 2001).

#### 15.5.4 Thermally segmented manikin

The thermal insulation of readymade garments, including jeans, can be measured with the help of a thermally segmented testing manikin named Charlie, developed at the Hohenstein Institute. Using what are known as human thermoregulation models, the heat generated by adults and children is set. The segmented manikins are made of copper or synthetic materials and have been fitted with a computer controlled heating system that allows the heat generation for different parts of the body to be regulated individually and independently of one another. The more heat emitted from the arms or legs, for example, the worse the thermal insulation of the garment is for those areas of the body. The movement of air very significantly influences these values when the body is in motion. Therefore the latest version of the segmented manikin, Charlie 4, has been set up so it is able to move during testing, as if it is out for a brisk walk.

The assessments made using the thermally segmented testing manikins are an important complement to those made using the Hohenstein skin model, because the influence of the way the item or garment is made (fit, elasticised cuffs, turtlenecks, etc.) can be taken into consideration. The measurements are carried out using the thermal manikin according to EN ISO 15831. During testing, it is dressed with a complete clothing system. To measure the thermal insulation of this system, the manikin is placed in a climatic chamber either in a standing position and/or is set to

move. The temperatures can be set between -20 and +40 °C, humidity is freely selectable and possible wind speeds are between 0.3 and 10 m/s (Pavlidou and Paul, 2014; Hohenstein Institute).

#### 15.5.5 Skin sensorial properties

In addition to thermo-physiological wear comfort (heat and moisture management), skin sensory wear comfort is a key determinant of comprehensive wear comfort for denim or any textile that is worn in contact with the skin. The skin sensorial properties are quantified where the number of contact points between textile and skin shows whether a textile feels clammy or sticky on the skin. With the values describing thermo-physiological and skin sensorial properties of a textile, it is possible to calculate a Wear Comfort Vote. The following five different measurements quantify various textile characteristics that influence skin sensory wear comfort:

- The wet cling index indicates how likely a textile is to adhere to perspiration moistened skin.
- The sorption index uses time and contact angles to measure how quickly a water droplet is absorbed by the textile.
- · The surface index expresses the hairiness or roughness/smoothness of a textile.
- The number of contact points between the textile and skin states how fast a textile will be sensed as clammy or damp.
- The stiffness of a textile is an indicator how good a textile will adapt to body shape.

According to the intended use of the textile, the values and their weight is adjusted and the formulas are different for sports clothing and casual wear like denim. In general, the skin sensorial comfort is negatively affected by hydrophobic and smooth surfaces that easily cling to sweat wetted skin, or which tend to make textiles stiffer, and the use of spun yarns and hydrophilic treatments improve skin sensorial wear comfort (Hohenstein Institute; Pavlidou and Paul, 2014).

## 15.6 Future trends

In future, thermo-physiological and skin sensorial comfort properties will be one basic demand of clothing users. It depends mainly upon the heat and moisture balance between the human body and the environment. Fabric structure and types of fibres are the main contributors in thermo-physiological comfort. There are many possible ways to produce denim fabrics and garments with better thermo-physiological comfort. The most established way is the production of denim by varying fibre contents.

A number of studies have been conducted to investigate the impact of fibre blending and in future, apart from blending, several other parameters will be studied to improve the comfort aspects of denim and other garments. More studies are still needed on the combination of different fibres, selection of suitable fabric formation technique, application of different textile auxiliaries and even new washing techniques with reduced quantity of water. In such future studies, the use of new generation functional fibres as well as new textile auxiliaries containing novel nanoparticles, may play an important role. Textile engineers, fashion designers, fashion industry leaders and many more people will have to strive together to fulfill the demand for a denim that is really comfortable under diverse conditions and climates.

Considering the wide acceptance of denim garments the world over, it is very clear that all cotton traditional denim is here to stay, but in future, apart from this traditional denim, more and more functional denim garments will be made to provide thermal, psychological, social, active and sensorial comfort to users in different conditions and climates. As the feel of denim is related to its hand and moisture transport, the selection of raw materials in its manufacture will become increasingly important. The functionalities of such newly developed functional denim (moisture transport, wicking, water uptake and drying time) should certainly be of a high standard. It should provide higher thermo-physiological comfort under diverse conditions and should also be versatile enough for making customised garments.

# 15.7 Conclusion

Cotton fibre is used to make conventional or traditional denim, which is much prevalent and is utilised to fabricate dress for individuals of every age and socioeconomic class. This denim is profoundly spongy because of open-end yarn made of 100% cotton. Sponginess of customary denim is greatly requested, under typical dry atmosphere. If there should arise an occurrence of sticky atmosphere, cotton denim assimilates a great deal of dampness and gets to be wet and make discomfort for the wearers.

In this context, the development of functional denim fabrics, made with distinctive fibres, transforming its porosity and applying different textile auxiliaries is discussed. Especially, functional denim fabrics made by using Spun PP and AT PP give the best dampness administration and do not lose thermal resistance attributes under wet conditions. Additionally, they are lighter in weight and give a soft feel, dry rapidly and give a dry and warm feeling to wearers under highly wet conditions. Correlation of traditional denim and functional denim demonstrates that functional denim is an answer to maintaining a strategic distance from hypothermia under wet conditions.

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**Part Three** 

# Novel applications and environmental aspects

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# Novel varieties of denim fabrics

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## 16.1 Introduction

It is really commendable that denim has survived through all these years since its creation. Although conventional denim is still in use, many novel variants have been developed, driven by fashion, comfort and ease in production. For quick manufacturing and complying with orders in a short time, generic denims were developed. Pseudo denims developed on similar lines and are also helpful for quick delivery of products. Reverse denim is another quality of denim for fashionable wear. The actual practice of making these may vary from the theory explained. The weight of classic 3/1 twill woven generic denim has come down from 14 oz/yard<sup>2</sup> to around 8–11 oz/ yard<sup>2</sup>.

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Among blends, stretch denims have been found to be very useful from the wearer's point of view. These denims containing a small percentage of lycra contribute substantially to the wearer's comfort and hence have become quite popular. Apart from cotton, wool and silk are now used for making novel varieties of denim. The weft is now getting replaced with polyester filament yarn or spun yarn to make some variants. The polyester gives strength to fabric even at lower cotton content and also brings down the average weight of fabric. This has widened the application of denim fabric to luggage, hand bags, etc. Interestingly, Tencel denims now make a very fashionable segment of jeans for both men's and women's wear. This relatively new regenerated cellulosic fibre, when blended with cotton, enhances the fabric properties significantly. A few other new biodegradable fibres like polylactic acid (PLA), soybean protein (SPF), bamboo, etc. in blends with cotton also find use in denim. In apparels, water repellent and antibacterial denims are among the new additions in terms of finish applications. With all these options available, the domain of denim has become enriched due to numerous variants serving fashion and functional requirements.

## 16.2 Pseudo denim and generic denim

Fashion as well as business needs have driven many conventional apparel manufacturing techniques towards modified process routes. Traditionally, as we know, denim is a warp faced cotton fabric, made from indigo dyed warp and undyed weft yarns. Since it is a 3/1 twill weave with the warp set closer together than the filling, the former predominates on the surface of the fabric. Although blue denim fabric has been a consumer favourite for many years, the product also comes in different shades and tones. With the advent of garment dyeing and innovative wash effects, denim fabrics have become a popular substrate with processors. As per the conventional method of manufacturing, the colour of the denim fabric must be selected prior to weaving so that the dyeing can be done during the slashing operation. Denim slashing ranges are complex and expensive. Shifting frequently from one dye to another for small yardages is also uneconomical. Moreover, it is preferred to have minimum inventories, with the supplier capable of resupplying needed products in the shortest possible time (Reinhardt and Blanchard, 1988). All these considerations are suggestive of a place for generic denim in the supply chain. Such a product will permit rapid conversion to a wide range of colours adhering to the concepts of just-in-time and inventory control.

To have such a generic denim, a difference in dye receptivity between the warp and the filling yarns of the fabric is required. One way of achieving it is to use one fibre in warp yarns and another type of fibre with different dye receptivity in the fill. However, in the case of all-cotton denim fabrics, a suitable chemical process has to be done for accomplishing simulated yarn dyed denim. There are two reported ways for doing it. One method is based on a fabric treatment involving a low wet pick up procedure, leading to a material in which only the face of the fabric has a yarn dyed appearance after dyeing. This type of denim is called *pseudo denim*. The other method is based on warp yarn treatment employing a unique sizing process, producing a *true generic denim* after colouration, subsequent to weaving (Paul, 1997b). In this case, the warp yarns can be selectively dyed via fabric dyeing.

#### 16.2.1 Pseudo denim

The production of pseudo denim is based on the transfer of a chemical finish to the raised ridges of a natural denim fabric. The chemical finish imparts a cationic character to the raised ridges, which permits selective dyeability to these areas of the fabric. The fabric used for the application should be through with all preparatory wet processes, i.e. it should be properly desized, scoured, bleached and mercerised. The transfer technique used for the production of pseudo denims is a simple loop pad process. In this process, the fabric loop, which is a cotton knit, is padded with the finish solution, squeezed at high pressure (601b) to control solution content, and then squeezed at lower pressure (20–301b) against the face of the denim fabric being treated (Paul, 1997b; Anon., 1990). The specific formulation consists of a cross-linking agent like dimethylol dihydroxyethylene urea (DMDHEU), choline chloride or magnesium chloride hexahydrate, and a wetting agent.

The second pressure is adjusted to give a desired wet pick up (8-17%). The denim fabric is then dried, cured and washed. In certain instances, a delayed cure is performed. In this case, trials have been effective with the fabric padded, dried, fabricated

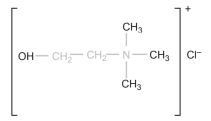
into trouser cuffs, pressed and then cured. The fabrics are dried for  $7 \min at 60 \,^{\circ}C$  and cured for  $4 \min at 160 \,^{\circ}C$  for flat fabrics or  $12 \min at 160 \,^{\circ}C$  for cuffs. For a higher level of durable press (DP) performance, the denim fabric is first conventionally padded with 6% DMDHEU, 2.5% magnesium chloride hexahydrate and 0.1% wetting agent and then dried at 60  $^{\circ}C$  for  $7 \min$ . A loop treatment is then performed as stated earlier, except the solution for loop padding contains only 16% choline chloride and 0.2% wetting agent (Paul, 1997b).

Systems based on a cross-linking agent and a reactive additive, as mentioned above, can be used to achieve differential dyeability. If the fabric has a grafted quaternary or amine group, dyeing is performed under acidic conditions with a reactive or acid dye. This kind of chemical treatment, known as cationisation, has been studied extensively in the past and discussed in the literature (Anon., 1988; Chattopadhyay, 2001).

#### 16.2.1.1 Choline chloride as cationising agent

Cellulosic fibres, when they come in contact with water, produce a slightly negative charge due to ionisation of hydroxyl groups. As most of the dye classes suitable for cotton are anionic in solution, there is repulsion between fibre and dyestuff leading to limited bath exhaustion. Cationisation of cotton is one way of overcoming the problem by which the anionic dyes will get easily exhausted onto the fibres. In the particular case of denim, this concept is of significance to have differential dye depth between warp and fill. A novel concept of cationising cotton, using choline chloride as a reactive additive and different cross-linking agents, was evolved by Harper (Anon., 1988; Harper and Stone, 1986). Choline chloride contains both a quaternary group and an alcohol moiety, as shown in Figure 16.1 (Anon., 1988). The basic purpose of such a treatment was to produce cationic fabric with easy care performance and enhanced dyeability. The approach provided a method of producing postdyeable garments and fabrics and allowed dyeing subsequent to cross-linking. The treated fabric is reported to be dyed substantially with reactive dyes from an acidic bath.

Many other cationising agents have been worked on by scientists for introducing cationic sites on cellulose. Compounds containing epoxy radicals are one such category of compounds. Among them, glycidyl trimethyl ammonium chloride, commonly



**Figure 16.1** Structure of choline chloride. Anon. (1988).

$$CI - CH_2 - CH - CH_2 - N^+ - CH_3$$
  
 $| + + - CH_3 - CH_3 - CH_3 - CH_3 - CH_3 - CH_3$ 

**Figure 16.2** Precursor of glytac. Chattopadhyay (2001).

known as glytac precursor, shown in Figure 16.2, is widely studied and proved to be effective in action (Chattopadhyay, 2001). However, it suffers from certain drawbacks like unpleasant odour, low substantivity and poor thermal stability. Other types of cationising agents include polyepichlorohydrin-type polymers, N,N'-dimethyl azetidinium chloride, 2,4-dichloro-6-(2-pyridinoethylamino)-s-triazine (DCPEAT), polyepichlorohydrin dimethylamine, etc. Choline chloride is considered to be the best among these.

#### 16.2.1.2 DMDHEU as cross-linker

DMDHEU is one of the most efficient cross-linkers applied on cotton for a wrinkle free effect. It has four hydroxy groups, which are capable of reacting with cellulose, though the *N*-methylol groups are more reactive than the other two hydroxy groups. When glyoxal (CHO–CHO) is reacted with urea under neutral to slightly alkaline conditions for 8–16 h at room temperature, dihydroxyethylene urea crystallises from the solution. This compound may be dimethylolated with formaldehyde (mole ratio 1:2) at pH 7–8 at room temperature to form DMDHEU, as shown in Figure 16.3 (Shenai and Saraf, 1987).

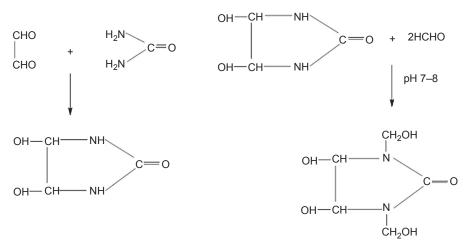
The principal reaction of DMDHEU products is the cross-linking of adjacent cellulose molecules (Schindler and Hauser, 2004). The action is catalysed by a suitable acid liberating agent, the most preferred being MgCl<sub>2</sub>·6H<sub>2</sub>O.

#### 16.2.1.3 Fabric treatments

As stated earlier, the prescribed solution is applied to the face of the denim fabric with a low wet pick up. After the necessary drying and curing, dyeing is preferably done with reactive colours under suitable conditions. As a result, the pseudo denim fabric takes on a yarn dyed appearance. For large scale applications, the pad transfer technique can be used. Likewise, the application is also possible via a printing operation. In fact, the choline chloride system has been successfully applied by screen printing (Paul, 1997b).

#### 16.2.2 Generic denim

A true generic denim should be selectively dyed in the warp yarns while the fill yarns are undyed. The production of such denims is based on the concept of



**Figure 16.3** Synthesis of dimethylol dihydroxyethylene urea. Shenai and Saraf (1987).

conferring a potential cationic character to the warp yarn via sizing and splashing, fixing the chemical subsequent to weaving and removal of most of the size during subsequent preparation. Normal sizing agents such as starch or polyvinyl alcohol react with cross-linking agents used in the reactive additive system. Therefore, a method is needed in which the bulk of the size is removed while the reactive additive system is retained on the warp yarn. Polyacrylate sizes that are inert to reaction with the cross-linker are the suitable option here (Dürrbeck, 1984). The alkali soluble polyacrylate size gives necessary protection to the yarn in weaving and can be removed later without affecting the other required ingredients in the formulation.

One effective way of producing the denim is started with preparation of a warp section beam. The beams are first sized with a formulation containing 8% polyacrylate sizing agent and 0.1% wetting agent. The yarns are sized on a conventional slasher and dried on steam cans at approximately 120 °C. The section beams are resized with a resizing formulation containing cross-linking agent, magnesium chloride hexahydrate, polyvinyl alcohol and choline chloride. The sized section beams are then combined to a loom beam for use as the warp of a fabric. This warp, together with untreated cotton yarns as filling, is used to weave the desired fabric. The fabric so woven with finish cured on it may be subjected to the desired preparatory wet processes. The alkaline wet pretreatment will also help in removal of the size component. This fabric so prepared can then be dyed as and when required. The general process sequence is given in Figure 16.4 (Anon., 1990).

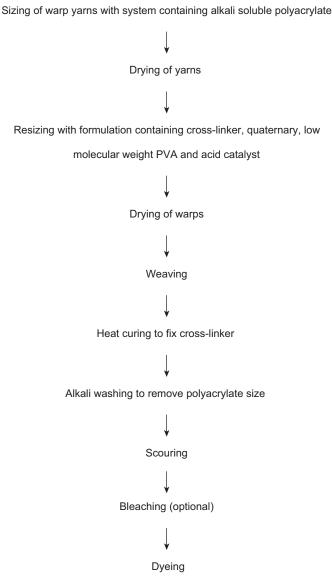


Figure 16.4 Steps in preparation of yarn dyeable generic fabrics.

## 16.3 Reverse denim

A reverse denim is one in which the warp yarns on the face of the fabric are not coloured, whereas the background fill yarns are coloured. This effect is achieved by blocking dyeability of the warp yarns unaffecting the fills. For this, the technique to

be followed is application of a cross-linking finish to the raised warp yarns in the face of the fabric. Subsequent to the cross-linking treatment, the fabric is piece dyed to achieve the reverse denim appearance. Since dyeing is delayed until finishing, the fabric is a generic one and dyeing can be performed after the garment fabrication. The system is also amenable to produce fabrics with two colour effects, if dye is included with the cross-linking finish treatment (Paul, 1997a; Harper and Lambert, 1993).

The advent of garment dyeing has in fact created opportunities to produce generic denims. The creation of the above finish effect, leading to a reverse denim on dyeing, has thus a potential role to play. Interestingly, the face of a normal ring dyed indigo denim after extended wear, usage and laundering takes on the appearance of a reverse denim, in that the raised portions of the warp yarns are relatively colour free while the recessed part of these yarns remains dyed. Thus in the process a kind of reverse denim look is achieved. However reverse denim and worn out denim have subtle differences:

- In reverse denim, the raised warp yarns are selectively treated with cross-linking agents, and much of the face of the fabric is cross-linked thus giving a crisp look to the fabric with a smooth dry performance. However, worn out denim does not have this effect at all.
- Because the cross-linking treatment does not reach either the recessed filling yarns or the yarns on the back of the fabric, both of these areas become coloured on piece dyeing of the fabric unlike a worn out one.

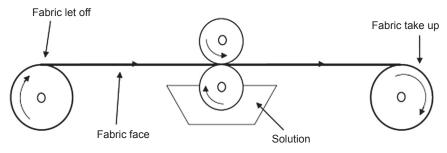
#### 16.3.1 Manufacturing process

The procedures utilised to produce mock or generic denims can also be employed for production of reverse denim. The major difference is that the chemical formulations are to be modified to lead to dye resistance rather than dye enhancement. Here, a cross-linking agent along with catalyst and auxiliaries may be applied first by a pad-dry-cure method. Then they may be dyed with reactive dyes by conventional dyeing procedures with alkaline fixation. As regards the chemical finish, the recipe may have DMDHEU, MgCl<sub>2</sub>·6H<sub>2</sub>O, glycolic acid and wetting agent. The application can be done by the loop transfer technique discussed in the pseudo denim section. Reverse denims made by such techniques have been found to give good durable press (DP) rating as well as the desired coloured effect on subsequent dyeing (Harper and Lambert, 1993).

A second approach for the production of reverse denims is a kiss-roll padding technique, as shown in Figure 16.5. In this operation, the resin finishing is carried to the face of the fabric with the add-on adjusted as per requirement. With the kiss-roll system, a liquid application as low as 10-20% can lead to an even distribution on substrate (Shenai and Saraf, 1987). After padding the fabric by this technique, it is dried and cured. On dyeing the cured fabric, the back side of this fabric is completely dyed, in contrast to regular denims.

#### 16.3.2 Printing techniques

A third approach for producing reverse denims is by use of a printing technique for application of the resist-resin application using a clear screen with an acid dye as marker.



**Figure 16.5** Kiss-roll padding technique. Harper and Lambert (1993).

Printing using a Zimmer MDF print machine has been found suitable for producing reverse denims. Experimental work with varying recipes has been attempted in the past. A typical print paste formulation includes cross-linker, acid catalyst, thickener, wetting agent and a small amount of an acid dye. The catalyst used is based on 2-hydroxycarboxylic acid. The catalyst is for grafting on cellulose to help improve the resist characteristics of the printed areas (Harper and Lambert, 1988). The fabric so printed is then dried and cured. The fabrics can then be dyed with the desired colour to get a reverse denim effect.

## 16.3.2.1 Print applications for the two colour effect

A two colour effect is possible by incorporating a reactive dye in the printing formulation containing cross-linker and acid catalyst. Once the finish is fixed, the resulting fabric or garment segment can be dyed with a second colour under normal dyeing conditions. The areas of the fabric treated with the resin system and dye are resistant to the second dyeing, thus leading to a two colour effect (Hebish et al., 1986).

## 16.4 Stretch denims

Consumers always demand increased comfort. Stretch denims are one such product used for function and at the same time fashion as well. As an additional property of denim, elasticity is used to achieve outstanding stretching performance for ultimate fit. It has already made its presence in sports and leisure garments and is also exploring new areas in different apparel segments. For a long time the elastic denims have enjoyed an increasing popularity because they possess a high wear comfort, crease resistance, durability, require minimum ironing and have a pleasant drape and hand. The stretch property is induced in the denim due to core spun wefts which contain elastane filaments.

## 16.4.1 Elastane filaments

The elastane filaments are known by the generic name 'spandex'. This filament was first discovered in 1937 by the Bayer Farben company in Germany, and was

commercialised by the US firm DuPont in 1960. DuPont marketed it in under the brand name of Lycra. The Lycra brand name is now owned by Invista USA. Thereafter many elastane filaments became available under different trade names like Dorlastan, Roica by Asahi Kasei Spandex, Acelan by Hyosung Corporation, Texlon by Kolon Industries and Golspan by Radici Spandex (Kamordina and Ushakova, 1995).

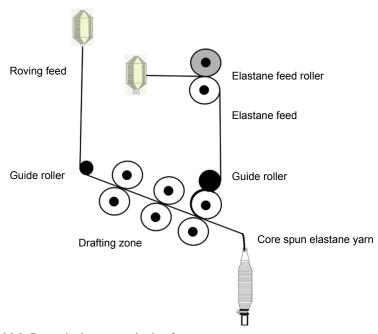
Elastane is a synthetic linear macromolecule with a long chain containing at least 85% segmented polyurethane bonds (Senthilkumar et al., 2011). Polyurethanes range in properties from types having high hardness and high tenacity to types showing soft, elastic properties and low tenacity. Segmented polyurethane lies chemically between these two extreme types. Segmented polyurethane has alternating units of different composition, which is a block copolymer. These blocks are, according to their structure, described as 'hard' polyurethane segments and 'soft' polyether or polyester segments. The soft segment is responsible for the rubber like high stretchability of elastane yarn. The 'hard', crystalline segments are so widely separated by the 'soft' segments that the polyurethane can be stretched several hundred percent (Fabricius et al., 1995).

This is the only synthetic fibre used in the filament form but not in the staple form. This filament is manufactured by various spinning techniques like wet spinning, reactive spinning and melt spinning. But 80% of this filament is produced by the dry spinning technique. Lee et al. (1998) studied the internal structure and orientation behaviour of two series of elastane fibres, which are made with different spinning systems. The structure characterisation was carried out by Fourier transform infrared spectroscopy, polarising light microscopy and the Instron Tensile Tester. They concluded that the dry spun elastane filaments exhibit better elastic recovery properties than the melt spun filaments. The spinning conditions, especially the take up speed, the spinning temperature and the false twist insertion, have a significant effect on the physical properties of elastane filament yarns (Fabricius et al., 1995).

Elastane yarns are never used alone in fabrics, but rather in combination with other yarns, either core spun or as covered elastic yarns. This coating is used to avoid the pretension of the elastomeric component, to limit the degree of stretch of the elastomeric component, to protect the elastomer from damage, to improve the feel or handle and to give a dyeable covering to the elastomer. Elastane combination yarns are used for the desired stretch effect, to improve the handle and aesthetics of the fabric and also to protect the elastane against the processing conditions (Bardhan and Sule, 2001). The fineness of the elastane fibre, the choice of the cover material and the nature of the covering process enable the properties of stretch goods to be tailored to meet their required end-use (Tse, 1991).

#### 16.4.2 Yarn manufacturing techniques

Core spinning is a process by which fibres are twisted around an existing yarn, either filament or staple spun yarn, to produce a sheath–core structure in which the already formed yarn is the core. Core spun yarns are a two component structure with core and sheath. Generally, continuous filament yarn is used as the core and the staple



**Figure 16.6** Core spinning system in ring frame. El-Ghezel et al. (2009).

fibres are used as the sheath covering. Core spun yarn is used to enhance functional properties of the fabrics such as strength, durability and stretch comfort (Tse, 1991). The production of core spun yarns can be done successfully by all types of spinning systems, but each spinning system has its own features. Conventional ring spinning, with an additional attachment (Figure 16.6) for the placement of elastane filament, is widely used for the production of this type of yarns, but the core positioning of the elastane filament in the centre is difficult and a major strip back problem may arise during subsequent processing (El-Ghezel et al., 2009). In Dref III, the core positioning can be set accurately and used to produce the industrial and conductive yarns. Research has progressed to produce core spun yarn in different spinning systems with additional attachments over the normal spinning machines. The physical and mechanical properties of core spun yarns produced by the ring spinning method are dependent on the various process variables like core-sheath ratio, pre-tension applied to the core material, spinning draft, number of roving feeds and twist. It has been found that increase of the elastane ratio will increase the tensile strength, extensibility and evenness of the core spun yarn (Rupp and Bohringer, 1999; Su and Young, 2004; Balasubramaniam and Bhatnagra, 1970). Apart from producing the core spun yarn from the ring spinning method, rotor and air jet spinning methods used to produce core spun yarns are mainly in the research stage (Lawrence, 2003) and Ortlek and Ulku, 2007).

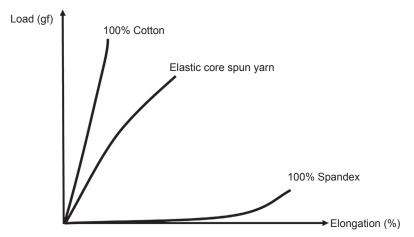


Figure 16.7 Load elongation curves of cotton, spandex and core spun yarn.

#### 16.4.3 Properties of core spun yarns

Development of core spun yarn with the ring spinning system unveils a path for new products including high performance textiles, sewing threads and in the garmenting areas due to its exceptional strength, outstanding abrasion resistance, consistent performance in sewing machines, elasticity for the stretch requirements, excellent resistance in perspiration, ideal wash and wear performance and permanent press. The load elongation curve (Figure 16.7) has been compared among 100% cotton yarn, 100% spandex and a core spun elastane yarn (El-Ghezel et al., 2009). The trend shows that the core spun yarn exhibits better stretchability and acceptable tensile performance. Hence these yarns are used for the production of stretch denims to induce a definite stretch in the denim.

#### 16.4.4 Stretch denim weaving

Denim is made from rugged tightly woven twill in which the weft passes under two or more warp threads. The characteristics of stretch denim are dependent on various factors including the type of twill weave. Twill weaves can be constructed in a variety of ways. The main feature of these weaves that distinguishes from other types is the presence of pronounced diagonal lines that run along the width of the fabric (Gorkarneshan, 2004). Using the elastic yarn, a defined elongation in the warp, the weft, or in both directions can be achieved with complete reliability (Widhaber and Nef, 1998). Elastane threads, core twisted with texturized filament yarns or staple fibre yarns, or covered with staple fibres, are used for the defined stretch, matched to the garment and the wearer. The major properties of the stretch denim depend upon the snap back (elastic recovery), dimensional stability and the preservation of stretch over the entire useful life of the garment.

Stretch denim is mostly produced by inserting core spun elastane yarns in the weft directions and cotton yarns in the warp direction. But warp elastic denim production is also feasible. To produce warp elastic denim fabrics, corresponding adaptations have to be made during production of the warp itself. The weaver's beam must be produced in a sectional warping machine, but precautions must be taken for a constant, uniform and low amount of tension along the warp sheet. The weaver's beam must be sized to block the stretchability of the warp sheet. This will help to achieve the desired weavability of the warp sheet. These modifications will help to weave the stretch denim, almost like a normal warp sheet. If elastic yarns are used in the weft, a suitable weft insertion system must be chosen, and various components of the machine designed in accordance with the yarn properties. Weft elastic yarns need a larger reed width. To achieve adequate elasticity of the fabric, the warp elasticity may, in extreme cases, be blocked. Elastic yarns can be woven on all types of weaving machines. All the machine types can be adapted to meet the special requirements for processing elastic yarns, e.g. by the use of appropriate weft feeders, weft brakes, projectiles, gripper clamps and roller surfaces. The free ends of elastic yarns always have a tendency to snap back, and therefore have to be gripped and held with high accuracy and the necessary clamping force. Besides the clamping force, special attention also has to be paid to the clamping area. Weaving systems should have an electronically controlled warp left-off with warp tensioner and electronically controlled cloth take up. These enable the warp tension and weft density to be maintained with great precision. This results in a uniform, reproducible stretch over the entire warp length (Behera, 2008).

#### 16.4.5 Physical and mechanical properties

Garments made from stretch denim are mostly under strain due to the movement of body parts such as knees, elbows and the lower back (Voyce et al., 2008). Therefore, stretching is a very important aspect of human comfort. So the garments that are subjected to repeated stretching actions with the body movements must retain their original shape without much deformation. If the garments do not possess the shape retention ability with great stretchability, then the resulting property is called bagging. So this is an important property of stretch denim that leads to a lot of research. Apart from bagging properties, the other most common fabric properties that are also important include tensile, tear and fabric handle properties.

Zhang et al. (2000) theoretically investigated the stress distribution in isotropic as well as anisotropic fabrics and related the bagging force to internal stresses in the fabric section. They observed that the internal stresses were distributed non-uniformly between the warp and weft yarns for an anisotropic fabric.

Meriç and Gürarda (2002) studied the mechanical properties of fabrics containing elastane and concluded that high elastane content makes the yarn flexible; however, the yarn that will be used with elastane should allow the fabric to move freely and should not cause any deformation in the fabric. They also found that the elastane drafting ratio plays an important role in the tensile and tearing strengths of fabrics. The tensile and tearing properties of fabrics decrease with increasing rates of the elastane ratio within the fabric (Shawney and Ruppenicker, 1997; Jou et al., 1996; Ramasamy, 1998).

Ozdil (2008) studied the stretch and bagging properties of stretch denim with different elastane ratios. It was found that as the elastane content increases, the stretching and the maximum stretching percentages increase owing to the high elasticity of elastane, whereas the permanent stretching percentage decreases due to the rather high recovery properties of elastane. It was also noted that the bagging and permanent bagging values decrease, and the elastic recovery values increase along with an increase in elastane content in the fabric. Therefore, it can be stated that the disturbing appearance caused by bagging deformation decreases as the amount of elastane increases.

The tensile and tearing strength of denim fabrics decreases with the increase in elastane ratio. This observation is due to the fact that the breaking strength of the core spun yarns containing elastane is lower than the breaking strength of non-elastane yarns. Further, the bending rigidity values of denim fabrics show an increasing trend with the elastane ratio. This observation indicates that the higher amount of elastane in the fabric structure introduces a higher degree of stiffness, which will deteriorate the total handle value (THV) of the fabric.

Khedher et al. (2009) studied the effect of matter, types of launderings (stone wash, enzyme wash, mixed wash and rinse), special treatments applied during the manufacturing process of garment washing (brushing, sanding, resin treatment, bleach treatment, permanganate spray and softening) on the fabric mechanical properties: tear strength (TS) and breaking strength (BS). They observed that all these treatments, applied to obtain a more worn appearance and aged look for the garment, decreased the mechanical properties. Moreover, the resin treatment is the most aggressive for stretch denim garments in the set of the special treatments. In fact, whatever the following washing process is stone washing or mixed washing, the finishing resin treatment destroys the matter and reduces the mechanical resistance a lot. Thus, it is suggested that in the case of washed denim fabric, it is advisable to avoid the line of succession of treatments containing the resin treatment and mixed washing process.

El-Ghezel et al. (2009) studied the effect of the ratio of elastane as well as finishing process on the elasticity and dynamometric properties of fabrics in which weft yarns are cotton covered elastane core spun yarns with the same twist factor and varying elastane ratio. Their first observation was that an important relaxation in the weft direction occurs during the blaze and mercerising operations due to the width shrinkage, the rise of weight per area unit, noteworthy decrease of the washing shrinkage in the weft direction and a less considerable decrease of the washing shrinkage in the warp direction. Their other observation was that the heat setting process reduces the washing shrinkage and the stretch in the weft direction. In fact, because of heat, the elastane is fixed at a more relaxed stage. The third observation was that sanforising is accompanied by a considerable decrease of the washing shrinkage and an increase of the extensibility in the warp direction. This is due to the result of the relaxation in this direction. Concerning the dynamometric properties, heat setting considerably weakens fabric resistance in the weft direction, with this mechanical degradation being attributed to high temperature. Besides these, a decreasing trend of the elongation at break in the weft direction was observed while the elastane ratio increased. Higher draft of elastane causes more retraction forces, which ultimately lead to higher width shrinkage and more elongation at break in the weft direction.

## 16.5 Denim of other fibres and blends

#### 16.5.1 Tencel/cotton blend

Lyocell is a wonder fibre surpassing all other cellulosic fibres in terms of properties, aesthetics and nevertheless ecology in manufacturing. Among the various names with which lyocell is available, Tencel and its non-fibrillating variant Tencel A 100 are the most prominent and widely used. They have an extremely soft and silky feel with lustre. Tencel retains 85% of its dry strength when wet. It is the only man-made cellulosic fibre to be stronger than cotton when wet. Other attributes include being lighter, being finer, good breathability, dimensional stability and moisture retention. It has moderate resiliency, and does not crease as badly as cotton and rayon. Tencel A 100 exhibits high reactive dye yield, and hence reduces dyes and chemicals cost and also generates less effluent. At the end of useful life, the products are biodegradable as well (Chavan and Patra, 2004; Patra, 2010).

Tencel denim, with at least 40% lyocell made by Lenzing AG, Austria has virtually reshaped the concept of denim worldwide. Lyocell is almost twice as strong as cotton. The new regenerated fibre provides all the durability we look for in denim garments, yet is neither harsh to the body nor tough looking. Also due to high strength, Tencel jeans make good sportswear. They can be used as active sportswear even for mountain climbing and horse riding with less fear of damage to the garment. Quite importantly, Tencel denim is more comfortable than cotton denim. Due to its high breathability, it has a good cooling effect. It can absorb more moisture than cotton and hence while sweating in a humid environment, one feels drier. Tencel denim is lighter and easier to pack than heavy cotton jeans.

It is a good solution for casual and children's wear. Tencel denim has a very good soft feel and can be made into various styles with different garment washing effects like enzyme washing, bleaching and over-dyeing. These denims are available in different qualities like 100% Tencel denim, Tencel/cotton blended denim, Tencel/viscose blended denim and Tencel/stretch blended denim. The 100% Tencel denim is luxurious and self-indulging. With excellent touch and drape, it flows nicely with body movements and can be rated as an upscale denim. Tencel/cotton denim creates a look with more body and excellent texture. It is a good choice for men's wear. Tencel/viscose denim is often conceived to be a compromise between 100% Tencel and Tencel/cotton. It makes a very good denim, softly textured with a great feel. Moreover, Tencel/viscose denim is preferred as it is less expensive than 100% Tencel (Got to be Tencel, 2013).

In the context of lyocell blended denims, AG Jeans has produced a new denim wash called Grant that contains 55% cotton/43% lyocell/2% PU. Many interesting denims containing Tencel are in fashion for women's wear. Shiny and skinny Tencel jeans are in demand. Low rise mini pleat wide leg trouser style Tencel jeans for women are in vogue these days (Anon., 2013).

#### 16.5.2 Wool denim

Denim made with cotton is widely used, but this denim lacks some of the important characteristics like protection against cold and comfort. To overcome these properties, denim manufacturers have tried to add new denim products. The new denim fabrics are made with different type of blends. Wool denim is usually produced with 85–90% cotton and 10–15% wool. These cotton and wool blend denims generally meet the denim property requirement. The biggest challenge of producing wool denim is the shrinkage of wool. For this the scales of the wool are removed with the help of acids or the wool surface is coated for wool processing. The grey denim is finally processed chemically to reduce the shrinkage during washing and have a desired aesthetic look. This denim is generally softer and warmer compared to traditional denim (Cruthers, 2014).

## 16.5.3 Silk denim

Silk fabrics are very popular due to their properties like softness, suppleness and strength. Silk is preferred for its lightness with warmth, sheerness with strength and delicacy with resiliency. Hence research has been pursued to produce silk denim with different combinations of silk to have light weight denims, aided by elasticity and resilience and excellent drapability. Silk denim garments are soft to touch, light in weight, comfortable to wear in all the seasons, blended with the luxury and smooth feel. The eri silk has thermal properties nearly equivalent to wool, which makes 100% eri silk denim garments used for winter. Silk and cotton, as well as silk and linen union denim fabrics, are more cost effective without losing their comfort and silky appearance (Kotrannavar et al., 2014).

## 16.5.4 Polyester blend denim

This type of denim is made of polyester blends that wash and dry quickly, and is lightweight and dressier. They usually appeal to a slightly older market, but also find favour for pantsuits when the look is meant to be dressy but casual. Use of polyester blended denim has in fact steadily increased. First, the production cost per metre is cheaper, which makes selling of denim fabric easier. Second, the loom efficiency is better, with polyester replacing 100% cotton weft.

## 16.5.5 Linen denim

Linen is considered to be an elegant, durable and refined luxury fabric. In fact, the fashion led movement towards an unstructured casual look brought it back into the limelight. Being cellulosic in nature, its chemical processing is similar to that of cotton. Medium weight linen denim of approximately 6 oz/yard<sup>2</sup> quality is considered perfect for fuller skirts, dresses, slacks, jackets, etc. A 70/30 cotton/linen blend is often preferred, which is cost effective with good hand and drape. Similarly, denim today is made using other bast fibres like hemp, jute, etc. and their blends.

## 16.5.6 Ramie/cotton denim

These blends are found in a variety of combinations with a wide price range. Ramie is a plant fibre usually added because it reduces wrinkling and gives a silky lustre to the fabric. In fact ramie is not as strong as cotton, but stands up as a good denim material in a blend.

## 16.6 Biodegradable denims and their properties

The fast changing lifestyles of humans accelerate the demand for a new product line. This product line now requires new functional fibres that must comply with the ecological norms. The popular synthetic fibres like polypropylene, acrylic, polyester, etc. are hazardous to the environment and have to be replaced at some stage by the new biodegradable and environmental friendly fibres.

A biodegradable material can break into simpler substances naturally and it is nontoxic and decomposable in a relatively short period on a human time scale. The biodegradability of fibres also depends on their chemical structure, molecular weight and super molecular structure. The biodegradable polymers can be classified into three main groups: (1) natural polysaccharides and biopolymers (cellulose, alginates, wool, silk, chitin, soybean protein); (2) synthetic polymers, especially aliphatic polyesters (polylactic acid; poly ( $\varepsilon$ -caprolactone)); and (3) polyesters produced by microorganisms (Blackburn, 2005). A fair amount of research has been carried out to use various biodegradable fibres to produce novel denim varieties; the possibilities are for bamboo, polylactic acid and soy protein fibres.

#### 16.6.1 Bamboo fibre

Bamboo is considered to be the ultimate green material (Netravali, 2005), as there is a continuous supply of bamboo and hence it meets the definition of renewable resource. The bamboo fibres possess high tenacity, whiteness index at par with bleached viscose, good antibacterial properties, high moisture regain value, high fabric handle and high level of breathability (Das, 2010).

#### 16.6.2 Polylactic acid fibres

Polylactic acid is a natural, biodegradable organic substance present in the bodies of animals, plants and microbes. Polylactic acid as such cannot be found in nature but needs to be industrially prepared with lactic acid polymerisation. The lactic acid used for the synthesis of polylactic acid is derived from genetically altered corn grains (Rijavec and Bukošek, 2009). These fibres are manufactured with the melt spinning technique with a wide range of properties. PLA is different from PES or PA6 fibre although they have a similar line of production (Rekha and Purnima, 2004). The fundamental polymer chemistry of PLA allows control of certain fibre properties and makes the fibre suitable for a wide range of technical textile applications and functional apparel. The PLA fibres have excellent mechanical properties, low flammability, high UV protection index, low refraction index and low moisture regain value (Lou et al., 2008).

## 16.6.3 Soybean fibres

Soy protein fibre is the only plant protein fibre (Rijavec and Bukošek, 2009). It is a liquefied soy protein that is extruded from the soybean after the extraction of oil, and processed mechanically to produce fibres by using new bioengineering technology. Fibres are produced by wet spinning, stabilised by acetylating and finally cut into short staples after curling and thermo-forming. A soybean protein fibre has not only the superiority of natural fibres but also possesses the physical properties like synthetic fibres. They are also cheaper as well as possessing a high fabric handle, moderate moisture regain like cotton but better moisture transmission properties, moderate tensile strength and excellent anti-crease, easy wash and fast dry properties (Yi-you, 2004 and Brooks, 2005). The comparative assessment of the above fibres as against some conventional fibres is shown in Table 16.1 (Dubrovski, 2010).

## 16.6.4 Mechanical properties

The mechanical behaviour of textile material is described with the change of shape by the material resistance on the activity of external forces. The response of the textile material depends on the material properties, loading condition and its tension. With regard to the direction of the applied force, deformations at stretch and compression are known. To the mechanical properties of fabrics uniaxial or biaxial tensile properties, compression, shearing properties, bending rigidity, bursting and tear resistance can be listed. The fabric mechanical properties are affected by several factors. But these factors can be classified as per the following points:

• Fibre parameters like fibre physical properties (length, fineness, etc.), molecular properties and their mechanical properties.

| Properties                   | Bamboo   | Polylactic<br>acid (PLA) | Soybean<br>protein fibre<br>(SPF) | Silk                                  | Wool    |
|------------------------------|----------|--------------------------|-----------------------------------|---------------------------------------|---------|
| Length (mm)                  | 38–76    |                          | 38–76                             | $3.5 \times 10^{6} - 9 \times 10^{6}$ | 50–200  |
| Fineness (dtex)              | 1.3–5.6  |                          | 0.9–3                             | 1-3.5                                 | 4–20    |
| Tenacity<br>(cN/dtex)        | 2.33     | 3.7–5.5                  | 3.8-4.0                           | 2.4–5.1                               | 1.1–1.4 |
| Breaking<br>extension (%)    | 23.8     | 20–35                    | 18–21                             | 10–25                                 | 20–40   |
| Moisture regain<br>(%)       | 13.3     | 0.4–0.6                  | 8.6                               | 11.0                                  | 14.5    |
| Density (g/cm <sup>3</sup> ) | 0.8–1.32 | 1.25–1.27                | 1.29–1.31                         | 1.34–1.38                             | 1.32    |

#### Table 16.1 Physical and mechanical properties of some fibres

- Yarn parameters like linear density, twist per unit length.
- · Fabric parameters like fabric areal density, thickness, type of weave.
- Process parameters like type of spinning machines used, weaving conditions (loom type, loom settings, weaving preparation condition).

#### 16.6.5 Tensile properties

Tensile properties are the most important aspect of any material to assess its performance. Strength and elongation are the most important properties of fabrics governing the fabric performance in use. Their measurement involves many difficulties due to a great degree of bulkiness in the fabric structure and strain variation during deformation. The woven fabric consists of a large amount of constituent fibres and yarns, and hence any slight deformation of the fabric will subsequently give rise to a chain of complex movements of the latter. This is very complicated, since both fibres and yarns behave in a nonlinear way during deformation (Hu, 2004).

The stress-strain curve of a woven fabric has three regions, as shown in Figure 16.8. A higher initial module at a tensile test occurs, due to the resistance against friction and bending of fabrics. In the tested direction, in the direction of force, crimp yarns are straightened. When the yarns are straightened, the force in the fabric increases sharply and fibres and yarns begin to extend. The tensile properties of fabrics mostly depend on the tensile properties of yarns (Grosberg, 1969). A major difference between the shapes of the curves occurs in the first region of the curve, i.e. in the Hook's zone (zone I). This is influenced by a crimp of warp or weft yarns, when they begin to straighten. The elongation of the fabric is already increasing under a low force (still before the zone in which Young's modulus is calculated). Here, the crimp is interchanged between the warps and wefts. The crimp decreases in the direction of force applied; however, it increases in the perpendicular direction. Consequently, the tension of the threads of the system, which is perpendicular to the direction investigated, increases. When a tensile force acts on the threads of one system, the threads of

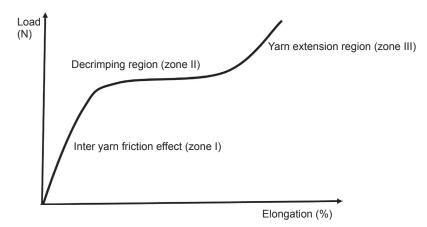


Figure 16.8 Stress–strain curve of a typical woven fabric.

both systems undergo extension. Due to the crimp interchange, the maximum possible elongation of perpendicular threads depends on the fabric geometry (Saville, 2002; Gabrijelčič et al., 2008; Realff et al., 1991). The elastic or Young's modulus provides resistance against the deformation of the fabric.

Zone II is the viscoelastic deformation region. In this zone, the material recovers to its initial length after a certain time of relaxation. The relationship between the stress and deformation is not linear. The limit between the elastic and plastic deformation is the yield point, on the stress–strain curve seen as a turn of curve. Zone III represents the permanent deformation region where the material does not recover after relaxation.

#### 16.6.6 Comparison of biodegradable denims

Dubrovski (2010) studied the mechanical properties of common fabrics including denim with cotton warp and biodegradable yarns (bamboo, PLA and SPF) as well as cotton in weft and compared the properties with the 100% cotton fabrics where all the fabrics have similar areal densities. The observations are listed in Table 16.2. The authors observed that the highest breaking force in the warp direction is exhibited in the fabrics with the highest tensile elongation: SPF, PLA and bamboo yarn, followed by the fabrics with cotton yarn in weft. The material used in weft has almost no influence on the breaking elongation in warp direction; it is influenced almost only by weave. In the weft direction, cotton fabrics have the highest tensile force, whereas lower tensile strength is observed in the fabrics with PLA, SPF and bamboo wefts. The materials also have the highest influence on the tensile elongation of fabrics in the weft direction. In general, it can be claimed that fabrics with PLA, SPF and bamboo yarn in weft have a lower tensile force in comparison with pure cotton fabrics but higher tensile elongation compared to pure cotton fabrics. The tensile elongation or extensibility of fabrics is an important property for feeling comfortable when wearing clothes.

## 16.7 Other types of denim

#### 16.7.1 Dry denim

Dry or raw denim, as against washed denim, is a denim fabric that is not washed after being dyed during its production. Conventional denim is washed after being crafted into an article of clothing, to make it softer and give the desired preshrink. In addition the non-dry denim is sometimes given a worn out look by artificial means. On the contrary, appeal of the dry denim lies in the fact that the fabric will fade in a manner similar to factory distressed denim on use. The fading is affected by the body of the person who wears it and also by the daily activities of the wearer. Predominantly found in premium denim lines, dry denim represents a small niche in the overall market. This type of denim is identified by its lack of wash or fade. So, it typically starts out as a dark blue denim which gradually fades with time and use.

|           |              |                                      | Wa                   | rp                | Weft                 |                      |                   |  |
|-----------|--------------|--------------------------------------|----------------------|-------------------|----------------------|----------------------|-------------------|--|
| Weave     | Weft content | Areal density<br>(g/m <sup>2</sup> ) | Breaking load<br>(N) | Elongation<br>(%) | Breaking load<br>(N) | Tenacity<br>(cN/tex) | Elongation<br>(%) |  |
| 1/3 Twill | Bamboo       | 168.21                               | 815.44               | 7.98              | 336.05               | 54.29                | 21.69             |  |
| 2/2 Twill | Bamboo       | 167.44                               | 812.6                | 7.83              | 350.98               | 59.69                | 21.99             |  |
| 1/3 Twill | PLA          | 169.09                               | 806.48               | 7.93              | 360.12               | 64.31                | 46.6              |  |
| 2/2 Twill | PLA          | 169.35                               | 845.43               | 8.08              | 352.82               | 61.68                | 48.75             |  |
| 1/3 Twill | SPF          | 159.32                               | 788.65               | 7.23              | 332.87               | 78.14                | 30.53             |  |
| 2/2 Twill | SPF          | 152.35                               | 817.92               | 6.98              | 340.38               | 78.79                | 33.19             |  |
| 1/3 Twill | Cotton       | 161.61                               | 730.2                | 7.93              | 433.9                | 81.56                | 15.62             |  |
| 2/2 Twill | Cotton       | 161.8                                | 771.94               | 7.58              | 451.16               | 84.2                 | 19.18             |  |

## Table 16.2 Fabric tensile properties with different weft types

#### 16.7.2 Selvedge denim

This variant of denim, also known as selvage denim, forms a clean natural edge that does not unravel. It is usually presented in the unwashed or raw state. Typically, the selvedge edges will be located along the outseam of the pants, making it visible when cuffs are worn. This type of denim is made on an old-style shuttle loom. The selvedge edge is usually stitched with coloured threads like green, brown, red and yellow, with red being the most common. Most selvedge jeans today are dyed with synthetic indigo.

#### 16.7.3 Organic denim

Organic cotton is an ecofriendly cotton variety that is cultivated without using synthetic agricultural chemicals like fertilisers and pesticides. Cotton farming is carried out in 2.5% of the cultivated land globally but requires 16% of the total consumed insecticides. This agrochemical is one of the major causes of pollution. Swezey et al. (2006) found that the quality of cotton (cotton fibre length, strength and micronaire) does not differ much between conventional and organic cotton. So for sustainable development, denim manufacturers are encouraged to use organic cotton rather than standard cotton with a premium price of the product.

#### 16.7.4 Natural dyed denim

Natural dyes are obtained from natural sources such as vegetable matter, minerals and insects. These dyes find use in the colouration of textiles, food, drugs, cosmetics, etc. (Gulrajani, 2001). Although the market for natural dyes is very small and is less than 1% of the world synthetic dyes consumption, they have a demand in the niche segment mostly due to their ecofriendly attribute. Use of natural dyes in denims is one such limited domain. Natural indigo, *Indigofera tinctoria*, is the only natural vat dye and gives a similar shade to that of synthetic indigo. However, the former needs to be applied at a higher concentration as it is weaker than the synthetic one (Paul and Deo, 2007). Dyeing of denim with several other natural dyes, and using ecofriendly mordants, is possible, by which different shades are achieved on denim (Deo and Paul, 2004). Onion extract has been attempted on denim using natural and synthetic mordants. A synergistic effect of natural mordant combinations like a tartaric acid and tannic acid combination has been reported, giving good results by the meta-mordanting process (Deo and Paul, 2000).

## 16.8 Future trends

There is already a trend to use fibres other than cotton in denims. In times to come, denims may not simply remain cotton's preserve, giving way to blends and other cellulosics. Added properties and fashion are one reason for this, while on the other hand limited cotton production may not be sufficient to cater to the needs of the users. The conventional shades and weave patterns also are likely to change, and the

concept of denim may become a little different. Stretch denims are here to stay, and speciality finishes like water and stain repellents will catch the fancy of both user and maker.

## 16.9 Conclusion

Denim fabric started as pure cotton with indigo dyed warp yarns has now many variants. The colouration techniques possible now are far from conventional. Use of different fibres in combination with cotton has improved the functionality of the denim material. With changing lifestyle, fashion needs and usage requirements, novelty is the by-word. Ecology being a new dimension globally, use of biodegradable fibres is absolutely imperative. The complete range of qualities in denims is a welcome change for the conventionally casual look fabric.

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# Non-apparel applications of denim



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## 17.1 Introduction

Nowadays, denim has a wide range of applications extending from casual and elegant apparel to high performance worker suits. Indigo, known as a living dye, makes denim fabrics unique and exclusive products. Changing consumer trends, demand and competition, as well as new technological and ecological approaches, have aroused demand for creativity and unique products. Designers, textile engineers, producers, academicians, textile artists and craftspeople have been collaborating to enhance progress and increase denim market share. Industrial works are mainly focused on generating new markets, while academic and artistic works mostly deal with questions of more conscious consumption and social responsibility.

The original source of the blue cotton denim we know today, and which has influenced the whole world, is closely related to the history of Turkish textiles. The archive of the Marseille Chamber of Commerce (*Chambre de Commerce*) is one of the outstanding archives on the trade of the Eastern Mediterranean with France. In his study based on the research of this archive, French historian Paul Masson mentioned that a huge number of blue cotton products were exported from Izmir to Marseille, and these products were bought by Spain. These durable, cheap blue cotton products were used by Spain and Portugal to dress slave workers who were working in South American plantations. Fibres of cotton products. These cotton products were dyed with indigo imported from India and widely consumed by the public (İnalcık, 2008).

Denim is a timeless and irreplaceable fabric, has created a culture and has achieved a cult following. Customer trends pave the way for production methods and technological development, and these factors interact with each other. The fact that denim is used by a very wide range of consumers, its classic worn out look owing to the sourcing and use of indigo dye, and its many practical uses, have rendered this fabric a timeless product. However, technological and social changes combined with customer demands and trends to cause diversification in the usage of denim. These trends are currently towards environmentally friendly denim fabrics made of organic cotton and increasing increments of non-apparel use.

## 17.2 Classification of non-apparel denim products

Denim has a significant market share and the potential to be used in almost all applications. The development evolves in connection with innovative technology, design and ecological approaches. Various denim types and uses can be encountered in line with changing consumer demand. Existing non-apparel denim products and potential uses were identified by an intensive exploration of current and future possibilities. These alternative and extraordinary uses are classified in Table 17.1.

## 17.3 Analysis of the current situation

Unique textile products can be manufactured and handled with technology and design approaches that utilise environmentally friendly materials and processes. The denim fabrics used mostly in fashion design and garment production have constantly evolved, based on the demands of fashion and garment washing technology. Such trends have recently been towards the production of denim fabrics by organic cotton and other natural fibres that do not harm the environment and endanger human life (Yıldırım and İşmal, 2011).

Global warming, decreased water sources, chemical waste problems and ecological legislation make ecologically sensitive production a consideration in every manufacturing industry. Considering the ecological effects of a product from the beginning is the inevitable result of growing environmental consciousness. With a wider point of view, ecological elements of design that add positive value and are closely connected to technology should be evaluated and not ignored. From this connection, designers should work together as an interdisciplinary team along with technical workers. Many concepts have been suggested nowadays such as green, organic and ecological textiles, as well as design for the environment (DfE), sustainability, life cycle assessment (LCA) and design for sustainability (D4S). The concept of DfE is the detailed consideration of the process starting from material selection, product packaging and product life cycle up to the recycling of products at end of life (İşmal and Yıldırım, 2012).

Denim apparel can be turned into different products by giving them new functionality and aesthetic properties through recycling. These extend to a large range including insulation, accessories, new patchwork products and decorative pieces. Fundamental approaches for production of these items are based on recycle, upcycle and sustainability. The utilisation of obsolete apparel and production wastes has ecological and economic value.

#### 17.3.1 New approaches and initiatives

Although the characteristic properties of denim have been maintained since its initial creation, current fashion trends and progressive technological and chemical methods have led to outstanding changes. Quite a few studies have been conducted of non-apparel applications for denim; one of the major reasons for this is the faster rate of change in the fashion sector compared with that of other textile categories. Thus, Research and

| Category                                       | Applications and potential uses   |
|--|---|
| Living rooms                                   | Curtains, upholstery, furniture, ornaments, wallcoverings,<br>mattresses, cushions, lampshades, seat covers, separators,<br>kilims, rugs, mats, doorstops   |
| Dining rooms                                   | Curtains, window valances, upholstery, furniture, ornaments,<br>tablemats, wallcoverings, lampshades, separators, table-<br>cloths, runners, napkins, rugs, mats, kilims, bed hangings,<br>doorstops  |
| Bedrooms                                       | Curtains, bedcovers, headboards/footboards, wallcover-<br>ings, bed linens, duvet covers, bedsheets, quilts, pillows,<br>bedskirts, lampshades, ornaments, rugs, mats, mattresses,<br>kilims, wardrobes, doorstops  |
| Bathrooms                                      | Shower curtains, towels, bathrobes, ornaments, laundry<br>baskets/bags, closet sets, rugs, mats, toilet bowl lid covers,<br>toilet paper holders, toilet tank lid covers, organisers,<br>bathroom rugs, doorstops   |
| Kitchens                                       | Curtains, aprons, oven gloves, potholders, mats, tablemats, table<br>skirts, runners, sacks, kilims, rugs, mats, tablecloths, organ-<br>isers, ornaments, refrigerator covers, coasters, doorstops  |
| Baby/children's rooms, toys<br>and nurseries   | Curtains, bed coverings, headboards/footboards, wallcov-<br>erings, ornaments, quilts, pillows, bedskirts, rugs, mats,<br>doorstops, accessories, mummy bags, baby strollers, baby<br>carriages, organisers, diaper covers, baby soft bibs, crib<br>bedding sets, etc.  |
| Accessories for personal use                   | Shoes, slippers, bags, neckties, bow ties, scarves, shawls,<br>stoles, luggage, wallets, suitcases, saddlebags, umbrellas,<br>straps, beach bags, belts, necklace, bracelets, rings, hats,<br>earflaps, headphones, backpacks, notebook covers, mobile<br>phone/notebook/laptop cases, straps, card holders, school-<br>bags, organisers, masks, etc. |
| Souvenirs and special occasions                | Giftwrap, gift boxes, holiday stockings, holiday decorations, wedding accessories, ornaments.   |
| Office furniture and accessories               | Wallcoverings, chairs, sofas, armchairs, storage baskets, file<br>covers, ornaments, organisers, coasters, mobile phone/<br>notebook/laptop cases   |
| Pets and animal clothes and accessories        | Nests, cat/dog beds, dog/cat collars, clothes, straps, horse blankets, etc.   |
| Outdoor and camping                            | Garden furniture, mattresses, tents, parasols, sleeping bags, can/bottle coolers, hammocks, surfboard covers  |
| Automotive, marine and transportation textiles | Seat covers, helmets, caps, yacht/boat furniture, curtains, etc.  |
| Technical textiles                             | Industrial clothes, insulation  |
| Denim wastes for industrial purposes           | Thermal insulation, vehicle noise insulation, acoustical automotive padding   |
| Artwork  | Indoor and outdoor exhibition, interior and exterior design   |

## Table 17.1 Non-apparel applications and potential uses of denim

Development (R&D) and Product and Development (P&D) studies are mostly concerned with fashion trends. In addition, production methods and chemicals aimed especially at creating special effects and comfort properties have been developed. All of these production and consumption relationships take shape in line with new trends and concepts that are revealed as global socioeconomic and cultural concepts. Industrial development covers many applications and concepts, such as environmentally benign production methods, increased productivity and profitability, ecological chemicals and auxiliaries, recycling, etc. Table 17.2 shows some novel approaches for denim production.

At the present time, natural indigo, ecological synthetic dyestuff, recycling and ecological collection are also are implemented in denim production by some companies (Orta Anadolu Tic. ve San. İşl. T.A.Ş.; Çalık; Bossa; İsko; Kipaş). The Orta Anadolu denim mill in Turkey has come up with a unique denim fabric finishing process that changes the fabric structure. The process has a number of pluses, but the biggest is its eco-sustainability, with about 90% of chemicals being used in closed circuits and with almost no water consumption (Agarwal, 2011). Flatness, wrinkle resistance and a nice soft touch are major advantages of this environmentally friendly process, and are especially important to cutters during the garment sewing process (Molu, 2012).

Some attempts have been made to combine fashion and aesthetic properties with technical functions achieved through innovation. These developments have led to expansion of unconventional uses for denim fabric. Companies have been exploring new and alternative markets for denim by collaborating with designers. For example, Alexander Wang has designed a denim boat using the water resistant system of Cotton Incorporated (Cotton Inc.).

Environmentally friendly waterless applications such as ozone, laser and liquid ammonia are favoured and promising technologies. Ozone processing is a sustainable production method to give bleached effects to denim surfaces. Dry and wet ozone denim processing machines are available for industrial applications (Ozone Laundry Systems).

Rising demand for creativity and functionality from other (high added value) textile substrates, personalised textiles and increased focus on environmental compatibility and costs have led to an increased interest in physically induced surface modifications. The laser ablation/etching principle is to irradiate the polymer with a high energy laser radiation source that is absorbed locally by the material and then converted into thermal energy, inducing reactions to occur on the surface. Because no chemicals are needed, the process is environmentally friendly (Parys).

It is reported that use of the laser designing process on denim fabrics has ensured successful results and is a serious competitor to conventional technologies. It enriches the aesthetic quality of the finished product and creates a positive effect on its strength, value and overall quality. Developing new designs by using the computer and transferring the designs that are obtained to textile surfaces will not only increase and facilitate production in a more practical manner, but also help to create identical designs. Laser designing does not cause any wearing off or deformation of the fabric texture, unlike stone washing, and does not include any aftertreatments such as drying and fixating that increase production time and costs (Özgüney, 2007; Öndoğan et al., 2005).

| Non-apparel  |
|--------------|
| applications |
| of           |
| denim        |

## Table 17.2 Novel approaches for denim production

| New<br>approaches to<br>design   | Innovative<br>processes  | Finishing   | Fibres and<br>yarns   | Fabrics   | Performance   | Print   | Appearance  |
|--|--|---|---|---|---|---|---|
| Life cycle<br>assessment<br>(LCA),<br>design for<br>sustainability<br>(D4S), design<br>for environ-<br>ment (DfE),<br>ecodesign,<br>carbon/water/<br>ecological<br>foot print,<br>eco-index,<br>Biomimetic,<br>organic<br>fibres, upcyle,<br>recycle | Environmen-<br>tally friendly<br>indigo dyeing,<br>ecological<br>chemicals<br>and auxilia-<br>ries, sulphur<br>free dyeing,<br>electrochemi-<br>cal bleaching,<br>electrochem-<br>ical dyeing,<br>enzymatic<br>and ultrasonic<br>processes,<br>ozone, laser,<br>etc. | Smooth and<br>refined denim<br>finishes,<br>destroyed<br>coating treat-<br>ments, thick<br>resin coatings,<br>pastel and<br>pearlescent<br>finishes,<br>plastic shine,<br>functional<br>finishings,<br>nonformalde-<br>hyde resins,<br>self cleaning<br>finishings,<br>nanofinishings,<br>phase-change<br>materials,<br>microencap-<br>sulation and<br>nanoencapsu-<br>lation, etc. | Hemp denim,<br>linen/cotton,<br>silk denim,<br>acrylic/cot-<br>ton, stretch<br>denim with<br>Tencel<br>blends,<br>denim/cupro<br>blends, wefts<br>made from<br>recycled<br>coloured<br>plastic<br>bottles, super<br>stretchy<br>metallic<br>yarns,<br>dual core<br>yarns, nappy<br>imperfections<br>with various<br>effects,<br>multicolour | High stretch<br>denims,<br>stretch<br>jeggings,<br>rigid stretch,<br>coloured<br>weft, Jac-<br>quard weav-<br>ing, double<br>faced fabrics,<br>compact fab-<br>rics, selvedge<br>denim, Hon-<br>eycomb and<br>herringbone<br>construc-<br>tions, broken<br>twill varia-<br>tions, strong<br>white weft,<br>etc. | Soil/stain releas-<br>ing, flame<br>retardant, arc<br>protective,<br>antistatic, high<br>abrasion resis-<br>tance, tempera-<br>ture regulating,<br>antibacterial,<br>colour changing,<br>etc. | Indigo/<br>discharge<br>print, dig-<br>ital print,<br>lace print<br>denim,<br>Jacquard<br>patterns,<br>geometric<br>and floral<br>designs | Authentic looks,<br>sculptural/<br>moulded/<br>relief and<br>polished<br>looks, shiny<br>looks, three<br>dimensional<br>weaves,<br>waffle<br>appearances,<br>jersey look<br>indigo or<br>indigo look<br>knits, cord<br>like surfaces,<br>deep ridged<br>textures,<br>clean<br>looking<br>denims,<br>denim look-<br>ing with digi-<br>tal printing |

Combining laser techniques with ozone technology has the potential to create a step change in the industry in terms of reducing the environmental footprint of denim jeans production (Kininmonth, 2012). These approaches are encouraging the creation of unique designs in an ecofriendly manner. Actually, all textile wastes can be utilised for non-apparel applications such as bags, fleece, insulation material and filling, and industrial and personal purposes. Significant funds have been spent on social projects to arouse awareness of denim recycling and draw attention to social responsibility. Figure 17.1 shows the components of a recycling process. Denim wastes can be classified as being from two major sources, production (yarn, weaving, finishing and apparel) and customers.

More than 200,000 pairs of recycled jeans were transformed into building insulation, consequently keeping them out of landfills. This insulation contains no formaldehyde or chemical irritants and performs better than traditional fibre insulation (Saleem et al., 2010; Cotton Inc.; Textile World). Denim insulation material could be used in wide variety of industries including automotive, appliance, and acoustic, as well as heating, ventilation and air conditioning. UltraTouch<sup>®</sup>, a non-woven insulation material, is made with 80%–90% post consumer recycled cotton fibres derived from denim. These cotton fibres were made fireproof by treating with a nontoxic solution of borate, which is also a pest inhibitor and natural biocide – inhibiting mold, mildew, bacteria and fungal growth (Bonded Logic, Inc.; McManus).

Denim insulation also offers thermal and acoustic performance. It can be used as interior and exterior wall insulation, as well as for most ceiling applications (Eco-Friendly Builder; EHow Demand Media, Inc.). Some automotive suppliers use acoustic insulation material made from recycled old denim to reduce vehicle noise (Leigh Fibers, Inc.). A huge potential exists for recycling in the denim industry. Some initiatives are being driven by companies to use scrap denim remnants to produce currency notes in the United States – this paper is made of cotton instead of wood (Saleem et al., 2010).

Initiatives encourage the reuse of denim garments to produce yarn and the recycling of used plastic bottles for the production of denim. However, the balance between cost and gain should be carefully taken into consideration. For example, reuse of a garment produced from yarn may be disadvantageous in terms of the cost and technical properties of the fabric (Molu, 2012).

Indigo dyestuff usage and denim with worn out looking effects created by the washing methods used in carpets are becoming popular (Bozdağ, 2012). Figure 17.2 shows a denim looking Jacquard carpet woven with indigo dyed acrylic/cotton blend yarn and denim washed. These are not direct examples of non-apparel denim applications, but indicate that denim influences fashion all over the world and has a high impact on the design of other indigo coloured products having a denim look. There are even extraordinary examples such as refrigerator and motorbike coverings (Reinhold; Smeg).

Denim studies apparently force the limits of the characteristic properties of denim and imagination. In connection with yarn and weaving constructions, blend compositions and finishing technologies, many kinds of denim fabrics have been developed for a wide range of consumers. These improvements are promising for non-apparel

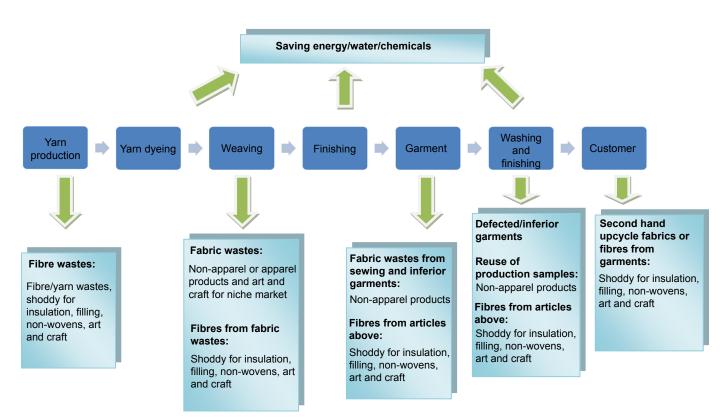


Figure 17.1 Recycle/upcycle line of denim garment manufacturing.



**Figure 17.2** Jacquard carpet with denim looks. Royal Halı (2012).

applications of denim. Textile companies have focused on home textile and interior design sectors with remarkable market shares. Diversifying of denim production determines the direction of these markets. On the other hand, the demand for non-apparel products also drives changes in denim fabric, and a triggering effect and mutual interaction obviously appear. For example, Jacquard fabrics, which are favourites for furnishings, led to the production of Jacquard denim fabric. On the other hand, the wet and dry crocking fastness of indigo seems to be a problem for these fabrics.

Obtaining indigo colours by sulphur dye or the application of medium and pale shades of indigo could be solutions for this problem. Reactive dyestuffs do not ensure indigo like appearances and result in different lustres and penetrations as well. Consequently, more dull and highly penetrated fabrics have resulted from reactive dyestuffs (Molu, 2012).

Some technical issues and challenges associated with unconventional applications of denim should be discussed. Production processes vary depending on product and design properties. The typical worn out appearance and surface effects of denim are obtained by applying wet and dry finishings to sewn garments. However, unlike denim apparel, non-apparel denim products, especially home textiles, have some challenges in the use of finishing treatments. This is because existing finishing processes must be applied to the open-width fabrics and larger sewn pieces that are typical of non-apparel denim products. Technical problems, namely crease forming, strength loss and some surface defects have to be overcome, and ensuring the necessary fastness and technical properties should be taken into consideration in the production of non-apparel denim applications.

Denim is defined as a semifinished product unless sewing and finishing processes are performed. Although denim fabrics are utilised to produce home textiles like curtains, cushions, bedsheets, bedcovers and duvets, crocking and washing fastness of indigo and a fabric width of 150–160 cm have become restrictive factors. Unlike other reactive and disperse dyed fabrics, denim fabrics have no practical use unless wet/dry finishings and sewing processes are performed. Besides woven denim fabrics, knitting fabrics made with indigo dyed yarn currently exist in the market (Berkem, 2012).

#### 17.3.2 Academic and artistic studies

Multidisciplinary research and denim projects are under way all over the world. The initiatives are conducted in collaboration with stakeholders, namely fabric producers, dyestuff/chemical producers, academicians, students, artists and designers. Many denim research projects with sustainability themes are taking place at universities (graduate and postgraduate level). One example is the project 'Planet Denim' at the Royal College of Art in London, and focuses on developing new techniques that consider the impact of design on the environment (Agarwal, 2010).

Some initiatives for sustainable denim development and production combining craftsmanship and sustainability such as The House of Denim Project were realised. Interdisciplinary projects aim to develop innovative ways of combining research methods into cultural material through the collaboration of social sciences with natural and applied sciences (the School of Social Sciences and the School of Materials at the University of Manchester). In this project, the assumption of either technological determinism (wherein meanings are created through design and manufacture) or the autonomy of the clothes wearer to impose meaning on clothing was challenged.

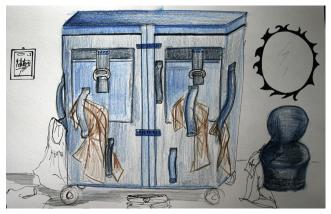
Moreover, hand woven denims coloured with natural dyes have become popular due to demand for authentic denim looks. Coloured hand woven selvedge denims are produced using *Indigofera tinctoria*, *Rubia cordifolia*, *Terminalia chebula* and *Acacia arabica* for blue, red, yellow and brown colours respectively (Industry of All Nations). Research projects for naturally coloured denims have been conducted in collaboration with industry and university partners. Orta Anadolu and Bossa are two examples of companies with R&D projects in this area (Bozdağ, 2012; Molu, 2012).

Academic studies aimed at broadening the scope of non-apparel denim applications are also active. In this sense, Dokuz Eylül University, Faculty of Fine Arts, Department of Textile and Fashion Design (İzmir), Mimar Sinan Fine Arts University, Department of Textile and Fashion Design (İstanbul) and Okan University, Faculty of Fine Arts, Department of Fashion Design (İstanbul) have conducted the projects 'Use of Denim in Home Textiles and Alternative Applications' (2008–2010), 'Dialogues with Denim' (2008), 'I am Denim' (2009) and 'Legend of de Nîmes', respectively.

A part of the project held by Dokuz Eylül University, Faculty of Fine Arts, Department of Textile and Fashion Design, was published (Yıldırım and İşmal, 2011). An artistic and creative approach to non-apparel denim design in conjunction with



**Figure 17.3** Wardrobe sketch: Şahmeran. Yıldırım (2008) and Yıldırım and İşmal (2011).



**Figure 17.4** Wardrobe sketch: Vagabond. Yıldırım (2008) and Yıldırım and İşmal (2011).

industrial techniques was presented. This study implemented a series of designs and works, related to home textiles, as alternatives to conventional use of denim. Inspiration was taken from slogans such as 'Denim living interiorly' and 'Jeans wardrobe for every home'. Some sketches and an example of an application can be seen in Figures 17.3–17.5.

Okan University, Faculty of Fine Arts, Department of Fashion Design held the 'Legend of de Nîmes' installation curated by İdil Tarzi in 2012. An installation with carpet, armchair and pouf represented non-apparel denim applications relevant to the concept 'My Home and Denim' was presented in Legend of de Nîmes Exhibition (Okan University, Faculty of Fine Art) as shown in Figure 17.6.



**Figure 17.5** Wardrobe detail: Çatalhöyük. Yıldırım (2008) and Yıldırım and İşmal (2011).



**Figure 17.6** Legend of de Nîmes Exhibition: carpet, armchair and pouf. Carpet design: Meleknaz Çılgın; armchair and pouf design: Janset Kaplan.

Industrial and artistic approaches are presented in the projects of Mimar Sinan Fine Arts University, Department of Textile and Fashion Design (Mimar Sinan University of Fine Arts). Denim is also such a rich and cultish material that it often takes the place of art media (Berry). These versatile works include components of



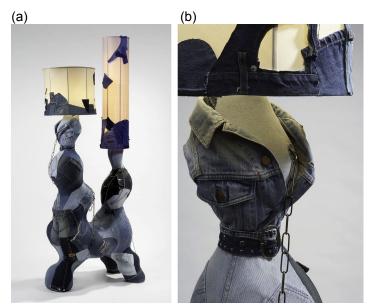
**Figure 17.7** Punk London: Denim on Denim. Ian Berry/Denimu.

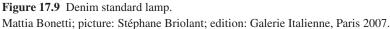


Figure 17.8 Denim armchair. Mattia Bonetti; picture: Stéphane Briolant; edition: Galerie Italienne, Paris 2007.

ecology, art and creativity in terms of recycling and using denim wastes. Extraordinary artistic works using denim fabrics and indigo colours have been created, as shown in Figure 17.7. Initiatives like these also support social projects.

Figures 17.8 and 17.9 show different denim uses and designs. As a designer, Mattia Bonetti revealed a new aesthetic comment in the design of an armchair (beech structure upholstered in denim, metal and leather accessories) and lamp (denim applied on resin, silk and denim lampshade) by highlighting unique denim characteristic. There are additional unique works and products made of denim fabric and recycled out-of-date denim (Gas Jean).



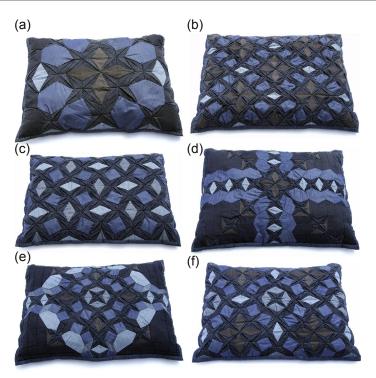


Denim furniture, beds, couches, chairs and armchairs are designed and produced by various companies, similar to producing a pair of jeans, as a timeless collection (Diesel; Hilfiger; Lauren). Figure 17.10 shows a series of pillows ( $26^{\prime} \times 20^{\prime}$ , handsewn denim with polyfill and organic cotton batting) created by Julie Floersch (2006-2008) for the window ledge made from high quality indigo dyed Swiss and Italian denim that should slowly fade over time from the intense sunlight (Floersch).

Figure 17.11 shows the curtains  $(60'' \times 96'')$ , handsewn denim with metal grommets) made by Julie Floersch (2008) for the dressing rooms that were not backed or quilted down, so the viewer could experience the piecework both from inside the dressing room and out. Denim culture, with its social, economic, psychological and philosophical bases, strongly affects the society. Searching for alternative uses of denim forces the limits of imagination. Such searches could even lead to the creation of vessels on a balcony (Gardens inspired).

# 17.4 Other interesting developments

While developing innovative denim fabrics with different surface effects, losing the characteristic properties of denim should be avoided, as the loss of these unique properties will cause changes in the typical denim appearance, which would render denim nothing more than an indigo coloured fabric. With that in mind, however, it is predicted that wool, silk, hemp, linen, polyester, polyamide and Tencel<sup>®</sup> denim blends



**Figure 17.10** Indigo pillows. Julie Floersch.



**Figure 17.11** Indigo curtains. Julie Floersch.

will continue to be produced and increasingly be preferred in the development of both the aesthetic and comfort properties of alternative uses.

Fabric width is another important factor in non-apparel applications, especially for home and interior textiles. The predominance of selvedge denim resulted in primarily shuttle looms being used in denim production. In the European denim market, the minimum fabric width is 80 cm, which is a shuttle loom product. The most prevalent width in non-apparel denim application, however, is 160 cm, which is produced on a shuttleless loom (Molu, 2012).

Antibacterial, soil/stain/water repellant and flame retardant denims are predicted to see widely increased used for furnishings, curtains and other interior textiles. Denim fabrics for home and interior textiles appear to have met with more success than recycled products in creating new markets.

There is a close relationship between the socioeconomic situation and the prevalence of denim use in home/interior textile products. Consumption cycles for apparel are shorter than those for other textile types, including home interior textiles. To increase home textile consumption and time spent at home, and consequently home textile expenditures, more stable and prosperous living conditions are needed (Yıldırım, 2008). Moreover, technical properties have to be considered, and systems should be developed to overcome the challenges that arise from the use of denim in home textiles.

One of the unique and essential properties of denim is the worn out appearance of indigo dyestuff due to its poor crocking fastness. This 'living dye' property must be kept in mind. However, crocking fastness is often a crucial and desirable property of textiles, especially for furnishings. As a solution, medium or pale indigo dyeing can offer enhanced crocking fastness. Moreover, thick coating can be applied to these fabrics that contribute to the improvement of fastness, and the amount of indigo dyed yarn shown on the surface can be reduced through the choice of weaving type. Construction with high weft and low warp cover factors may contribute to crocking fastness improvement at the expense of a loss in conventional denim appearance (Molu, 2012).

It is predicted that denim insulation will be used and encouraged on a broader scale in the context of green building techniques. However, the reuse of old garments through social projects may be considered more humanistic and economical than recycling them to produce yarn and insulation material.

## 17.5 Future trends

The competitive world of textiles forces designers to produce value added products with unique and original designs, different looks, innovative approaches and alternative applications. Denim and home textiles are two important and popular sectors of the textile industry. In this sense, it is possible to generate synergetic effects and additional markets by combining these sectors. Popular for garment manufacturing while being fashionable all over the world for decades, denim can be used in home textiles as an alternative that is supported by related research and experiments. Interior uses for denim constitute a potential new market for the fabric. Using environmentally friendly materials and processes, unique textile designs can be manufactured in which technology and design are combined.

Consumer purchasing behaviour is highly influenced by factors such as visual appearance, demand for more durable and long lasting textiles, aesthetic properties, quality and added value from textile products. These factors and global competition increasingly force manufacturers to focus on innovative research and solutions. Creativity and sustainability will be the main drivers for the production of extraordinary and unique designs. Organic and ecological – as well as silk, wool, hemp, linen, Tencel, recycled polyester and polyamide – denim appear to be increasingly popular for all purpose uses worldwide. Coated, printed, Jacquard, stretch and high performance denim fabrics can create new horizons that increase the use of denim in non-apparel applications. Natural dyeing is of particular interest in the textile industry and the denim sector as well. Textile companies and mills are collaborating with researchers and research centres all over the world for alternative natural dyeing applications.

Technological innovation leads design and production to new dimensions such as *Trompe-l'œil* effects created by digital printing, as well as denim looking fabrics. Leather looking coatings, imitation shark and dolphin skins, extra shiny rainbow glitter and pearlescent coatings, denim fabrics with knitting effects, animal skin appearances, batik effects, camouflage patterns, floral printing designs with indigo colours, Jacquard patterns and striped denims are some examples of the various approaches to denim apparel and for new alternative denim opportunities for applications such as furnishings, curtains, etc.

Social projects that have social impact by utilising denim wastes and recycled denim in art and craftwork are expected to generate increased growth in niche markets and employment. Education to establish consumer awareness on ecological concerns, such as the donation of used clothing and upcycle/recycle concepts, is a must. As an essential issue for creating competitive, extraordinary and unique products, nowadays the understanding of design goes beyond its traditional meanings. Design includes not only design of the product, but also its environmental and social impacts. It is obvious that denim has transformed from its traditional appearance to novel sophisticated versions, through the combination of design and technological innovation and incorporation of different points of view and inputs. Approaches to the use of non-apparel denim encompass some important and big textile sectors, such as interior and home textiles, that have huge potential for growth in market share.

It can be predicted that creative state-of-the art designs, aesthetic concepts, ecological concepts, material preferences and care habits will change depending on the acceptance and willingness of consumers to change their preferences and habits. Many possibilities will emerge for the design and production of textiles and apparel, in line with the emerging technologies and trends. Designers who are capable of working on multidisciplinary

projects, thanks to their aesthetic vision and technical skills and know how, will have a mission to establish a connection between producers and consumers.

# 17.6 Conclusion

It appears that denim will continue to have a cult following, depending on various technical, social and economic parameters. However, it is necessary to change denim production and consumption habits in order to achieve and maintain sustainable life globally. From this point of view, the adoption of slow fashion concept that incorporate the ecological evaluation of denim will be beneficial. The circle of production – consumption – recycling can be carried out by social projects. Utilisation of old denim garments to produce non-apparel denim articles will be more economical and offers the potential to develop new market niches. If denim fabrics are used directly for non-apparel denim applications, especially in home/interior textiles, their market share should increase considerably.

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# Recovery and recycling of denim waste



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# 18.1 Introduction

The textile industry has a remarkable impact on the environment as it consumes huge quantities of energy, water and chemicals during the different production stages. After the manufacturing stage, as the consumers continue to buy new textile products, textile waste continues to be generated, and eventually ends up in municipal landfills.

Traditionally, the textile and clothing industry is a linear industry: make, use and discard. The dumping of post consumer textile waste is a huge urban waste problem, and there is a common practice of commercial and charity organisations collecting discarded textiles. A small portion of textile waste is thus recovered in this way, but the rest is normally discarded as solid urban waste, and there is a huge untapped potential to use this discarded waste, and the recycling possibilities are unlimited.

In order to become more environmentally friendly, a circular production system is needed in which discarded products are reused (second hand use) or used as a source of raw material (resource efficiency). The principles of a circular economy have been described extensively by the Ellen MacArthur Foundation. In a report of this foundation, the impact of textile recycling in terms of economic value have been calculated and described. In creating a circular economy, recycling is an important option. In high end textile recycling, the intrinsic properties of the materials are used, implying that regained materials should be used in the most advanced way for high added value products (preferably the same type of product).

In this way, the economics of textile recycling are most often favourable and at the same time reduce the use of virgin materials. Nowadays, textile materials are recycled only on a limited scale and most often into low added value products while not using the intrinsic properties of textile materials. Textiles are usually triturated and converted into nonwoven felts used for insulation in construction and automobiles, but it is possible to shred textiles to get them back into a fibre form similar to that of virgin cotton.

The main problems in high end textile recycling are connected to return logistics (how to collect discarded textiles as a separated material stream that is not contaminated with other waste), the distance between production and use of products – and thus the place where the materials are discarded – and the reproducibility of material streams. This reproducibility is essential for companies to be able to use recycled

textiles of high and consistent quality. To this end, in order to recycle at an industrial scale, collected textiles should first be sorted. Many sorting systems and software programs are either available or under development for sorting textile waste according to colour and chemical composition.

In the European Eco-Innovation project Textiles for Textiles, an automated textile sorting machine was developed, and was able to sort discarded textiles by chemical composition and colour. The requirement of reproducible waste streams in high amounts can be realised with denim, and this is a main reason why considerable research and developmental effort is being expended on the high end recycling of denim.

# 18.2 Problem with denim waste

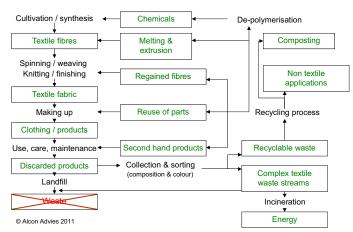
Denim is produced and used in large amounts, and the production, use and disposal of denim has a huge environmental impact. A comprehensive summary of the impact of denim was published by the International Solid Waste Association, highlighting the environmental aspects and opportunities to reduce environmental impact. In this report, all aspects of denim production, and the environmental effects connected to those production steps, are covered in detail. Most environmental impact is caused by the production of cotton fibres (even in the case of organic cotton, there is still considerable environmental impact) and the indigo dyeing of warp yarns. The production of indigo dye is a complex chemical process, and the production of natural indigo is connected to rather poor working conditions.

Cotton is the second textile fibre, after polyester, with an annual production of about 25 million tonnes, and a large quantity of cotton is used in the production of denim garments. At the end of their use, all of these products are discarded. As with all textiles, there are many waste recycling opportunities for denim. The opportunities and possibilities for textile recycling are shown in Figure 18.1.

All of the recycling options shown in Figure 18.1 are applicable to denim waste, with the exception of melting and extrusion. In another article, all post consumer options for textile waste are presented in more detail, indicating the end products that can be produced from post consumer textile waste. In many other publications, the fate of discarded textiles is described.

In practice, a large amount of denim waste is dumped in landfills or incinerated in solid waste incinerators. This is often called 'thermal recycling', but in essence it is the destruction of valuable materials that could have been recycled into high end products. Also, composting of denim is considered a recycling option, as it is part of the biocycle in the C2C philosophy. But options in which cotton material is destroyed, and the material itself is not recycled into sustainable products, hardly contribute to a reduction in the environmental impact of cotton material.

Other denim waste is shredded and used in the automotive industry for insulation. This application can be considered a very fast downgrade of the cotton material, because recovery of fibres after discarding the car is not an option due to the



#### Textile recycling options

Figure 18.1 Schematic overview of textile recycling options.

resin used to bind fibres and shape the end product. Therefore, it is much better from an environmental, and often also from an economic point of view, to investigate the feasibility of more advanced applications for denim waste.

In denim jeans production, the cutting waste is between 10% and 15%. Most cutting waste is recycled by unravelling and reusing the fibres in the production of insert yarns (weft direction). Because cutting waste is produced before washing and finishing, the dark blue (indigo) colour also colours the weft yarns. In jeans, this can be seen as they are turned inside out: the outside colour of the jeans is a deeper blue than the pale blue inside that comes from weft yarns made only from virgin fibres. The quality of jeans is not influenced by reuse of the cutting waste.

Post consumer denim recycling is more complex, because the material is less homogeneous in terms of colour, fibre quality and non textile parts like buttons, zippers, rivets and leather (look) labels. Also, collection and proper sorting is a problem. Most collected post consumer jeans are shredded and reused in low value applications for thermal and noise insulation and pressure distribution, but high added value end uses are targeted more and more nowadays. It has been commercially demonstrated on a large scale that post consumer jeans waste can be reused in clothing applications.

The interest in high end applications of post consumer jeans is rapidly increasing, due to the growing interest of consumers in sustainable products, and main retailers offering recycled products and taking environmental responsibility, as well as policies on national and international levels aimed at resource efficiency and green public procurement. In the EU, voluntary criteria for green public procurement of textile products are published.

Therefore, many research organisations have focused their development work on the high added value recycling of post consumer textiles, including jeans. An example of such an organisation is the open innovation foundation Texperium (NL), which focuses its activity on the sorting and selection of post consumer textile waste, shredding and unravelling of the waste, and spinning of recycled fibres.

# 18.3 Recovery techniques for denim waste

#### 18.3.1 Industrial denim waste

The recycling of industrial waste from denim production uses state of the art technology. Besides wasted yarns originating from the dyeing and spinning operations in denim manufacturing plants, most wastes are remains from the garment production process. Normally, 10%-15% of the denim fabric cannot be used in the final end product. This waste material is of high quality, as the composition is exactly known, the colour is (mostly) dark blue indigo dye and there is a massive amount of industrial denim waste available.

Denim waste is most often gathered and shredded into fibres. The shredding process is a mechanical process in which the pieces of fabric are unravelled into fibres. These fibres are mostly shorter than virgin fibres, but can be reused in weft insert yarns by mixing them with virgin fibres. Up to 50% of recycled fibres can be added without influencing the quality of the yarn, and the advantage is that these yarns have a blue colour, which in theory allows a reduction of dye in the warp yarns.

Most jeans producers recycle denim waste in their own spinning department (in the case of vertical integrated companies) or have contracts with textile waste recyclers to reuse the waste material in the spinning of new yarns. There is also substantial trade of denim waste all over the world. On some websites, huge amounts of denim waste are offered at prices of  $0.20-0.30 \in$  per kg, and for waste yarns the price is nearly double that amount (2013 prices; prices may differ and are related to the price of virgin cotton).

#### 18.3.2 Post consumer waste

Denim jeans are bought by end users in large amounts. The production of jeans is estimated at 3.6 billion pairs. If an average pair of jeans weighs 600 g, the total textile consumption of jeans is 2.16 million metric tons a year. This amount will be discarded after one or two years of use. This implies that in theory, there is a yearly potential of 2.16 million tons of post consumer jeans waste available. Only a small part of this amount is collected and reused or recycled. It is estimated that in Western Europe, only 35%–50% of textiles are collected.

A main problem is the collection of post consumer jeans. Although in many countries collection systems are in place (curb side collection, textile waste containers), many consumers discard their jeans (and other textile waste) as solid municipal waste. This waste is incinerated or dumped in landfills. Once mixed in with other waste, the jeans become wet and dirty and high end recycling is no longer an option. Jeans that are collected are mostly sold to textile sorting companies. They manually sort the rewearable jeans (especially branded jeans) for sale to second hand shops and in Third World countries. Manual sorting of non rewearable clothing is expected to be automated in a few years time. It is expected that the aforementioned automated sorting system developed by the Eco-Innovation project Textiles for Textiles can be programmed in such a way that jeans can be sorted as a separate fraction. This would strongly increase the quality of input into the denim recycling process (by manual sorting also, jeans made from cotton/polyester mixtures maybe sorted as 100% cotton jeans).

Non rewearable jeans are mostly sold to textile recycling companies. Those companies shred the jeans into fibres, yarns ends and pieces of fabric suitable for use in the nonwoven fabrics industry – a major application is as insulation felt in automotive applications. In many countries, more effort is being made to increase the amount of textile material (including jeans) collected. Dedicated actions are being organised by national and local authorities, in cooperation with charity and commercial textile waste collectors, in order to persuade consumers to discard their textiles separately and give them to charity and clothing banks.

Also in retail, post consumer textile collection has become an item. Companies like H&M and C&A have started to collect discarded textiles in their shops. The company I:CO, part of the SOEX Group, is assisting these retail organisations in collecting discarded clothes. Consumers receive a small discount on their next purchase when they discard their textiles at these shops. These textiles are also sold to clothing sorting companies and processed in the same way as other collected post consumer textile items.

The leasing of jeans was introduced in early 2013 by Mud Jeans in The Netherlands and Germany. In this concept, the producer or distributor of the jeans stays the owner. The user of the jeans only 'buys' the right to the use the jeans for a period of one year. If the jeans need to be repaired, it is at the cost of the lease company. After one year, the jeans are returned to Mud Jeans, and are either refurbished and leased again or shredded to reuse the fibres. Although in B2B (business to business), lease concepts are frequently encountered, this concept is new in B2C (business to consumer) relationships. This concept is also being used for other clothing products.

# 18.4 Recycling of denim waste

#### 18.4.1 Recycling techniques

In principle, denim waste can be recycled through several methods. In practice, however, only a few are encountered – these are the methods that are economically and ecologically preferred. Most often, recycling is done by shredding post consumer materials into fibres that can be reused in low grade products. Also, the reuse of parts of denim waste is practised only on a small scale. Other recycling methods such as composting are not frequently seen and cannot be considered as high end recycling methods. Post consumer denim waste that is not suitable as rewearable clothing is manually sorted at textile sorting companies. Sorted denim fractions are sold to textile shredding companies, and without any pretreatment, this denim fraction is shredded into fibres. The fibres are processed into nonwovens for specific applications. The automotive industry is a large user of shredded denim nonwovens for sound and thermal insulation. Also, nonwovens for insulation in houses, as a replacement for mineral wool, are made from these fibres.

High end recycling of post consumer denim waste may require additional steps in order to obtain pure fibres of good quality that can be spun into high quality yarn. The main problems of post consumer denim in high end recycling are posed by:

- · Metal buttons.
- Metal zippers.
- Rivets.
- Leather look labels.
- · Sewn-in labels used for composition and care instructions.
- Thick seams.

Non textile parts must be removed, as recycled fibres are not allowed to contain impurities such as metals. Parts that are difficult to unravel are returned to the process until the pieces are finally turned into fibres. The removal of buttons, zippers and most rivets can be done by cutting and using only the legs of the jeans – the top part, with its buttons, zippers, rivets and labels, either is not used, or is used in lower grade applications. The legs of the jeans, representing about 50% of overall weight, are shredded and unravelled. The resulting fibres may be carded in order to obtain a fibre mass practically free from impurities, yarn ends and fabric pieces. This material is generally suitable for spinning, although virgin fibres may have to be added to obtain a yarn with suitable mechanical properties.

If one wants to use the whole post consumer jeans in the shredding and unravelling process, the shredding equipment must be able to separate non textile parts from textile fibres. In most shredding machines of this type, like the Laroche Jumbo shown in Figure 18.2, step cleaners are used to separate heavier parts from fibres.

Also, metal detectors are used to remove metal buttons and zippers. In this way, most buttons and other metal parts can be removed, but even so, there is no guarantee that all non textile parts are removed. In further processing steps and especially in the prespinning processes, the last metal pieces and labels must be removed. Fibres recycled by this method can also be used in the open end spinning of yarns. As the fibres resulting from this process are a little shorter, more virgin fibres must be added to reach the same yarn quality achieved using only the legs of post consumer jeans. Figure 18.3 shows recycled denim fibres.

Besides this industrial process, many Internet references discuss the processing of jeans materials into products like handbags, toys, carpets, quilts and patchwork. A wide range of these products, as well as instructions on how to make them, can be found at. Although this form of recycling can be seen as high end recycling that creates added value, the economic importance of such activities is low – only a very small percentage of all discarded jeans can be reused in such a way.



**Figure 18.2** Laroche jumbo textile shredder. Picture: author.



**Figure 18.3** Recycled denim fibres. Picture: author.

Technological improvements in recycling are now expected all along the production chain:

- Collection of discarded textiles must improve. More textiles have to be collected, as the recycling rate is now quite low (about 30% is recycled in one way or the other).
- Sorting discarded textiles is essential for creating reproducible waste streams that can be reprocessed and recycled. Automated sorting has to be introduced on a large scale in order to provide the industry with a high and consistent quality of recycled (secondary raw) materials.
- Shredding and unravelling has to be improved in order to obtain longer fibres and less contamination from non textile materials.
- Implementation of 'design for recycling' (D4R) and 'recycling in design' (RiD) must be made on a much larger scale. It has been demonstrated that very functional jeans can be designed and produced that are also much easier to recycle. Special attention should be given to the use of labels, buttons, zippers and haberdashery.

- Spinning of short fibres into high quality yarns has to be redeveloped. In several projects and
  products (like G-Star Raw recycled jeans), post consumer denim fibres have been used in
  high percentages without interfering with product quality. Twining also may help to improve
  the quality of recycled yarns.
- RiD must become the standard for materials selection by designers. Wherever possible, designers and product developers should use recycled (denim) fibres. The design and technical specifications should be adapted to the special properties of the recycled fibres and yarns made from them.

#### 18.4.2 Design for recycling denim

In order to facilitate the high added value recycling of post consumer denim jeans, designers must apply D4R guidelines. As recycling of textiles will become the standard in a few years' time, it is essential that the recyclability of denim fabrics is improved. Several factors hinder high end denim recycling, including:

- Labels (artificial leather and acetate).
- Metal parts (buttons, zippers and rivets).
- Thick seams.

In the design of jeans, these hindrances should be considered and new solutions implemented. Several solutions were developed and demonstrated in prototypes at a workshop in 2013, in which students from four textile schools in Germany and The Netherlands worked together. Some solutions were:

- Use detachable buttons like the ones used in cufflinks.
- · Print the material composition and care instructions on the inside of the pockets.
- Use bleaching effects to replace leather labels.
- Use hot melts for joining parts, instead of sewing thread.

These solutions will not affect the looks and functionality of jeans, but would greatly contribute to their recyclability. Besides the D4R solutions presented, RiD options also must be taken into account, and his implies that designers look for opportunities to include recycled fibres in their products. The jeans of G-Star are a good example of RiD, as they managed to replace a part of the virgin cotton fibres with recycled ones. SomeD4R options are used in Glue jeans. In these jeans, the seams are glued instead of stitched, and this certainly improves their mechanical recyclability.

# 18.4.3 Upcycling denim waste

Another recycling technology under development for cotton in general, but also very applicable to denim, is the chemical recycling of cotton. In this upcycling process, cotton is used as the base material for the production of a lyocell type of viscose. Upcycling is a popular term that is often misused in recycling. This process is studied in different places under different names: Re:newcell (Sweden), SaXcell (The Netherlands) and an anonymous project in the United States.

Re:newcell was developed at the Royal Institute of Technology in Stockholm and allows for the environmentally friendly and economical production of new textiles from used fibres. The cotton waste is dissolved and spun, and a lyocell type of viscose is the end product.

The SaXcell development is taking place at the Saxion University of Applied Sciences in Enschede, The Netherlands. In this research, cotton waste is dissolved under controlled conditions in order to regulate the length of the cellulose polymer chain. Depending on the nature of the cotton waste, e.g. post consumer denim waste, the cellulose waste material maybe further purified to remove dyes and other impurities like finishes, before dissolution of the cellulose. The result of the process is viscose fibres that can be processed further into end products like denim.

The project in the United States uses cotton waste to produce nanofibres. The cotton is dissolved in a solution of ethylene diamine and thiocyanate salts, and the solution can then be electrospun to produce viscose nanofibres. The same approach but using a different solvent is reported by a research group in Thailand. All of these research projects show that at least in theory, cotton waste and more particularly post consumer denim waste can be upcycled to new textile fibres for a broad range of applications. As in the cotton cellulosic solution, functional chemicals can be added and a superior fibre produced (at least superior to the original cotton waste).

# 18.5 Development of recycled products

#### 18.5.1 New products from denim waste

After shredding, unravelling and carding, recycled fibres from post consumer denim are suitable for spinning yarns. In general, 50% virgin material has to be added in order to obtain a yarn with good mechanical properties. Yarns as fine as Nm 30 can be produced in this way by an open end spinning process. Figure 18.4 shows yarn developed from 50% post consumer denim jeans.

Yarns obtained in this way can be further processed by twining, in which two, four or more yarns are combined into one. The mechanical properties and evenness of the



**Figure 18.4** Yarn from 50% post consumer jeans. Picture: author.

yarns are increased strongly by twining. Also in twining, yarns from recycled fibres can be combined with those from virgin fibres. In most cases, yarns from recycled fibres are not as strong and have a somewhat lower abrasion resistance than yarns made from virgin fibres. That is the main reason why those yarns are preferably used as weft insert yarns and not as warp yarns (which must be much stronger and more abrasion resistant).

Yarns of Nm 30 size can be used in the weaving of jeans fabric. A brand using yarns with recycled content is G-Star. G-Star's Raw recycled jeans are based on post consumer recycled fibres. In the future, G-Star will not advertise the recycled content in its products, but sustainable fibres, including recycled ones, will be used in all products without compromising the look and feel of the garment. Also, Nudie Jeans is using post consumer denim waste as weft yarn in its jeans. Many other jeans producers are conducting experiments for using post consumer recycled yarns in their jeans.

It is easier to use yarns from recycled fibres in knitted textile products like pullovers. In knitting, twined yarns can be used more easily, resulting in nice knitted fabrics. Examples of knitting yarns produced from post consumer jeans can be found on the Internet. Using knitting yarns with a high recycled content maybe a little more difficult due to the unevenness of the yarn. However, this can be overcome in the design of the product by selecting a more complex knitting pattern that masks the unevenness.

#### 18.5.2 Denim from other waste materials

Another recent development is the use of other recycled fibres in denim. Levi Strauss has started to mix virgin cotton with recycled polyester fibres from PET bottles for the production of denim. By replacing virgin cotton with recycled polyester, the environmental impact from jeans is decreased. The effects of polyester content on recyclability may be positive; however, the polyester content may have a negative effect on the recycling of the cotton by the dissolving technologies described earlier.

Recently, Levi's also used Dyneema, a super strong polyethylene fibre, to strengthen its jeans. Tests show that the addition of 4% Dyneema fibres increases mechanical strength by 25% and improves abrasion resistance by 250%. The addition of Dyneema fibres does not affect mechanical recycling, but does improve the technical lifetime of jeans.

# 18.6 Environmental benefits of denim recycling

The need for resource efficiency is stimulating development and use of recycled materials. The European Commission's Roadmap to a Resource Efficient Europe states that the EU wants to become an environmentally sustainable society. Reductions in the use of materials, as well as increased recycling, play important roles in realising the ambitions of the EU. Although textiles and clothing are not mentioned specifically in the EU communication, textiles recycling will surely contribute to the realisation of the roadmap goals.

The roadmap states this vision for the future: 'By 2050 the EU's economy has grown in a way that respects resource constraints and planetary boundaries, thus contributing to global economic transformation. Our economy is competitive, inclusive and provides a high standard of living with much lower environmental impacts. All resources are sustainably managed, from raw materials to energy, water, air, land and soil. Climate change milestones have been reached, while biodiversity and the ecosystem services it underpins have been protected, valued and substantially restored'.

It is well known that cotton is a demanding crop that uses large areas of agriculture land, consumes enormous amounts of water (up to 20m<sup>3</sup> per kg) and needs in most cases large volumes of fertilisers and pesticides (except for eco-cotton). Therefore, the recycling of cotton is a sustainable activity. The shredding of jeans costs about 0.5 kWh electrical energy (1.8 MJ) per kg of shredded material, compared with about 60 MJ to grow and harvest virgin cotton. In addition, the recycling process is water free, so no drying is involved. The actual environmental gain, however, depends on sorting and selection prior to the shredding and use of recycled fibres. If recycled fibre can be used as it is produced, then an additional large environmental saving (as well as cost saving) can be realised during finishing by skipping the scouring, bleaching and dyeing processes. Also essential is the quality of the product from the recycled fibres. If the quality standard cannot be met, the product will be discarded in an earlier stage, and part of the environmental gain is lost.

A number of tools have been developed for calculating the environmental impact of a product during its life cycle. Normally, this Life Cycle Assessment (LCA) is very costly and difficult to perform – an LCA study of jeans is published on the Internet. Several alternative tools that are easier to use have been developed for assessing environmental impact. The Nike Environmental Design Tool is an example of a tool that estimates environmental impact (at least in comparison with an alternative product).

A very easy-to-use tool was developed by CE Delft and Alcon Advies by order of the Dutch Branch organisation for the textile and clothing industry, MODINT. The MOD-INT Ecotool has a large dataset that enables the user to make environmental calculations related to the whole life cycle of a textile product (from fibre production to the recycling of the product) and/or specific parts of the production chain; for example, the finishing of the textile product. The environmental impact is expressed in  $CO_2$  equivalents, energy use and water consumption. This tool not only uses default data, but also is able to handle company specific data, which makes it very versatile and accurate for specific scenarios. When calculating environmental benefits, the following aspects may be considered:

- · Replacement of virgin fibres by recycled fibres.
- No scouring or bleaching needed (when materials are presorted by colour, this is more or less the case when processing denim).
- · No dyeing needed.
- The lifetime of the resulting product is the same as products having the same functionality.

Using the MODINT Ecotool, version 2.0 (2013), the environmental benefits can be calculated. The use of recycled fibres will result in a saving of 3.25 kg of CO<sub>2</sub>

equivalents, 47 MJ of energy and about 7000 L of water. Skipping textile finishing processes will save another 3.2 kg of  $CO_2$  equivalents, 59 MJ of energy and 130 L of water. In total, nearly 6.5 kg of  $CO_2$  equivalents, over 100 MJ of energy and over 7000 L of water are saved when recycling 1 kg of denim. Although these calculations are for a specific situation, the order of magnitude is certainly correct, and they show very clearly the environmental saving potential of mechanically recycled denim fibres.

It also is important to educate consumers/end users about the environmental impacts of the textile products they want to buy, so that they are aware of the impacts of the choices they make. The Nike Environmental Design Tool, the Higg Index and new initiatives like the REMO key are important developments for creating awareness at the end user level. If end users want to buy a greater number of sustainable jeans and other sustainable textile products, producers will provide them with these products.

#### 18.7 Future trends

Denim recycling possibilities are unlimited, and the adoption of an effective strategy will reduce the environmental impact while simultaneously contributing to industry competitiveness by addressing the growing issue of raw materials access. In fact, the recycling of denim waste is a challenging business, and has numerous constraints related to proper utilisation of the discarded denim apparel.

The current state of denim recycling is merely the mechanical recycling, i.e. producing recycled fibres of a certain quality. This quality must improve in the coming years. This will be achieved by a combination of improved shredding and unravelling technologies, improved sorting and selection, and the introduction of new recycling technologies. It is important to work on all three aspects in order to recycle greater quantities of denim and use the resulting fibres in high end applications, thereby replacing some of the use of virgin cotton fibres.

These improvements will be needed because world fibre consumption will increase by 3%–4% per year over the next 5–10 years. This implies that cotton demand will probably rise from 25 million tons in 2013 to 33–37 million tons in 2023. Increases in production will probably not be sufficient to meet this increase in demand, resulting in shortages of virgin cotton and (much) higher cotton prices (as experienced during a brief period of cotton shortage in 2011). This implies that part of the growth in cotton demand will need to be compensated for by recycled cotton and/or alternative fibres like viscose, hemp and linen. Of course, higher prices for virgin cotton will have a positive influence on the high end recycling of cotton, resulting in an increased number of products, including denim, that have a higher content of recycled cotton fibres.

# 18.8 Conclusion

Recycling of textiles is gaining more attention, and terms like 'circular economy' are becoming common in the textile and clothing industry, at retailers and at the consumer level. Everyone is looking for an increase in sustainable production processes, products and lifestyles. The increasing attention on the high end recycling of denim is a good example of the opportunities recycling can offer. Already, several fashionable products are on the market with high proportions of recycled denim fibres. Although many problems must be solved, the first attempts are very promising. Improvements in denim recycling are expected from a number of technological and nontechnological developments.

On the nontechnological side, there is growing interest from consumers/end users in products that are more sustainable. Sustainable, fashionable and functional clothing is high on their priority lists. This is true not only for consumers, but also for institutional users of textiles. Green public procurement rules (until now only voluntary) are increasingly being adopted by governmental and industrial users. Informing consumers/end users about the environmental impacts of textile products also is also essential. The first signs are positive: more sustainable jeans have reached the market, and new retail concepts have been introduced. For all denim jeans producers, there will be no way back: sustainability is hot, and high end recycling plays an important role in making denim jeans more sustainable.

# Sources of further information

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# Effluent treatment in denim and jeans manufacture



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# 19.1 Introduction

In general, the textile industry consumes large volumes of water, especially in the wet processing stages for cleaning, dyeing and rinsing. Besides the water, in the production processes many resource inputs are consumed, and the textile industry is rated as one of the most polluting and chemically intensive industrial sectors. The environmental problems created by the textile industry have received increased attention, and especially those serious environmental problems caused by wastewater. Textile wastewater requires proper treatment before being released into the receiving environment, for both economic and environmental reasons.

Due to stringent regulations and increasing freshwater costs, industries should not only consider the treatment of generated wastewater, but also develop methods to minimise waste generation with an integrated approach (Brik et al., 2006; Shon et al., 2006; Uzal, 2007; Paul et al., 1995; Van der Bruggen and Braeken, 2006). Thus, the efforts at reclamation and reuse of wastewater coming from industrial activities have been increasing.

Denim and jeans production is one of the most important subsectors of the textile industry, and its products are some of the most highly used in textile clothing, with continuous fashion use and consumer preference, especially by young people. Dyeing and finishing/washing processes are major sources of wastewater pollution in this sector, and the resulting wastewater contains large amounts of dyestuff and alkaline chemicals. Considering the number of jeans produced per year, the extent of environmental damage caused by this industry is very clear. Today, the industry is looking for advanced denim production processes and adapting green applications in order to overcome these environmental and energy problems (Sustainable Denim Manufacturing Process).

In most denim and jeans production plants, the wastewater management strategy is not the treatment of waste streams separately. Rather, they are usually treated in the industry's centralised wastewater treatment plants after the mixing of all types of wastewater regardless of source. This implementation may make wastewater treatment more complex than it would be if the waste streams were treated separately. Whether separate treatment is a good alternative can be discussed, but the overall picture indicates that this is the case.

Denim textile wastewater is usually treated in a biological system called an activated sludge plant, in order to allow wastewater discharge within regulation requirements, but not to reduce it to a final effluent suitable for reuse in textile processes. In fact, considerable levels of recalcitrant contaminants still remain in biologically treated textile

effluent (Fersi et al., 2005). Both the water and chemicals that are treated could be recovered and used in production processes. In the future, many textile companies will face the requirement to reuse a significant part of all incoming fresh water, because traditionally used methods are insufficient for obtaining the required water quality, and recovering valuable chemicals also should be an important concern.

# 19.2 Characteristics of wastewater

High levels of salt, surfactants, pH concentration and colour are typical characteristics of textile (Setiadi et al., 2003), denim production and jeans washing plant wastewater. As a result, this effluent is some of the most difficult industrial wastewater to treat (Lotito et al., 2012; Nyström et al., 2004; Uzal, 2007). The wastewater contains fibres and large amounts of salts, acids or alkali chemicals from dyeing and finishing processes (Lotito et al., 2012; Capar et al., 2006; Fersi et al., 2005; Petrinic et al., 2007; Setiadi et al., 2003; Uzal, 2007). Furthermore, the composition of wastewater from textile processes varies greatly from day to day and hour to hour depending on the dyestuff, fabric and chemicals used.

For denim production, the main processes are spinning, dyeing, weaving and finishing. The most water consuming processes in denim and jeans production are dyeing and finishing/washing processes. Indigo, sulphur, reactive and vat dyes are the major dye types used, in combination with a huge amount of water consumption. In Figure 19.1, a typical flow diagram of denim dyeing/finishing processes is given. As can be seen from the figure, regardless of the dye type used, the major water consuming stages are the rinsing stages of dyeing operations. For denim, rinsing is commonly carried out through several stages including dyeing, desizing, stone/ enzyme washings, finishing and softening, all of which consume a huge quantity of water and energy. In dyeing operations, high levels of alkaline chemicals are used, and these chemicals require more concern before discharging them to the receiving bodies (Ibrahim et al., 2008).

In denim production, dyeing and finishing wastewater also contains a significant number of suspended solids (SS), dispersing agents, salts and trace metals. In Table 19.1, a typical dyeing recipe and the chemicals used in denim processes are given (Uzal, 2007). This highly polluted wastewater can cause serious environmental problems due to its high colour content, large amount of SS and high chemical oxygen demand

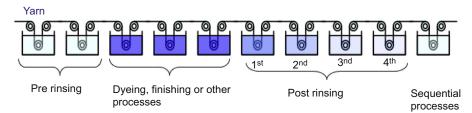


Figure 19.1 Flow diagram of denim dyeing/finishing processes.

| Recipe                              | Amount (%) |
|-------------------------------------|------------|
| Dye                                 | 34         |
| Complexing agent                    | 3          |
| Sodium hydrosulphite $(Na_2S_2O_4)$ | 31         |
| Sodium hydroxide (NaOH)             | 29         |
| Stabilising agent                   | 1          |

Table 19.1 Typical denim dyeing recipe

(COD). In addition, dye consumption is gradually increasing each year due to increasing demand from the production of denim and jeans (Boussu et al., 2006; Nyström et al., 2004; Uzal, 2007).

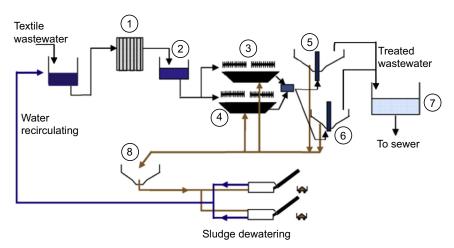
Due to serious concerns about the treatment of industrial wastewater, laws are becoming more stringent, and a large number of studies have been initiated to find more efficient methods for treating textile wastewater (Solis et al., 2012). The first step in reducing textile industry pollution is to prefer new and less polluting chemicals and technologies in production processes, in order to minimise wastewater production. The second step is effective treatment of heavily coloured effluent containing high salt concentrations, in order to meet specified discharge requirements, but this should be performed after considering alternatives for recycling and reusing the wastewater before discharge (Ramesh Babu et al., 2007).

# 19.3 Techniques for treating wastewater

In general, the objective of textile wastewater treatment is to reduce the level of organic pollutants, heavy metal, SS and colour before releasing the treated wastewater to the environment (Setiadi et al., 2003). Conventional treatment methods for textile wastewater are mainly physicochemical (Fersi et al., 2005; Nyström et al., 2004; Petrinic et al., 2007; Sahinkaya et al., 2008) or biological (Sahinkaya et al., 2008). The situation is similar for denim and jeans production plant wastewater.

Colour and other auxiliary chemicals can be removed from wastewater by chemical and physical methods including coagulation, flocculation, adsorption, oxidation and electrochemical processes. These methods are quite expensive, have operational problems (Froneberger and Pollock, 1976; Young Denim Fabric), and generate huge quantities of sludge (Allegre et al., 2006). Amongst the low cost viable alternatives available for effluent treatment and decolourisation, biological systems are recognised for their capacity to reduce biochemical oxygen demand (BOD) and COD through conventional aerobic biodegradation (Sustainable Denim Manufacturing Process; Fersi et al., 2005; Hessel et al., 2007).

However, higher pH, conductivity, BOD and COD in denim plant wastewater make it resistant to biological degradation, and for effective treatment a pretreatment alternative is required prior to biological processes. The schematic diagram of a conventional



**Figure 19.2** Conventional activated sludge treatment plant in the denim industry. Reprinted from Ben Amar et al. (2009), with permission from Elsevier.

biological treatment using activated sludge and installed for wastewater originating mainly from denim dyeing operations, is given in Figure 19.2. In this treatment plant, wastewater first flows through acid neutralisation and homogenisation processes in order to decrease the alkalinity to levels acceptable for biological treatment (pH 7–9). The activated sludge process consists of two aerated basins (3 and 4). At this stage of the treatment there is an optional tank, and if necessary a polymeric coagulant is used for removing the dissolved solids in this tank. Then the wastewater enters two parallel clarifiers (5 and 6) and is stored in a tank (7) before being discharged (Ben Amar et al., 2009).

Denim and jeans processing plant wastewater generated from different processing stages, especially dyeing, finishing/washing and rinsing processes, contains a huge amount of pollutants that are very harmful to the environment if released without proper treatment. In Table 19.2, the characterisation of typical denim plant wastewater, as well as indigo and sulphur dyeing wastewater, is summarised. As can be seen clearly from the table, the sulphur dyeing process has higher pollution potential than indigo dyeing, especially in terms of COD and colour parameters (Froneberger and Pollock, 1976; Sahinkaya et al., 2008).

Many attempts have been made to treat textile wastewater using conventional wastewater treatment methods such as chemical coagulation, electrochemical oxidation, filtration and biological treatment (Petrinic et al., 2007; Ramesh Babu et al., 2007; Shaw et al., 2002; Vandevivere et al., 98), but most of these are incapable of treating wastewater up to the discharge limits when applied individually (Lotito et al., 2012). The regulatory limits imposed by important denim producing countries for effluent discharge from denim production plants are shown in Table 19.3 (General Standards for Discharge of Environmental Pollutants; Global Effluent Guidelines; Su kirliliği kontrolü yönetmeliği; Discharge Standards of Water Pollutants; Haque; Malik, 2002; Savin and Butnaru, 2008). Levi Strauss & Co. has also set global effluent regulations, which mandate strict wastewater discharge limits for its supply

| Parameter               | Indigo dyeing<br>wastewater | Sulphur dyeing<br>wastewater | Denim plant<br>wastewater |  |
|-------------------------|-----------------------------|------------------------------|---------------------------|--|
| COD (mg/L)              | 750–950                     | 2500-3500                    | 1500-3100                 |  |
| Colour (Pt–Co)          | 5500-7000                   | 24,000-34,000                | 1147-3547                 |  |
| TSS (mg/L)              | 50-300                      | 100-340                      | 150-300                   |  |
| TDS (mg/L)              | _                           | _                            | 4000-8000                 |  |
| pH                      | 10.5-11.5                   | 10-11                        | 9–13                      |  |
| Conductivity (mS/cm)    | _                           | _                            | 6–12                      |  |
| Total phosphorus (mg/L) | -                           | -                            | 0–3                       |  |
| Total nitrogen (mg/L)   | -                           | -                            | 17–23                     |  |

Table 19.2 Characterisation of denim dyeing process wastewater

chain contractors to ensure specific sustainability. These limiting standards are given in Table 19.3.

Physicochemical technologies for the treatment of textile effluent include several methods of chemical precipitation and adsorption, as well as advanced oxidation processes (AOPs) and membrane processes, both individually and in combination (Allegre et al., 2006). Physicochemical treatment techniques are effective for colour removal but use more energy and chemicals than biological processes (Vandevivere et al., 1998). However, owing to the low biodegradability of most textile industry dyes and chemicals, their treatment by conventional biological systems does not always meet with great success; in fact, most dyes resist biological treatment (Allegre et al., 2006). In some cases, for the adequate treatment of these wastes, decolourisation methods have to be combined and then applied together. The most important effluent treatment techniques are briefly discussed in the following sections.

# 19.3.1 Chemical precipitation

Textile wastewater containing a huge amount of dyestuff together with significant amounts of SS, salts and trace metals can be treated by chemical precipitation (coagulation/flocculation), and certain removal efficiencies can be achieved. Studies of chemical coagulation/flocculation have shown that they are some of the most widely used technologies in textile wastewater treatment. Regardless of the considerable volume of sludge generation, these technologies are still used in developed and in developing countries. Colour removal by coagulation is very effective in some cases, whereas it has failed completely in others.

Using a coagulation process, destabilisation of colloidal or suspended particles is usually brought about by adjusting the solution pH to achieve certain levels of colour and COD removal (Gao et al., 2007; Kim et al., 2004). Water insoluble vat dyes used in denim production are removed by a pretreatment step using coagulants/flocculants like lime, alum, ferrous sulphate and polyelectrolyte, and in the activated sludge process that follows, other contaminants are eliminated. However, the basic disadvantage of physicochemical methods is the production of a large amount of sludge that poses handling and disposal problems (Shaw et al., 2002).

| Parameter            | Turkey <sup>c</sup> | China <sup>d</sup> | Romania | Pakistan | Bangladesh <sup>e</sup> | India <sup>e</sup> | Levi Strauss |
|----------------------|---------------------|--------------------|---------|----------|-------------------------|--------------------|--------------|
| COD (mg/L)           | 250                 | 80                 | 500     | 150      | 200                     | 250                | _            |
| BOD (mg/L)           | _                   | 20                 | 300     | 80       | 50                      | 30                 | 30           |
| SS (mg/L)            | 160                 | 50                 | 350     | _        | 150                     | _                  | 30           |
| $NH_4-N$ (mg/L)      | 5                   | 10                 | 30      | -        | 50                      | 50                 | _            |
| Free chlorine (mg/L) | 0.3                 | 0.5                | 0.5     | _        | _                       | _                  | _            |
| Total Cr/Cr(VI)      | 2                   |                    | 1.5     | 1.0      | 0.5/0.1                 | 2.0/0.1            | 0.1          |
| (mg/L)               |                     |                    |         |          |                         |                    |              |
| $S^{-2}$ (mg/L)      | 0.1                 | _                  | 1.0     | _        | 1                       | 2.0                | _            |
| $SO_3 (mg/L)$        | 1                   | 0.5                | 2       | -        | _                       |                    | _            |
| Oil and grease       | 10                  | _                  | _       | 10       | 10                      | 10                 | _            |
| (mg/L)               |                     |                    |         |          |                         |                    |              |
| Fish acute toxicity  | 4                   | -                  | _       | -        | _                       | 10 <sup>b</sup>    | _            |
| test                 |                     |                    |         |          |                         |                    |              |
| Colour (Pt-Co)       | 280                 | 50 <sup>a</sup>    | _       | _        | 150                     | _                  | а            |
| рН                   | 6–9                 | 6–9                | 6.5-8.5 | 6–10     | 6–9                     | 5.5–9.0            | 6–9          |

 Table 19.3 Effluent discharge limits in some denim producing countries

<sup>a</sup>Qualitative observation.

<sup>b</sup>90 % survival of fish after 96 h in 100% effluent.

°Regulations for cotton textile wastewater.

Regulations for dyeing and finishing wastewater. Regulations for dyeing and finishing wastewater.

In an interesting study, saline industry wastewater was used as a coagulant source for treating indigo dyeing process effluent.  $MgCl_2$  has been reported as an advantageous coagulant for treating textile wastewater, and in this study wastewater was used as a coagulant source. The coagulation process was based on the use of  $Mg^{2+}$  in saline wastewater for charge neutralisation. The colour removal performance of saline wastewater was compared with a known coagulant  $Al_2(SO_4)_3$ . Higher colour removal efficiencies were obtained with saline wastewater. For a 100 mg/L cation dosage, 80% or higher colour removal efficiencies were achieved with saline wastewater (Albuquerque et al., 2013).

In order to overcome some disadvantages of chemical precipitation and to increase the efficiency of the coagulation/flocculation process, a new polymer was synthesised for the treatment of high concentration real reactive dyeing wastewater. In this study, a new polymer flocculant was synthesised using cyanoguanidine and formaldehyde, and applied with alum or ferric salts as inorganic coagulants for the treatment of dyeing wastewater. The applicability of this organic/inorganic flocculant was tested for both synthetic wastewater containing four model reactive dyes (Black 5, Blue 2, Red 2 and Yellow 2) and for the real wastewater containing reactive dyes from the dyeing industry. The results of the study showed that alum/polymer combination improved colour removal up to a 60% efficiency level (Joo et al., 2007).

#### 19.3.2 Biological treatment

Biological treatment processes are generally efficient for BOD and SS removal in textile wastewater treatment, but are largely ineffective at removing colour and conductivity from wastewater. The recalcitrant nature of various dyes, together with their toxicity to microorganisms, make aerobic treatment difficult (Frijters et al., 2006).

In this context, denim and jeans processing wastewater contains a high amount of biodegradable fraction, and the treatment of this biological fraction can be achieved in an activated sludge reactor. Although high COD removal efficiency is possible with conventional wastewater processes, colour and conductivity removal is not so effective, and the main removal mechanism is indicated to be adsorption (Sahinkaya et al., 2008).

Georgiou et al. (2004) conducted a preliminary study to investigate cotton textile wastewater decolourisation using an anaerobic digestion process in a pilot plant scale treatment system. In this study, an anaerobic digestion technique was applied to azo-reactive dye aqueous solutions and cotton textile wastewater, aiming at colour elimination. Anaerobic digestion of cotton textile wastewater without the addition of an external organic substrate led to poor decolourisation results. However, anaerobic digestion using acetic acid as an additive substrate, along with acetate consuming bacteria, seemed to be a very promising technique for the decolourisation of textile wastewater. Besides anaerobic processes, aerobic bioprocesses also have been applied in indigo dye containing textile wastewater treatment. In a study, a continuousstirred tank reactor and fixed film bioreactor were combined for the treatment of indigo dyeing wastewater, and higher colour removal efficiency of about 97.3% was obtained (Khelifi et al., 2008). The low biodegradability of many dyes and textile chemicals indicates that biological treatment will not always be successful in the treatment of cotton textile wastewater, at least in terms of colour removal. Within this context, Pala and Tokat (2002) performed a study for the treatment of cotton textile wastewater, in which powdered activated carbon (PAC) was directly added to the activated sludge laboratory pilot plant. The results of the study proved that addition of PAC directly into an activated sludge system can effectively remove colour from cotton textile wastewater. The highest colour removal efficiency was 77% for the addition of 200 mg/L PAC.

In another study, decolourisation of simulated wastewater containing vat (C.I. Vat Blue 1: indigo) and azo dyes (Reactive Blue H3R and Reactive Red HE 7B) was carried out under anaerobic conditions using mixed bacterial cultures with long hydraulic retention times (HRT). Laboratory scale semicontinuous reactors were operated using simulated cotton dyeing wastewater. In the indigo dye containing reactor, COD removal of 90% and colour removal of up to 95% were achieved. The results indicated the usefulness of semicontinuous reactors for the degradation of recalcitrant compounds such as azo and vat dyes (Manu and Chaudhari, 2003).

The literature on textile wastewater treatment reveals that most denim and jeans production plant wastewater is treated using conventional activated sludge systems due to their known technology and easy maintenance. However, the effluent quality of activated sludge systems is not satisfactory for reuse of the water. Because of this, effluent of biological systems is filtered through membrane systems in order to attain reusable water. In a study, biologically treated wastewater from a cotton thread factory was subjected to nanofiltration (NF) directly, and after a pretreatment stage of ultrafiltration (UF). The plant has a biological treatment system based on the activated sludge process. To verify the possibility of reusing textile wastewater treated by NF, three NF membranes of different pore size (NF90, NF200 and NF270 from Dow FILMTEC) were studied. The NF90 yielded a COD reduction of 99% and the highest salt retention (75%-95%). As the permeate quality obtained with this membrane was satisfactory, long duration experiments were performed with a spiral wound module in order to scale up the system and study the effects of fouling. These experiments showed that the levels of COD removal and salt retention were not significantly affected by fouling, and that a high flux percentage could be retrieved after cleaning. Finally, UF and NF experiences were coupled in order to study the effects of UF as pretreatment in an NF system. In this case, the permeate flux of NF increased greatly (about 50%), and COD concentration in the NF feed was reduced by about 40% (Gozalvez-Zafrilla et al., 2008).

#### 19.3.3 Advanced oxidation

Ozone, UV, hydrogen peroxide, permanganate and photocatalysis with  $TiO_2$  are the most common oxidising agents used in chemical processes used to change the chemical composition of pollutants in textile wastewater. The most important strategy is to produce high amounts of hydroxyl radicals to decompose pollutants such as dyes and chemical auxiliaries. Amongst these oxidants, ozone is the most widely used because of its high reactivity with dyes and good removal efficiencies. However, in some cases it can react slowly and the decolourisation efficiency decreases (Verma et al., 2012).

Arslan et al. (2000) performed a study on decolourisation of simulated dye house wastewater by the application of ferrioxalate photo-Fenton and titanium dioxide mediated heterogeneous photocatalytic treatment processes. In this work, synthetic dye house effluent containing the five most representative reactive dyes used in denim production at a local dye house, and their corresponding auxiliary chemicals, were prepared. Effective degradation of various types of reactive dyes in simulated dye house wastewater was achieved, and according to the results of the study, decolourisation was faster using ferrioxalate-Fenton/UV-A oxidation, whereas the  $TiO_2/UV-A$  process is slightly better at overall UV 280 nm removal.

In another study, Colindres et al. (2010) investigated the ozonation of the Reactive Black 5 dye, one of the most common dyes used in cotton fibre dyeing. The results showed shorter treatment times such as 10 min for treated water of a quality that could be reused for dyeing of cotton with direct and reactive dyes. The big disadvantage of this treated water appeared in the form of accumulated oxidation by-products. When treated water containing these by-products was reused for cotton dyeing, it was found that they affected the colour quality of the products.

UV irradiation is an AOP applied in the treatment of textile effluent. Kusic et al. (2013) studied the decolourisation of dye solutions under UV-C irradiation, and nine different reactive dyes with the triazine group as the reactive centre were used as model pollutants. According to the results of this study, dyes with larger spherical molecular structure, higher masses and fewer rings are more suited to biodegradation, whilst the formation of readily biodegradable by-products, upon reaching 95% decolourisation by UV-C irradiation, is influenced by the size and electrophilicity of the parent dye molecules.

In another study, decolourisation and mineralisation of cotton dyeing effluent containing C.I. Direct Black 22 dyes in wastewater, by means of AOPs, was investigated. The performance of  $UV/H_2O_2$ ,  $O_3$  and pre-ozonation coupled with  $UV/H_2O_2$  processes were evaluated both with synthetic and real plant wastewater. The significant result from this study is that dye bath effluent was more difficult to decolourise than synthesised dye wastewater because of its complex composition. Therefore, it is obvious that lab scale experimental results of AOP applications in denim textile wastewater treatment should be supported by pilot and full scale results (Shu and Chang, 2005).

Because of the recalcitrant nature of synthetic dyes and the high salinity of wastewater containing dyes, conventional biological treatment processes are ineffective for the discharge or reuse of water from production processes. Photocatalysis is another increasingly attractive approach for degradation of textile dyes.  $TiO_2$ ,  $V_2O_5$ , ZnO,  $WO_3$ , CdS and  $ZrO_2$  are the various types of semiconductors used to achieve higher removal efficiencies, but  $TiO_2$  mediated photocatalytic oxidation has been applied more extensively for dye studies because of its low cost, stable nature and optical absorption in the UV region (Han et al., 2009; Rauf and Ashraf, 2009).

Although AOP appears to be an important alternative for degrading textile wastewater, oxidation by-products and operating costs have limited its feasibility at an industrial scale. However, it is possible to take advantage of a combination of AOPs and biological processes. In these systems, AOP is used to improve the transformation of recalcitrant compounds in highly biodegradable by-products so that degradation of the residual organic carbon might be feasible using biological processes. Within this context, a study tested the applicability of a ferrous oxalate mediated photo-Fenton pretreatment combined with aerobic systems to mineralise indigo dyes, and it was reported as a promising alternative to existing decontamination methods (Vedrenne et al., 2012).

#### 19.3.4 Adsorption

Another popular method of treating textile wastewater is adsorption technology. Activated carbon is the most commonly used adsorbent and can be very effective for many dyes. The limitations of this technology are the ecofriendly disposal of spent adsorbents, excessive maintenance costs and the need to pretreat the wastewater to reduce SS to within an acceptable range before feeding the adsorption column. For these reasons, field scale application of adsorption technology has satisfied the requirements for neither the colour removal of textile wastewater nor other water and wastewater treatments (Verma et al., 2012).

Paul et al. (1996) have studied the dye adsorption capabilities of a wide variety of natural waste materials. Ahmad and Hameed (2009) have performed a study with a newly developed activated carbon from bamboo waste (BAC) for reduction of colour and COD in real dyeing wastewater from a cotton textile facility. The purpose of this work was to prepare BAC by a chemical activation method using phosphoric acid and to assess the possibility of using this adsorbent for the treatment of cotton textile wastewater. The wastewater samples were taken from the discharge point after the activated sludge treatment unit in the facility. This study revealed that bamboo is a promising precursor in the preparation of activated carbon for reduction of colour and COD from cotton textile wastewater.

A recent research trend in adsorption studies of textile wastewater treatment is the use of nanomaterials and nanocomposites as adsorbents for colour and COD removal. The removal of heavy metals, anions, colour and COD from cotton textile wastewater was investigated and polyaniline (PAn), polypyrrole (PPy) and their blends and nanocomposites with rice husk ash (RHA) were studied and compared. It was found that PAn/RHA and PPy/RHA could be used as effective adsorbents in the removal of anions, heavy metals, colour and COD from cotton textile wastewater. Nanocomposite regeneration was also performed using NaOH, deionised water and H<sub>2</sub>SO<sub>4</sub>. After regeneration, the nanocomposites were used for wastewater treatment (Ghorbani and Eisazadeh, 2013).

In another study, biodegradable hollow zein nanoparticles with diameters less than 100 nm were developed to remove reactive dyes from simulated postdyeing wastewater originated from the colouring of cellulosic materials such as cotton and rayon. In this research, biodegradable zein nanoparticles showed high adsorption capacities for dyes. Hollow zein nanoparticles showed higher adsorption for Reactive Blue 19 than solid structures, and the adsorption amount increased as temperature decreased, pH decreased or initial dye concentration increased. The adsorption capacity was much

higher than that of various biodegradable adsorbents developed to remove reactive dye. It is suggested that hollow zein nanoparticles are good candidates for removing reactive dye immediately after the dyeing process (Xu et al., 2013).

#### 19.3.5 Membrane filtration

One of the most commonly known methods in the treatment of textile effluent is filtration technology. Filtration methods such as UF, NF and reverse osmosis (RO) have been used for water treatment, reuse and chemical recovery (Verma et al., 2012).

Within membrane technologies, ceramic membranes have become more attractive due to having better chemical and mechanical properties than those of polymeric membranes. Ceramic membranes are preferred for the treatment of the complex structure of textile effluent, and in particular dye bath effluent, because of their more resistant and suitable structures. With this point of view, a study was conducted using a multichannel UF ceramic membrane to decolourise Reactive Black 5 dye at different concentrations (50 and 500 mg/L). According to the results of this study, 79.8% rejection efficiency was obtained. With an increase of dye concentration, a decrease in rejection performance was observed (Alventosa-deLara et al., 2012).

The performance of different types of commercial membranes for the treatment of denim and jeans wastewater has been tested and reported in the literature. Jiraratananon et al. (2000) investigated the initial performance of commercially available negatively charged NF membranes (ES20, NTR-729HF and LES90) in the treatment of effluent consisting of reactive dye and salt. The feed solutions consisted of 180 and 300 ppm of reactive dye. The membrane experiments were performed using a thin channel circular type cross flow module under 10 bar of feed pressure. ES20 and LES90 membranes achieved higher salt rejection than NTR-729HF. LES90, however, suffered a great loss in salt rejection as the concentration of NaCl increased.

Due to water scarcity problems, wastewater reuse is an important option in the treatment of textile wastewater. In order to reduce the quantity of disposed water and at the same time reuse treated water, cotton textile effluent was treated by NF membrane. A detailed investigation of the quality of the treated wastewater was performed at various operating and feed solution conditions, even at extremely high recoveries and feed concentrations. An excellent performance for the NF membrane was seen, and this type of membrane can achieve complete decolourisation of the dye effluent while reducing total salt concentration by more than 72% (Avlonitis et al., 2008).

In another study, the performance of a pilot wastewater treatment plant consisting of UF and RO units was investigated. The textile industry considered in this study was mainly using reactive dyes for printing and dyeing of cotton. According to the results of this study, the quality of the wastewater was improved by UF, but its effluent still did not meet discharge limit specifications. After UF, the RO process was employed to meet the required specification, and thereafter the treated wastewater could be reused in the washing process of the plant. Another important point reported in this study is that the UF step guaranteed good performance by, and prolonged the lifetime of, the RO membrane (Sostar-Turk et al., 2005). In textile wastewater treatment, membrane processes are considered superior to other treatment processes, especially with higher colour concentrations and COD removal efficiencies, as well as required reuse of treated wastewater and chemicals in production processes. Khouni et al. (2011) examined the decolourisation efficiency of textile effluent using different processes: coagulation/flocculation, enzymatic catalysis by a commercial laccase, and NF. A series of experiments was conducted on laboratory prepared wastewater that combined two chemically reactive dyes (Bezaktiv Blue S-GLD 150 and Novacron Black R), auxiliaries and chemicals used in the dyeing of cellulosic fibres. According to the results of this study, the NF process was found to be the most efficient in colour removal from textile wastewater, and the permeate obtained could be reused in the dyeing process in the textile industry.

#### 19.3.6 Membrane bioreactors

The membrane bioreactor (MBR) process is a combination of conventional activated sludge processes with membranes, and has become an attractive option for the treatment and reuse of municipal and industrial wastewater from various industries including food processing, slaughterhouses, pulp and paper, chemical production, pharmaceuticals, mining and metal production, textiles, etc.

Yigit et al. (2009) investigated the performance of a pilot scale MBR system for the treatment of highly concentrated mixed wastewater from wet processes (dyeing, finishing and sizing) of a denim producing textile facility. The MBR system contained a submerged hollow fibre membrane module in the aeration tank and was operated aerobically for about 3 months on-site at a continuous flow mode. The results indicated that complex and highly polluted denim textile wastewater could be treated very effectively by MBR systems. The high colour values were significantly reduced, indicating that MBR effluent could be reused in production processes.

#### 19.3.7 Combined methods

In textile wastewater treatment, the use of combined processes has been suggested to overcome the disadvantages of individual processes and satisfy the regulatory discharge limits for receiving environments. This fact is also obvious for denim and jeans processing wastewater, and due to the complexity of jeans washing wastewater, any single treatment method would be inadequate.

Ben Amar et al. (2009) investigated the treatment and reuse of wastewater originated mainly from the dyeing operations of a denim facility. In this study, the wastewater was treated by an activated sludge plant to meet discharge standards; the schematic diagram of a plant in the denim industry is given in Figure 19.2. The performance of the activated sludge treatment plant with either the NF or RO membrane process to recycle and reuse water was also evaluated. Study results indicate that in this pilot scale membrane process application, water reuse quality was achieved, and it was reported that NF is an appropriate tertiary treatment for the denim textile industry.

Catalytic thermal treatment (thermolysis) accompanied by coagulation has been used for the removal of COD and colour from composite cotton textile wastewater and reported as another alternative for treatment.  $CuSO_4$ ,  $FeSO_4$ ,  $FeCl_3$ , CuO, ZnO and PAC were used as catalytic agents during thermolysis. Similarly during coagulation, aluminum potassium sulphate at a coagulant concentration of  $5 \text{ kg/m}^3$  was found to be better than any of the other coagulants tested, namely commercial alum,  $FeSO_4$ ,  $FeCl_3$  and PAC. The results of the study revealed that the application of coagulation after thermolysis is most effective in removing nearly 100% of COD and colour at a lower dose of coagulant (Kumar et al., 2008a).

In another work, the removal of organic compounds and colour from a synthetic effluent simulating cotton dyeing wastewater was evaluated using a combined process of Fenton's reagent oxidation and biological degradation in a sequencing batch reactor. This study showed that chemical pretreatment must be carried out under operating conditions that increase wastewater biodegradability, as the overall removal efficiencies are considerably higher than those corresponding to conditions that maximise colour removal (for example), although there is a very small penalty in the overall colour removal performance (Kumar et al., 2008b).

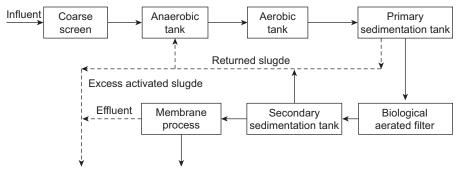
In a good example for the use of combined methods in denim wastewater treatment, ozone oxidation was carried out to assess a combination of biological and chemical oxidation. A treatability study of highly polluted and recalcitrant azo-reactive dye baths from cotton textile dyeing processes was conducted using fixed and upflow fluidised bed type reactors packed with brown coal. COD removal efficiencies ranged from 70% to 93%, and up to 99% colour removal was attained. Brown coal is an inexpensive material, and the system has economic and operational advantages over treatment options such as other AOPs (Baban et al., 2010).

# 19.4 Wastewater recovery and reuse

The textile industry is faced with increasing production costs and problems of water supply and wastewater discharge. Water is the principal medium in the textile industry for the removal of impurities and the application of dyes and finishing agents. Amongst the largest industrial consumers of water, the textile industry, and in particular the denim and jeans processing sector, is a prime candidate for the development of intensive water recycling strategies and methods to recover valuable chemicals and water. In typical textile manufacturing, for each ton of fabric produced, 20–350m<sup>3</sup> of water is consumed (Brik et al., 2006). Therefore, a systematic approach to water management for controlling water input, consumption and output, as well as gearing all water related activities to one another, is required for this industry (Van der Bruggen and Braeken, 2006).

In a large scale textile processing sector, the applicability of a  $600 \text{ m}^3/\text{day}$  pilot plant with a biological treatment system and membrane process in the reclamation of the wastewater was investigated. The flow diagram of this textile wastewater recovery pilot plant is given in Figure 19.3.

In this wastewater pilot plant, the first process is a screen filter, after which the effluent goes through a two stage anaerobic–aerobic treatment system. After primary sedimentation, the wastewater is passed through a biological aerated filter process, and then through the second sedimentation tank. Lastly, the wastewater was filtrated by a



Wastewater treatment plant reclaimed water

**Figure 19.3** Flow diagram of the textile wastewater recovery pilot plant. Reprinted from Lu et al. (2010), with permission from Elsevier.

membrane process with the aim of reusing this wastewater in the dyeing and finishing processes at the textile plant. It was reported that the treated effluent could be used for dyeing and finishing processes except for light colouration applications, with a total cost for wastewater reclamation of approximately USD 0.25/m<sup>3</sup> (Lu et al., 2010).

Pollution prevention is the main aim of modern environmental management and is gaining in importance over the 'end of pipe' treatment approach. In this context, segregating waste streams from dye baths having strong pollutant characteristics could become highly profitable, and treatment and reuse of relatively clean streams for process purposes could become feasible. For pollution prevention in denim and jeans production plants, the main issues to be considered are minimisation of chemical, dye and water usage; substitution of chemicals; prevention of leakages and other good housekeeping actions (Maryan and Montazer, 2013).

Novel strategies such as the standing bath technique and repeated reuse of indigo vats without replenishment were studied by Deo and Paul (2004), and a series of different shades was developed on denim fabrics. Maryan and Montazer (2013), performed a study of denim garments and one step bio-desizing and biowashing, producing a garment with a worn-out appearance though a biotreatment process using amylase, cellulase, laccase and their combinations. The results indicated successful treatment with one step bio-desizing and enzymatic biowashing using a mixture of amylase, cellulase and laccase. The colour obtained on samples treated with all three enzymes did not differ significantly from that of a bio desized garment treated with cellulase, laccase or cellulase/laccase. Combining the different processing stages reduced water and energy consumption, thereby increasing the production yield while decreasing production costs.

Wastewater often requires extensive treatment before it can be discharged. Further purification to obtain water of a quality fit for reuse is often a realistic option in terms of the additional treatment cost versus the benefits of using recycled water. Three advantages are to be taken into account: (1) recycled water is a supplementary and reliable source of fresh water, which can add to existing sources or replace them; (2) the net volume of water consumed decreases drastically; (3) the volume of wastewater

to be discharged (and consequently, also costs and taxes) decreases; permits may no longer be impediments to a company's expansion (Van der Bruggen and Braeken, 2006).

The main challenge for the textile industry today is to modify production methods so that they are more environmentally friendly at a competitive price, by using safer dyes and chemicals and by reducing the cost of effluent treatment/disposal. Another option is to regenerate wastewater and recycle it as process water, both to save a valuable resource and to control pollution (Ramesh Babu et al., 2007).

Membrane processes are now being successfully used to obtain water of recyclable quality (Shon et al., 2006). Membrane based separation processes have gradually become attractive alternatives to conventional separation processes in the treatment of wastewater. The application of membrane filtration processes not only enables high removal efficiencies, but also allows reuse of water and some of the valuable waste constituents (Brik et al., 2006; Fersi et al., 2005).

Allegre et al. (2004), worked out a process for the treatment of cotton dyeing wastewater using reactive dyes that consists of four steps: prefiltration, neutralisation, NF and RO. Industrial effluent that resulted directly from facility dyeing was used in the study. Every step of the process was studied separately, as well as together, so as to optimise the whole process. An industrial process was developed that provides not only reuse of wastewater but also recovery of salts and chemicals. The water and the salts recovered were tested for reuse in a new dyeing operation, and prosperous results were obtained.

Besides water reuse, chemical recoveries could also be an alternative solution for minimising both the environmental hazards and the production costs of denim producing plants. Porter (1990) has reported the recovery of caustic and indigo dye from denim dyeing effluent. For caustic recovery from the mercerisation process, a water evaporation process could be used when the caustic concentration was above 2%-3%. An important disadvantage of these systems, however, is the build-up of fabric impurities in the caustic recovered from the mercerisation process. To solve this problem, a UF membrane is needed before the evaporation process. Recovery of indigo dye with the UF process is also reported in this study, where a multistage membrane system was used. Before the membrane system, a coarse filter was employed to remove impurities. The interesting outcome of the study was that the indigo dye recovery system has paid for itself in less than 2 years and operates with minimal problems.

In a different study, the potential recovery and reuse of the solid part of indigo dye textile effluent as a commercial by-product was investigated. For this, indigo dyeing wastewater was first filtered, and then the solid part was adsorbed onto palygorskite clay and used as a pigment called Maya blue. This work is a very good example of synthesis of a potential commercial by-product from waste material (Wambuguh and Chianelli, 2008).

As denim jeans washing processes consume huge quantities of water and energy, combining different processing stages can reduce water and energy consumption and thereby increase the production yield and decrease production costs. As mentioned earlier in this chapter, the bio-desizing and biowashing of denim garments has been successfully carried out in one step using amylase, cellulase and laccase in combination, with no remarkable colour change when compared with a desized sample treated with cellulase and laccase. Meanwhile, both operating time and energy consumption have been reduced significantly. The samples treated with cellulase and laccase enjoy lower creasing with reduced weight loss. The nondesized samples treated with amylase/ cellulase and laccase show properties similar to those of samples treated in two steps of bio-desizing and biowashing. Also, fabrics treated with all three enzymes indicated decreased back staining with reasonable abrasion resistance up to 10,000 cycles. This can be prolonged by the application of other enzymes such as lipase to extend desizing quality and improve colour reduction, or by using other materials such as silicone softeners to enhance other characteristics of the garment such as the handle (Maryan and Montazer, 2013).

#### 19.5 Case studies

Although lab scale experiments have been performed and their results have been published in the literature for the denim and jeans processing wastewater treatment, pilotscale and full scale applications are still extremely limited. Some of these case studies are summarised below.

The textile industry is developing quite rapidly and becoming one of the most important industries in developing countries, from an economic point of view. In a good example of a denim fabric production wastewater treatment study, laboratory experiments were conducted, and based on lab test results, a facility scale for treating the wastewater was established. The textile plant producing denim fabric uses only indigo dyes in its dyeing processes. According to the laboratory experiments, effluent quality met regulatory discharge requirements if treated using anaerobic and aerobic systems, and according to those results, the full scale plant was designed, built and operated, with a designed flow rate of 20 m<sup>3</sup>/h. The biofilter was selected as an anaerobic process with an HRT of 24 h. The aerobic process was determined, and extended aeration with the HRT was also 24 h. When the system was complete, steady state conditions were achieved. From 4 months of operation, COD, BOD and colour removal were 87%, 93% and 90%, respectively. Currently, treated effluent is recycled back to the denim processing plant and used in washing machines (Setiadi et al., 2003).

In another case, a full scale application of jeans washing water treatment has been developed. The treatment process combines chemical coagulation, hydrolysis/acidification and Fenton oxidation and was tested for jeans washing wastewater treatment. The wastewater was obtained from a jeans washing industrial zone with 11 small companies, and the effluent from all of the companies was collected at a wastewater treatment plant with a system capacity of 2700 t/d. The sample raw wastewater was drawn from the equalisation tank and then screen filters were used to remove the large SS prior to the next step.

After the pretreatment by screen filters, the wastewater was homogenised in an equalisation tank. Injected with chemical coagulant into the pipe ahead of the feed pump, the wastewater was lifted to an inclined board sedimentation tank, after which the sludge was pumped into sludge thickener, and the supernatant flowed into a hydrolysis/acidification tank. The effluent then was oxygenated by Fenton oxidation and filtered using a sand filter. The use of a sand filter as a final polishing process was based on the consideration that jeans washing companies hoped to reuse the treated wastewater in their jeans washing operations, because water quality requirements are not very rigid in some production stages such as rinsing processes. The combined system was run continuously for 1 year, and the results of the study showed that the effluent quality met the required standards for textile wastewater discharge (Wang et al., 2008).

#### 19.6 Future trends

Denim is the most extensively produced and used textile apparel, but high energy and water consumption costs have affected the denim industry's overhead, and today the industry has chosen relocation to developing countries as a preferred way of reducing production costs. To remain dominant in the textile market, denim producers will need ecofriendly developments that result in ecofashion products. Very limited work has been reported on the treatment of denim and jeans production plant wastewater for reuse in production plants.

Considering the industry's dependence on cost effective technologies for wastewater treatment, a much greater volume of research must be conducted to determine the treatment technologies that best achieve discharge limits and allow for water reuse. From this point of view, a greater number of alternative treatment technologies also must be investigated and assessed for effectiveness. Establishing the effectiveness of these novel or hybrid treatment technologies also requires that research is carried out for full scale denim and jeans processing wastewater treatment with these technologies. Finally, for the environmental sustainability of denim products, the industry needs further research into the development of green chemistry processes.

## 19.7 Conclusion

Denim and jeans production plant wastewater presents a substantial environmental problem because of its complex nature and high volume. Considering the number of jeans produced per year, the serious environmental damage caused by this industry is easily understood. Wastewater can be treated by several methods using biological or physicochemical processes, but it is not easy to decompose this type of wastewater so that it meets the discharge levels established by regulatory standards. However, a comprehensive treatment process that enables reuse of wastewater and chemicals in the production process is the preferable alternative in terms of environmental and economic considerations. In addition, pollution prevention by such in-plant measures would lead to significant reductions in water and energy consumption.

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# Environmental impacts of denim manufacture



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# 20.1 Introduction

Denim, especially blue jeans, is the biggest single textile product type sold around the world. This is because of its popularity in all geographic regions, social strata and age groups. The production chain is optimised for bulk production and with the capacity to meet this global demand. This means that the overall environmental impact of denim manufacture is significant. Improvements in each step of denim production offer potentially significant reductions in overall environmental impact as well as cost saving for the industry.

In assessing the environmental impact of denim manufacture, it is important to take a holistic approach that accounts for all of the activities involved in the creation of a product, such as raw material extraction, manufacturing, transportation, use and disposal. A standard approach is Life Cycle Assessment (LCA), which is internationally recognised in standards such as ISO 14040 and 14044 (Muthu, 2014). There are four key stages in LCA:

- Goal and scope definition.
- Inventory analysis.
- · Impact assessment.
- Interpretation.

The first stage is critical in establishing the boundaries of the LCA, for example whether the study includes all production, distribution and use stages for the product from 'cradle to grave', including how finished products are used and then disposed of by consumers. Inventory analysis includes categories such as energy requirements, raw material needs, emissions (to air, water and land) and waste related to production of raw material and finished products. Life cycle impact assessment evaluates the potential environmental impacts of a product throughout its life, whilst interpretation identifies the most significant types of impact and makes recommendations for improvement (Escamilla and Paul, 2014).

In 2007, Levi Strauss & Co. conducted an LCA study to assess the environmental impact of a pair of Levi's jeans from cotton seed to landfill. This study has provided insights on the environmental impact caused by jeans outside the bounds of the direct sphere of influence of the company. The environmental impact was assessed in the

following categories, which environmental scientists and LCA experts used to calculate overall environmental impact:

- · Contribution to climate change: quantifies amount of greenhouse gas emissions.
- · Energy use: quantifies how much energy is used in production.
- · Renewable energy use: percentage of energy use from renewable sources.
- · Water consumption: measures water usage in cubic metres.
- · Land occupation: amount of land needed to produce a product.
- Qualified sustainably grown fibre content: a content analysis of fibres grown under a recognised cultivation program to address areas of sustainability.
- Waste generation: surveys the primary solid waste content during production and finishing.
- · Materials efficiency: how much of the primary materials end up in the final product.
- Recycled content: assesses the amount of materials used from post consumer recycled sources.
- Land transformation: amount of land transformed from its original state by production.
- · Eutrophication: measures the impact of harmful nutrients discharged to freshwater bodies.

From this work, an idea was born in 2008 to develop a life cycle based product environmental impact assessment method (E-valuate) that relied heavily on primary data, making it both actionable and dynamic. This method was created in the hope that key stakeholders could be informed about how their business decisions influence the environmental attributes of the products they design, produce, merchandise and sell.

It was observed that the greatest opportunity to reduce the environmental impact of a new or existing product occurs during the design phase of its life cycle. Therefore, the primary objective of this LCA approach was to provide designers and developers with the information they need to produce more sustainable products. A secondary objective was to provide a scientific method to support any claims of environmental improvement of products. Although not an initial objective of this effort, it was later realised that the methodology also provides a rigorous means to communicate environmental performance to suppliers (Levi Strauss & Co.). Based on these studies, Levi Strauss & Co. has later launched the Water<Less and Waste<Less collections.

Another potential output of a technique such as LCA is information for consumers about the environmental impact of denim production, and labelling such as eco-labels that identifies products that have better environmental profiles. Since they do not have knowledge of all the relevant aspects of denim production and how they can be optimised, consumers do not want to be flooded with figures and scientific details, but need a clear message that allows them to make an informed choice between different products (Schrott). In practice, there has not been enough standardisation in eco-labelling, which has been both confusing and misleading. Eco-labelling needs to be based on established methods such as LCA, and linked to Best Available Technology (BAT) criteria and sustainability standards such as ISO 26000.

Other techniques have been developed, such as Eco-Efficiency Analysis, which combines ecological and economic parameters, developed by BASF of Germany. This methodology has been applied to denim production to assess such issues as the different kinds of indigo used (Saling et al., 2002). So, in addition to a greater concern about the environmental impact of products, it is important to be aware that consumers are also increasingly interested in the social and economic impacts of the way products

are manufactured, such as the working conditions of those involved in the industry. This broader concept of sustainability is enshrined in the ISO 26000 standard for social responsibility and sustainability. In the future, the concept of eco-denim will need to account for these wider social and ethical concerns.

Whilst there are variants to produce special effects in denim fabrics, the standard manufacturing and distribution process for denim is as follows:

- Cotton production (including growing and harvesting).
- Yarn production (including spinning and warping).
- Warp yarn dyeing (including dyestuff and auxiliaries production and use).
- Sizing (including size production and use).
- Weaving.
- · Flat fabric finishing.
- Cutting and sewing (garment manufacturing).
- Garment washing/finishing (including the production and use of chemicals, auxiliaries, enzymes, etc.).
- · Retail (marketing, logistics/distribution, sales outlets).
- Use by consumers (including laundering).
- End of life (disposal or recycling/reuse).

As noted, it is important to look at the entire life cycle of the product including raw material production, distribution and sale, use by consumers and the end of the useful life of the product (recycling or disposal). Current LCA studies identify the washing of jeans, both during the production process and also by consumers during use, as having the greatest environmental impact. Manufacturers also have a responsibility to educate and inform consumers about washing clothing in a more environmentally friendly way (by the use of shorter, lower temperature washes), as well as to manufacture apparel that can be cleaned effectively at lower temperatures and minimises wastewater residue.

# 20.2 Cotton production for denim

The most important raw material in denim production by volume and value is cotton, and denim accounts for nearly 20% of global cotton production. As a natural product, the quality of cotton varies depending on its geographical origin as a result of different soil and climate conditions, and from season to season. As a result, the skilled mixing or blending of different fibre varieties is necessary to ensure consistent raw material quality as the basis for good product quality at the end of the production chain. This need for quality can conflict with environmental needs. As an example, good quality cotton fibre may depend on extensive irrigation, the use of fertilisers and various kinds of pest control. Globally, cotton production can be segmented into:

- · Conventional cotton farming systems.
- Integrated pest management (IPM) systems.
- Organic cotton production.

The environmental pros and cons of each method are compared and discussed in detail in the literature. It is important to be aware that organic production may not

always be the best option, if conventional and IPM systems make the best use of scare land resources and produce the highest yields. On the other hand, all support processes and products used to optimise cotton yields must be harmless to the environment as assessed through LCA, and should not have an intensive energy consumption or carbon footprint. It is important to promote the use of chemicals that are not harmful to the environment and that biodegrade to leave harmless residues. In addition, it is essential to optimise dosages of fertilisers to avoid excessive consumption of chemicals that may be environmentally damaging to produce and use.

One important aspect of cotton production is recyclability, and at the end of life of a garment, there are many possibilities for recycling it. High quality cotton fibres may be converted to superabsorbent polymers by chemical modification, and can be used for the production of medical textiles such as diapers, incontinence products, etc. This may not apply to cotton from denim that was previously dyed and finished, but in that case the denim may be triturated and used for the production of nonwoven felts to be used as thermal and acoustic insulation materials in automobile and construction sectors. It has also the potential to be converted into art and drawing paper, by proper dissolution and further deposition of the pulp. It may also be possible to produce cellulose in powder form, which can be used as fillers or for blending with other polymers to develop composite materials (Schmidt and Paul, 2014).

Denim cotton can also be used as a raw material for developing new types of regenerated cellulosic fibres. Cotton can be recycled via the lyocell process (Firgo et al., 1996) by dissolving used cellulose material and spinning a fresh cellulosic fibre from *N*-methylmorpholine *N*-oxide as a highly recyclable solvent for the spinning process. The lyocell fibres can be modified by the nozzle structure and other spinning conditions, and by adding products to the fibre production process, including crosslinking agents, softeners and other modulators. In the lyocell process, recycled cotton, other cellulosic textiles, newspaper or wood material can be mixed with fresh cotton to make cellulose yarn of appropriate quality for production of denim or any other cellulose based textiles.

The benefits for environmental and sustainability parameters can be calculated for pure lyocell fibre denim and several blends such as 50:50 cotton/lyocell, compared with those of 100% fresh cotton using standard cotton (from Cotton Inc., United States) and lyocell (from Lenzing AG, Austria) production process parameters. In the case of a 50:50 blend of cotton and lyocell, the saving would be about 50% of current energy use in conventional cotton growing and harvesting, as well as 50% of the chemicals such as fertilisers that are needed for cotton cultivation. Transportation costs and environmental impacts are comparable to those of traditional cotton production. Yarn production (spinning) from cotton/lyocell blends is well established and cost effective, with only the addition of extra spinning oil required to ensure an efficient process.

# 20.3 Dyes for denim dyeing

Denim is mostly associated with blue jeans and characterised by the typical blue colour of indigo. As a result, indigo accounts for about 70%–80% of all dyestuffs used in denim production. The second most important colour is black, followed by

minor colours used to produce various fashion effects. To achieve the wash down effect required for most denim jeans, ring dyeing of the substrate fibre is used. The core of the fibre stays undyed (white), and only the surface of the yarn is dyed. Abrasion of the outer coloured covering of the yarn, later in the production process, exposes the white core of the fibre to produce the typical wash down or vintage effect. In the future, environmental requirements may increase the demand for denim that is fully dyed with optimised fastness of the dyed fabric. These products would potentially be simpler to manufacture and easier for consumers to wash at low temperatures.

The most important dyestuff for denim is indigo (C.I. Vat Blue 1), followed by sulphur black (C.I. Sulphur Black 1). Direct and reactive dyes are used in garment dyeing. Better fastness and a preference for a clean (rather than vintage) denim look, as well as for colours other than blue, may increase future demand for reactive dyes. This might also reduce the process gap between denim and the continuous dyed fabric products.

#### 20.3.1 Indigo dye

Indigo is available as both a natural and synthetic product. Natural indigo is extracted from various plants growing in tropical and subtropical areas of the world. Optimised indigo plant growing and extraction into a powder dyestuff product, compared with optimised chemical dyestuff production, is a clear example that natural production of dyestuffs is not necessarily more environmentally friendly than synthetic production (Schmidt, 1997).

The use of natural indigo dye for denim requires significant land area for the cultivation of plants such as *Indigofera tinctoria*, mostly grown in India and other subtropical regions, that contain the indigo dyestuff in 3%–4% of the plant by weight. A precursor of the chromophoric system, named indican, is fixed in the plant via a sugar type molecule bridge. This has to be cleaved by fermentation to release the indican that forms indigo molecules in the presence of air. The indigo molecules form the water insoluble pigment used as vat dyestuffs. Only 70%–80% of the dyestuff content can be extracted from the plant material, by the use of hot and strong alkali in a reductive extraction medium. The crude indigo dyestuff from plant extraction also has to be further purified from small particles out of organic plant material, which might otherwise cause problems in continuous indigo dyeing machines. This process means the energy balance of growing, harvesting and extraction of natural indigo to achieve pure dyestuff material is negative in comparison with a fully automated indigo dyestuff synthesis.

For economic reasons, the alkali used for the extraction procedure is not a highly purified chemical substance, but mostly a crude material that is slightly purified following its use in other industrial processes. This alkali normally contains a significant amount of heavy metals that mostly stay with the dyestuff during concentration. This heavy metal contaminated natural dyestuff is put into the indigo dyeing machine. Under the reductive and alkaline dyeing conditions, heavy metal ions exhaust onto the cotton fibre together with the dye, and remain after washing due to their high affinity for cellulosic fibres. The presence of heavy metal traces compromises product quality and may be regarded as unacceptable by some consumers.

There are significant quality variations between synthetic indigo dyes, with variations of 5%-20% in byproduct content that cause problems in subsequent wastewater treatment. The cheapest formulation is often (dedusted) powder, but this can pose an inhalation safety hazard for dye house workers. Dust free alternatives are Indigo Granular and Indigo Paste, a slurry of 20%-30% indigo by weight in water, which are both free of small dust particles that might otherwise be inhaled by dye house workers.

The latest development in the indigo market is a pre-reduced form of indigo developed by BASF as 20% solution that was launched to the global market by DyStar of Germany as 40% solution. This product is manufactured by catalytic hydrogenation from crude indigo (Blackburn et al., 2009). It is available as a product containing 20%–40% indigo by weight. This concentration process requires additional energy and cost, but eliminates volatile components from the dyestuff solution. The amount of aniline, a starting material in indigo synthesis, can be reduced to significantly below 1% of the dyestuff liquor. The aniline is then below the concentration that can be detected in the final product, as required by several eco-labels.

Indigo as vat dye has to be reduced by a reducing agent so that it can be converted into the water soluble leuco form that exhausts onto the cotton fibre. After the exhaustion phase in the dye bath liquor, the yarn needs to be aired to oxidise the leuco form of indigo and fix it as an insoluble pigment on the fibre. After the airing, the yarn passes through a second dye bath box with an alkaline and reductive medium. This process will be repeated five to eight times to ensure a strong ring dyeing process with indigo fully fixed on the surface of the yarn. This means repeated use of sodium hydrosulphite as a reducing agent to reduce the oxidised indigo after the airing phase. The final product derived from hydrosulphite use is sulphate, which is not poisonous but is corrosive against concrete. This creates problems in the treatment and reuse of wastewater.

Reusing of indigo dye baths for shade development on denim fabrics, instead of using fresh dye baths, could enhance the economic and environmental viability of indigo dyeing. It was found that there were no significant differences in colour yield between reused and fresh dye baths up to a certain level of reuse (Deo and Paul, 2004a). Additionally, repeated use of an indigo vat of very high concentration provided a wide range of lighter shades on denim fabrics, with a considerable cost saving, in the meantime offering the possibility of reusing the fully exhausted bath by replenishing (Deo and Paul, 2003, 2004b).

#### 20.3.2 Sulphur dyes

Sulphur black, the most important non blue dyestuff in denim, also must be reduced by a reducing agent into water soluble leuco form. Sulphur dyes are more easily reduced (redox potential) and more soluble than indigo dyes. Therefore, weaker reducing agents can be used and dyeing with sulphur black can be achieved with only one reduction/airing production cycle (Bechtold et al., 2000b).

Most of the cheap sulphur based reducing agents such as sodium sulphide have been banned due to toxicity. Glucose is now often used as the most environmentally friendly reducing agent for sulphur dyes. The reducing agent causes high chemical oxygen demand (COD) content in the wastewater, but the sugar products ending in the wastewater can be easily mineralised by bacteria in the biological segment of a wastewater treatment plant, ending up as carbon dioxide in the atmosphere (Teli et al., 2001).

The dyeing procedure with other sulphur dyes is similar to that of sulphur black. All sulphur dyes are oligomeric in character, with different sulphur containing structures. The chemical structures of the dyes are based on the raw material used as well as on synthesis conditions. The use of baking to produce sulphur dyes generates more byproducts than in other dyestuff classes, which then have to be treated in wastewater.

A groundbreaking eco-efficient technology from Archroma of Spain involving pre-reduced sulphur dyes is Advanced Denim which combines leading edge technologies with environmental and health benefits. It significantly reduces water use, power consumption and cotton waste, as well as totally eliminating the wastewater problem. More importantly, the visual effects and finishes made possible by Advanced Denim are often beyond the capabilities of conventional dyes.

#### 20.3.3 Natural dyes

There has been research into supplementing indigo with the use of natural dyes. One example is the dyeing of denim fabric with onion extract using eco-friendly natural mordants such as harda, tartaric acid and tannic acid, instead of using metallic mordants. It was also found that denim fabric dyed with turmeric and Indian madder using natural mordants or without any mordants exhibited wash, light and crocking fastness properties comparable to denim dyed with metallic mordants such as copper sulphate and stannous chloride. Techniques such as these have the potential to promote totally eco-friendly natural denim wear that is dyed using natural dyes without any metallic mordants. Even though it is highly improbable that natural dyes can ever replace synthetic ones, natural dyed denim wear can find some niche markets, especially for children and women (Deo and Paul, 2000, 2004c).

# 20.4 Dyeing auxiliaries

#### 20.4.1 Reducing agents

All dyeing processes using indigo, vat and sulphur dyes need a reducing agent in the dyeing process to form the water soluble leuco form that exhausts on the substrate and is then oxidised to the water insoluble pigment that gives the appropriate level of fastness. Significant amounts of reducing agent are needed to ensure full reduction of the dyestuff and appropriate solubility and homogeneity for optimum dyeing. Several reducing agents are used in industrial scale production. Besides cost and reductive strength (redox potential), an important consideration is environmental impact, especially potentially harmful residues in wastewater after dyeing.

Sodium hydrosulphite is still the most common reducing agent for vat dyes, but can pose a potential fire risk as well as requiring treatment as a wastewater residue. Organic sulphites have been used as alternative reducing agents, but have not been successful in denim due to problems such as higher cost and limited application (redox potential). BASF and DyStar have developed a catalytic hydrogenation process that reduces the need for hydrosulphite as well as showing improvements in quality and new application effects (deeper colour). To minimise reducing agent consumption in the future, reduced forms of vat dyes are also being used, and dyeing processes are being optimised. Reduced forms include pre-reduced indigo (20%–40% solution or paste) and reduced forms of sulphur dyes. Pre-reduced vat dyes are currently less common due to problems in application.

Reduced sulphur dyes offered by Archroma show saving comparable to pre-reduced indigo. The environmental benefits from reduced sulphur content are closely combined with high quality sulphur dye production to minimise sulphur containing byproducts. This means avoiding the use of cheap sulphur based reducing agents such as sodium hydrogen sulphide and other sulphides that are harmful to the environment.

The use of organic reducing agents is restricted by limits in their range of application, since their redox potential is not suitable for all vat dyes. Hydroxyacetone and other  $\alpha$ -hydroxy ketones (Federer-Lerch, 1995; Jermini, 1997) emit a strong smell that makes them difficult to work with. Other inorganic agents, including thiourea dioxide (Olip, 1995), have been tested against chemical (redox potential), technical (dyeing result), ecological (LCA) and commercial (total process cost analysis) criteria, but have not been found to be viable. The combination of boron hydride with hydrosulphite can significantly reduce the amount of hydrosulphite required.

#### 20.4.2 Process chemicals

In general, an optimum dyeing process should achieve a homogeneous colouration of the substrate in a short period of time. In vat and sulphur dyeing, auxiliaries can help to solubilise pigments effectively and keep leuco forms of dye in their soluble, reduced state. Alkali, mostly caustic soda, is necessary in the reduction process, to solubilise leuco forms of dye and to open (swell) the fibre substrates. Modulators are also added to the alkaline indigo dyestuff liquor to avoid full penetration of the yarn by the dye, as it should only dye the surface. Quick de-airing of the liquor and substrate is also important after the substrate enters the dyeing liquor, to ensure a homogeneous dyeing result. Typical process chemicals used in the dye house include:

- Wetting agents: alkyl sulphates, alkyl sulphonates, phosphoric acid esters, fatty alcohol ethoxylates, alkylphenol ethoylates and fatty amine ethoxylates.
- Washing agents: detergents, tensides.
- · Defoaming and de-airing agents: from many different chemical groups.
- Dispersing agents: lingo sulphonate, condensation products of naphthalene sulphonic acid, fatty acid esters.
- Sequestering agents: phosphonates, polyphosphates, amino carboxylic acids, polyacrylates, gluconate.

• Rebeaming agents (for rope dyeing machines): cationic softeners, silicone emulsions, polyethylene (PE) emulsions, waxes, polyacrylates.

All of these auxiliaries potentially end up in wastewater with a high COD value, which poses a potential environmental hazard unless further treated. It is important to metre quantities precisely to minimise unnecessary use. And wherever possible, auxiliary containing liquors should be recycled.

#### 20.4.3 Electrochemical reduction

The environmental problems caused by the use of reducing agents, which typically end up in wastewater that needs further treatment, can be solved completely by replacing the use of a chemical reducing agent with an alternative physical process. The best current alternative is electrochemical dyeing. Electrochemistry involves the use of electrical energy to initiate chemical reactions, replacing traditional chemical agents. Current technology involves indirect electrochemical reduction using another strong oxidising/reducing agent as a medium to make the technology applicable to different types of dyes. An example is a multicathode electrolyser using iron complexes as cathodically regenerable reducing agents.

Although the initial capital cost of the equipment is high, running costs are low. Over time, the process has been found to be cheaper as well as more environmentally friendly, because it reduces the use of chemical energy to produce reducing agents, and lessens the problem of hazardous wastewater with a high COD value and its associated costs of treatment and disposal. The process also allows better quality control and can be automated, as well as being adaptable to all types of vat dye-stuffs and many types of dyeing equipment. The current cost of investment may come down in the future as production is scaled up. The return of investment (payback period) will become shorter with increasing costs for reducing agents and chemicals, water, wastewater cleaning and labour in the dye house. In the future, if electrochemical dyeing gets established as an example of BAT in the dyeing process, it will be increasingly utilised by consumers and regulators (Roessler et al., 2002; Bechtold and Turcanu, 2009).

# 20.5 Combined dyeing processes

Due to the low affinity of indigo with cellulose, the denim dyeing process is a stepwise process. It achieves the required colour depth by adding successive layers on the yarn surface with each dyeing cycle. This layering process can be made more efficient by processes such as bottoming or topping.

#### 20.5.1 Bottoming

To achieve darker blue shades using indigo, a black layer can be put onto the cellulose fibre first, before continuing with the regular indigo dyeing and building up of the blue

dyestuff layers. In the case of later washing, the colour turns darker because firstly the blue colour disappears and the black bottom can be seen. If more colour is removed and the white core of the yarn is liberated, a stronger contrast is noted, compared with that of pure indigo dyeing. Bottoming is carried out by passing the warp yarn through a first dyeing box containing sulphur black, then passing through at least one wash box before passing regularly through several indigo boxes.

## 20.5.2 Topping

An even darker denim shade is produced by topping, where the warp yarn passes through several indigo boxes, then two wash boxes and finally one or two sulphur black boxes. This process produces the regular indigo layers on the yarn surface and on top a black layer. The colour of a topping is therefore darker, compared with a bottoming. Washing shows more intensive changes towards lighter shades, but the contrast is not as big as in the case of bottoming.

## 20.5.3 Overdyeing

A similar effect is achieved when standard indigo dyed denim (warp yarn dyed) is overdyed in flat fabric form. This can be sulphur black, but other colours and dyestuff classes used in continuous dyeing can also be used. The cost for an additional and separate dyeing process is higher than for bottoming or topping, and therefore is only used when the process on an indigo dyeing machine is not possible, like with colours other than vat dyes, or for special fashion effects.

# 20.5.4 Sandwich dyeing

The combination of bottoming and topping is known as sandwich dyeing, because the resulting dyeing structure shows the indigo layers between the bottom and top layer. This effect is used by a few denim producers to achieve special effects that can be seen after selective washing procedures. This process is not used often because of cost and problems in controlling the quality. The colour strength of individual layers may differ between the beginning and end of the dyeing lot. This causes different wash down effects between early and late dyeing positions.

# 20.6 Minimal application technologies

Minimal application (MINAP) technologies minimise the use of dyestuffs, textile auxiliaries (and energy). All MINAP technologies are related to ring dyeing of denim, because the colouration remains only on the surface of the substrate and not in the core of the fibres. These technologies are mostly well established for special applications, but will need further development to be fully deployed in denim production (Meyer et al., 2011).

## 20.6.1 Inkjet printing

Inkjet printers need to achieve competitive production speeds and running costs, compared with continuous dyeing processes, before this technology can be widely used in denim manufacture (Pai and Paul, 2005). However, inkjet technology has a role in developing new effects like mixing indigo with other dyes and printing several layers. The technology will enable new designs that are not available in the traditional denim dyeing process and should become very attractive for high end fashion garments.

# 20.6.2 Coating

Using pre-reduced or regular indigo in combination with eco-friendly binder systems on modern coating equipment will also make denim effects available without producing significant effluent problems. Coating is more attractive than other processes such as padding because it generates no wastewater and shows lower water and energy consumption. There are choices between solvent based coatings and water based coatings, with various quality, cost and ecological issues involved in determining an appropriate choice.

# 20.6.3 Spraying

Spraying onto fabric or warp yarn from a dyeing beam is a possible alternative technique that has already been tested on a lab and industrial scale. Unlike in the exhaustion method, in spraying it is possible to apply dyes only to the surface and to desired parts of the denim garment.

# 20.6.4 Foam application

Pre-reduced indigo is suitable for foam application on fabric and yarn, if an inert gas such as nitrogen is used as a foam forming medium. Lab and industrial trials have shown significant saving compared with conventional dyeing, as well as the ability to develop new effects by combining foam application with other products. The process can be automated and allows individual, handmade designs appropriate for high end fashion products (Aurich et al., 2011; Sütsch and Schrott, 2012).

# 20.7 Auxiliaries and finishing chemicals

Standard denim is produced from raw cotton that is not pretreated. In general, prewashing, bleaching and other pretreatment processes are not necessary, apart from applying some alkali on the fibres in the first wetting before entering the first dyeing box. However, a number of chemicals such as size or softeners are used during production, either to facilitate further processing (size) or to provide an appropriate finish (softeners). Manufacturers need to assess whether they can achieve the effects they want during existing processes such as dyeing, rather than adding a further process step. In using auxiliary chemicals, manufacturers also need to assess environmental impact by accounting for characteristics such as biodegradability and contribution to the COD value of wastewater.

#### 20.7.1 Size

After warp dyeing, the ropes of yarn are opened and put onto a beam before weaving. Size is a natural or synthetic polymeric material that is put onto the dyed yarn before weaving. It strengthens (lubricate and protect) the cotton yarn so it can survive the high stress of the high speed weaving process without breaking. Sizes can be categorised as natural or synthetic. Natural sizes are starch (natural starch and starch derivatives) and derivatives of cellulose. Starch can be obtained from potatoes, corn, cassava (in South America) and other natural products. Synthetic sizes are acid based and ester based polyacrylates and polyvinyl alcohol. Manufacturers often use mixes of natural and synthetic products at ratios between 3:1 and 5:1 because these have the best technical profiles in terms of bonding power, elasticity and film formation.

The dyeing beam of a slasher indigo dyeing range can be used directly for sizing after dyeing. After weaving, the size is typically washed off before any fabric finishing is done, because the size interferes with some finishing procedures and gives denim a harsh hand that most customers would not prefer. Typically, 5%–15% of size is applied to the cotton yarn. When it is washed off, it ends up in the wastewater and can represent over 70% of the total COD value of wastewater from a denim mill.

In many cases, desizing agents are used to achieve quick and complete removal of the size. Besides special washing agents, enzymatic desizing of starch based sizes is carried out using 1-2 g/L amylases. If the size can be separated from the washing liquor, the wastewater needs less further treatment, though there is still the problem of disposing of the separated size residue. Biodegradability is the most important environmental requirement for size, since recycling is currently not feasible on the grounds of both cost and the quality of recycled size.

#### 20.7.2 Softeners

Softeners may be applied in several steps of the production chain, but are most often used in the last rinse of the garment finish. They provide a smooth or soft hand to the garment, and only small quantities enter the wastewater. The following types of softeners are commonly in use:

- Cationic softeners: ester based cationic and quaternary softeners are readily biodegradable but can be toxic to aquatic life.
- PE emulsions: show COD input as well as biodegradability.
- Silicone emulsions: non biodegradable and potentially toxic to fish.
- Wax: biodegradable and partly removable by adsorption to sludge.
- · Polyacrylates: non biodegradable, but residual monomers may be vapourised.

#### 20.7.3 Fabric finishing chemicals

Fabric finishing or overdyeing is an exception in the denim production process. The major processes involve coating and foam applications with various finishing chemicals to give a soft hand, crease resistance or a shiny appearance. Only expensive denim articles requiring a particular appearance and hand that cannot be achieved in the garment finish are given a special fabric finish.

# 20.8 Garment washing and finishing

As noted, denim washing has a significant environmental impact. Originally this was a pure washing process supported by detergents to clean the denim by removing the indigo that had not fixed to the substrate surface. However, in response to the desire for a worn out appearance amongst a fashion conscious younger generation, new processes have been developed. Some processes, like the sandblasting of denim fabrics, have subsequently been banned to protect the health and safety of workers. The most widely used process is stonewashing, developed in the 1970s. Using naturally occurring stones (pumice stone) and detergents in laundry machines, not only excess chemicals and unfixed dyestuff are removed from the garment, but dye is rubbed off the most exposed parts of the garment to give it a more used appearance with contrasting light and dark coloured areas. In addition, the stonewash process gives the fabric a softer hand (Paul and Naik, 1997a).

The stonewash process has a number of environmental drawbacks. Removal of pumice stone debris after the process can be labour intensive. The process requires higher energy and water input than conventional washing and leads to increased machine wear and breakdown. Developments to improve the process include a perlite wash using a naturally occurring silicon rock that swells at high temperature (above 87 °C) and is softer to the denim garment and the washing machines. Synthetic stones made from plastic material also can be used, and also reused since they are not destroyed by the process.

Nowadays, the stonewash process can be supplemented or even substituted with an enzyme washing process called biostoning. The enzymes used, mostly cellulases, attack the most exposed garment surfaces through a biochemical reaction and achieve effects similar to those of the mechanical garment surface treatment using stones, but cause less damage to the fibre surface. Additionally, the quantity of water used for washing off is less, compared with the quantity used for pumice stones. In general, enzyme washing has a smaller environmental impact than that of stonewashing, because there is less energy use, water consumption, wastewater and damage to machines (Paul and Naik, 1997b). But it is important to be aware of other factors, such as potential allergic reactions to some enzymes amongst operators. Enzymes can be used at various stages of denim production, including:

- Desizing with α-amylases and aminoglucosidases.
- · Biostoning of cellulose.

- · Biopolishing with cellulases.
- · Enzymatic washing with lipases, proteases and hemicellulases.
- · Enzymatic bleaching with laccases and glucose oxidases.

The ecological impact of enzymes is in general lower than it is with other chemicals. There is some COD input, but with lower energy consumption in production since enzymes are active at lower temperatures. It is important to note that solid enzyme forms are finished with dispersing agents, mainly ethoxylate based surfactants, which can be toxic. The general use of enzymatic techniques is discussed in Paul and Genesca (2013).

One disadvantage of cellulases is back staining, which is caused by unwanted recolouration of threads and the lighter inner side of the denim fabric. This can be minimised by detergents and polymeric auxiliaries, which keep the dye waste in emulsion before washing off. However, it is possible that consumers will increasingly accept back staining as a byproduct of more environmentally friendly denim production. In contrast, they will be less inclined to accept more environmentally damaging processes and chemicals like moon washing with potassium permanganate, yellowing by hypochlorite and other chemicals and bleaching with chlorine containing chemicals or oxidative bleaching agents such as persulphate (which is toxic and liberates sulphate) and peroxide.

Several developments have focussed on minimising water consumption in industrial washing and the substitution of detergents with oxidising chemicals such as oxygen, ozone, hydrogen peroxide and other products. Biodegradable oxidised waste can be dealt with by conventional wastewater treatment plants. However, from an LCA perspective, it is important that water saved in industrial washing does not result in significant waste remaining on the denim garment that must then be removed in household washing by consumers. This creates a much more serious waste management problem than dealing with the problem during production.

One non chemical high end finishing technique that offers all kinds of structural effects is laser technology, developed by companies such as Jeanologia (Spain). Directing a laser beam onto the surface of the denim article allows local sublimations of indigo that show up as lighter (white) areas. In 2011, the main inventor of the stonewash, François Girbaud, launched Wattwash jeans with laser based effects, saving 97.5% of fresh water when compared with the stonewash treatment. If predyeing (before indigo dyeing) with non sublimatable dyes is carried out, laser treatment can be used to highlight the predyed material to produce additional complex colour effects.

Another area where significant environmental saving is possible is in the industrial laundry sector. Globally, this is a small scale industry, with many production units having 10 laundry machines or fewer. This sector was developed with low capital investment, production units with varied machinery and equipment, limited production flexibility and no potential for recycling. This sector will benefit from consolidation and the associated investment in new production units in strategic locations (regional distribution centres) with a production size based on 50 or more laundry machines. This enables maximum automation, and recycling of used water by wastewater segmentation, separation and optimised cleaning. This could result in a 50% saving of current energy consumption and water use in this sector.

Modern laundry machines not only are suitable for washing but also can be used for final colouration and other garment finishing processes. Small tonal changes in colour effected through the use of sulphur, vat, reactive and direct dyes, or by using pigments, are called tinting. If a strong colouration is done in the laundry machine with a predyed (indigo or sulphur black) or white denim article, the process is called garment dyeing. Softeners and a variety of functional finishes can also be applied to the garments in laundry machines (Paul, 2014). The finishing chemicals applied in laundry machines at the end of the production cycle are often not as permanent as those applied in a yarn or fabric process step.

# 20.9 Distribution and retail

Since its origins as a type of workwear in the United States during the nineteenth century, denim has become a global fashion brand sold all over the world to many different types of consumers. This has created a complex and sometimes inefficient distribution and retail network. Selling is optimised to offer the widest choice to consumers. However, having a wide range of types and sizes of denim articles available can waste resources, because significant quantities of the final article produced are not bought by consumers and then need to be dealt with by returning the articles to a distribution centre, recycling, etc. Transporting articles to the point of sale and potentially back up the supply chain if they are not sold involves significant transport, storage and other logistic costs and environmental impacts.

In the past, the most important consumption areas were the United States, Europe and Japan. Production was carried out mostly in other regions, especially in China, India and Southeast Asian countries having lower raw material and labour costs. This has resulted in high distribution costs. Air cargo transport is known to be a factor in global warming, but shipping also contributes to greenhouse gas emissions. This situation will improve in part because of shifts in global consumption from more mature economies to emerging economies including China, India, Southeast Asian countries and Central and South America.

Other factors that may reduce the environmental impact of distribution and retail operations include a move to a more regional structure for denim production, with production located in the same region as consumers in self sufficient regional value chains. Other factors include the growth of e-business and the development of production on demand systems. The use of body measurement data gathered using 3D body scanners in the shop for a specific consumer, together with online ordering linked directly to a production facility, will enable garment production tailored precisely to demand. Another benefit from the increased interest in sustainability concepts will be increased use of recycled material in denim wear as well as reuse of apparel. Recycling will impose new constraints on production in that it works best with standardised materials that can be easily repurposed. In practice, this means minimising variation in raw material, processing and chemical use.

#### 20.10 Future trends

In the future, there may be two different segments in denim: standard articles and premium fashion articles. For standard articles, colours and designs will be limited, with individual variations achieved primarily by physical and surface modification processes that have less environmental impact. All dyestuffs and chemicals should, wherever possible, be easily removed and recycled so that the articles themselves can be recycled, by reusing the base material in another garment. Small individual variations in denim articles, like logos, may become more important in differentiating garments. These can be placed onto the final garment by processes such as laser technology, stamping or other individual manufacturing processes. Features such as stitching (with cotton yarn) may also allow differentiation in different garments.

Fundamentally, consumers will use garments for longer periods, adding variation through the greater use of accessories. This trend requires taking greater care of textiles. Therefore, in city and urban living areas, a new logistic care system could be established with more laundering done by commercial services, saving time and effort for consumers and enabling optimal water recycling compared with that provided by typical household laundering.

Variation in premium fashion articles will be due to colour, effects, cut and changes in fashion cycles, much as it is today. More sophisticated production methods will be possible due to a higher price level for premium articles, and mixes with other chemicals and products will be allowed as long as all selected products fit specifications for final recycling or reuse. The integration of substrates other than cellulosic material (polyester, other synthetic fibre substrates, leather, metal foil and yarn) will be allowed only if a simple separation of the different substrates before recycling is possible.

Environmentally preferable MINAP technologies will be used to bring new structures and designs (by inkjet or laser technology) or effects (by coating or foam application) onto the surface. Finally, the premium fashion article segment will be characterised in the future by a high level of tailor made products, and wherever possible, specialist fashion effects will be added as late as possible in the production chain.

### 20.11 Conclusion

Denim is one of the most widely used textile fabrics. Its manufacture has a significant environmental impact, especially in such areas as cotton growing, dyeing and finishing, and a number of ways for reducing this environmental impact are reviewed in this chapter. Following the principles of LCA, emphasis has been put on taking a whole life cycle approach, from raw material production to consumer use and disposal. It has explored ways of reducing chemical use by allowing more recycling or by producing wastewater that is easier to treat. It has discussed replacing chemicals, either with more environmentally friendly alternatives, or with alternative production techniques such as electrochemical dyeing and MINAP technologies. Among all the processes, denim washing in production and household laundering seems to have the highest potential for environmental improvement. It is very clear that in the future, consumers will insist on denim that has been manufactured to the highest environmental standards, and will focus on the sustainability of the entire life cycle including production, use and recycling.

# Sources of further information

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