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Weaving technology for manufacturing high performance fabrics

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9.1 Principles of fabric formation

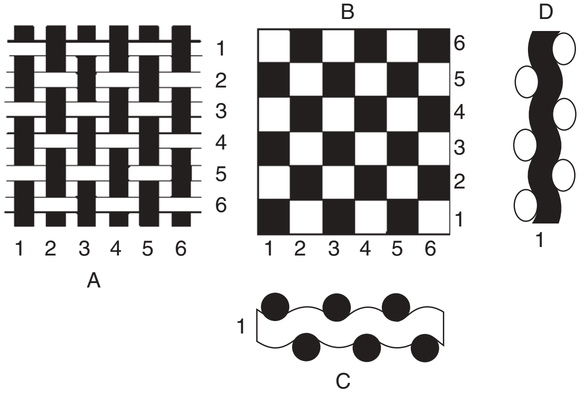
There are many ways of making fabrics from textile fibres. The most commonly used fabric forming methods are weaving, knitting, netting, tufting, braiding, lace making and nonwoven manufacturing. Among these methods, the most traditional and popular method of fabric manufacturing is weaving. Weaving is the interlacing of warp and weft yarns perpendicular to each other. There is a large variety of possibilities of interlacement between warp and weft yarns and the manner in which this is carried out determine the fabric structure. In woven structure the yarns are held in place due to inter-yarn friction. A prime requirement of textile fabric is that it should be flexible. Other requirements are very specific depending on the functionality desired in the fabric performance. The woven structures provide a combination of strength with flexibility. The flexibility at small strains is achieved by yarn crimp and by the freedom of yarn movement, whereas at high strains the threads take the load together giving high strength. In woven formation, great scope lies in choosing fibres with particular properties, arranging fibres in the yarn in several ways and organizing in multiple ways interlaced yarns within the fabric. This gives textile designer great freedom and variation for controlling and modifying the fabric. The yarn properties and the fabric structure together determine the properties of the fabric. The selection of fibre mix, yarn structure and fabric design predominantly depends on the end use application of the fabric.

Production of woven fabric starts with yarn preparation methods like winding, warping and sizing. During actual weaving process both warp and weft yarns are subjected to various complex stresses. The basic objective of yarn preparation methods is to prepare packages of desired size and build and also to make the yarns capable so that they can sustain all mechanical stresses during weaving. In fact the efficiency of weaving process and quality of fabric to a large extent depend on the quality of yarn preparation. After satisfactory yarn preparation, weaving is carried out on a machine called a loom. Normally weaving machines are named after their weft insertion systems. Broadly weaving machines are classified as shuttle and shuttleless systems. Shuttle looms have been used for centuries and have now become obsolete in developed countries and partly being used in some industrialized countries for manufacturing of some special products. Shuttleless weaving machines emerged in the mid-twentieth century as potential weaving machines for mass production of high quality woven fabrics. Weft insertion mechanisms such as rapier, projectile, air jet and water jet are now being used for manufacturing various kinds of fabrics depending on the type of raw material, fabric structure and overall economics of the process.

9.2 Fundamentals of woven structure

9.2.1 Weave representation

The pattern in which the warp and weft yarns are interlaced is called weave. Practically there is unlimited number of weaves. This is in fact an obvious advantage that a weaving technologist can avail to produce unlimited woven structures differing in their appearance, properties and performance. A weave is symbolically represented by a weave diagram as shown in Figure 9.1(B) in which the columns represent the warp yarn and the rows represent the weft yarns. Each square represents the crossing of an end and a pick. A mark in a square indicates that the end is over the pick at the corresponding place in the fabric that is warp up. A blank square indicates that the pick is over the end that is weft up. Figure 9.1(A) shows



9.1 Plan (A), weave representation (B) and cross-sectional view along warp (D) and weft (C) of plain weave.

plain weave in plan view and cross-section along warp and weft are shown in (D) and (C).

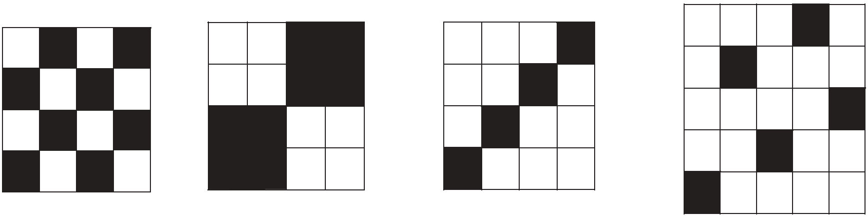
9.2.2 Fundamental weave characteristics

The fundamental weaves are those in which every warp and every weft thread within the repeat overlaps or is overlapped only by one thread of the opposite system. Consequently, the number of warp threads in a repeat must be equal to the number of weft threads. Here, Ro = Ry = R, where R = general weave repeat; Ro = repeat of warp; Ry = repeat of weft. There are three kinds of fundamental weaves: plain, twill and sateen weave. Each kind of fundamental weave is determined by two parameters, and each weave has its own values of parameters. Such parameters are: the repeat R of weave and the shift S of overlapping, or move. The shift is the distance between two neighbouring warp overlaps measured by the number of threads. There are two kinds of shifts: (a) Vertical shift (So) – the shift of two warp threads with respect to each other. This shift is often called the shift on warp where the count is made in vertical direction. (b) Horizontal shift (Sy) – the shift of two weft threads with respect to each other. This shift is often called the shift on weft, where the count is made in the horizontal direction.

The shift can be negative or positive. The vertical shift is positive, when the count is made upwards. The horizontal shift is positive, when the count is made from left to right, and negative when the count is made from right to left.

9.3 Basic weaves

There are three basic weaves such as plain, twill and satin weave. These are shown in Figure 9.2. However, innumerable derivatives can be developed from these three basic weaves; each of these fabrics has a different texture and properties.



1/1 plain

2/2 matt

1/3 twill

1/4 satin

9.2 Basic weaves.

9.3.1 Plain weave

Plain weave has the simplest repeating unit of interlacement. It has a one up–one down interlacement of warp and weft yarns: as a result the fabric has the same texture on both sides. It also has the maximum possible frequency of interlacements and therefore has the maximum level of yarn crimp in the structure. Plain woven fabric has low modulus compared with other structures having less crimp. The weave gives an equal number of warp and weft overlaps in unit of weave. Plain weave fabrics are classified as balanced and unbalanced. In balanced fabrics the warp and weft counts are similar, and the ends and picks per centimetre are also similar. The yarn crimps are usually equal. Plain weave fabrics are widely used, much more than fabrics of any other weaves. In plain weave the values of parameters are the simplest: repeat, $R = 2$; shift, $S = 1$. There are only two threads with different interlacings within the repeat. Two heald shafts are sufficient to produce plain weave. When the number of ends per centimetre is large, four or six heald shafts are used with skip draft. Usually, tappet shedding motions are installed on looms for producing these fabrics. Plain weave is widely applied in various branches of the textile weaving industry. In trade, terms like tabby, calico, batiste are applied to plain weave fabrics.

9.3.2 Twill weave

The twill weave is produced in a stepwise progression of the warp yarn interlacing pattern which results in the appearance of a diagonal line in the fabric. The weave is widely used for ornamentation of the cloth. This design helps to achieve greater weight, closer setting and better draping characteristics of the fabric as compared with plain weave fabric produced from the same yarn. Twill lines are formed on both sides of the fabric; however, if warp float predominates on one side of the cloth, the weft float will predominate on the other side in the same proportion. A twill cannot be constructed upon two threads, but upon any number, more than two. The simplest twill contains three ends and three picks. In the repeat of fundamental twill the number of picks equals the number of ends. The twill is usually denoted by a fraction. The numerator of the fraction is equal to the number of warp overlaps and the denominator is equal to the number of weft overlaps within the repeat. The sum of the numerator and denominator of this fraction is the repeat of the twill. For instance, in 1/3 twill, the number of warp overlaps within the repeat is 1, that of weft overlaps 3, and the repeat is 4. When the shift is positive, the single overlaps form a diagonal which runs from left to right. This is usually called weft face right-hand twill. But when the shift is negative ($S_y = -1$) the diagonal runs from right to left and the weave is called left-hand twill. In the other weave, i.e. 3/1 twill, the repeat of the weave is 4. On each thread within the repeat, there are three warp overlaps and one weft overlap. This is a warp-face twill. This weave has a warp effect in contrast to twill 1/3 which has a weft effect, since the proportion of warp overlaps to weft overlaps within the repeat is 1:3. While designing the fabric with a warp effect, it is preferable to select the density of warp threads higher than that of weft threads, and vice versa. It is common practice to use straight draft for producing twill fabrics.

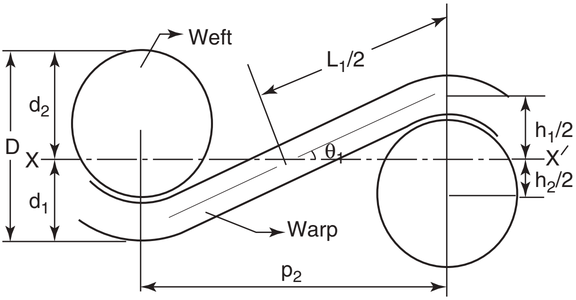
9.3.3 Sateen weave

In sateen weave, one yarn has a long float over several of the other yarns on one side of the fabric. This produces fabric with a high degree of smoothness, lustre and without any prominence of weave feature. Sateen weave enables one to produce fabrics of close thread packing and heavy construction. In pure sateen weaves the surface of the cloth consists almost entirely of weft floats, as in the repeat of weave each thread of weft passes over all and under one thread of warp. In addition, the interlacing points are arranged so as to allow the floating threads to slip and cover the binding point of one thread by the float of another, which results in the production of fabric with a maximum degree of smoothness and lustre and without any prominent weave features.

The parameters of sateen weaves are: $R > 5$; $1 < S < (R - 1)$. Besides, for the construction of the regular sateen the shift (S) and repeat (R) must be expressed by prime numbers, i. e. they must have a common divisor but unity. Sateen weave is denoted by a fraction. The numerator of fraction is equal to the repeat of the weave. The denominator is equal to the shift (Sy) of overlaps. The warp face fabric is called satin. Satin usually can be constructed using the vertical shift (So). Satin has the warp effect, and the density of warp is much higher than the density of weft.

9.4 Theoretical considerations in woven structure

The use of different weave varies the ability of component threads to move relative to one another; as a result, mechanical properties like shear characteristics and drapeability of fabric change significantly. Therefore, the design of a fabric to meet the requirements of a particular end use is a complicated engineering problem. Theoretically, it is possible to design a fabric structure to achieve any desired characteristic, but in actual practice it is not so easy because of inherent non-linearity and complex relationship between structure and properties of textile materials along with their viscoelastic behaviour. The factors associated with fabric design include fibre



9.3 Pierce model of plain weave.

type, yarn geometry, fabric structure and finishing method. Although it is difficult to predict the properties of fabric from these factors, there are empirical relationships between some fabric parameters and the fabric properties. There are also some established theoretical relationships based on fabric geometry and simple mechanics using first principles mostly for plain woven fabrics.

The formal structure of a woven fabric is defined by weave, thread density, crimp and yarn count. The interrelation between fabric parameters can be obtained by considering a geometrical model of the fabric. This model is not merely an exercise in mathematics but useful in determining the entire structure of a fabric from a few values given in technological terms. It also establishes a base for calculating various changes in fabric geometry when the fabric is subjected to known extensions in a given direction or known compressions or to complete swelling in aqueous medium. Mathematical deductions obtained from simple geometrical form and physical characteristics of yarn combined together help in understanding various phenomena in fabrics. In this chapter a basic Pierce's model for plain weave is shown in Figure 9.3. It represents a unit cell interlacement of a plain woven fabric in which the yarns are considered inextensible and flexible. The yarns have circular cross-sections and consist of straight and round segments. From the two-dimensional unit cell of a plain woven fabric, geometrical parameters such as thread-spacing, weave angle, crimp and fabric thickness are related by a set of equations. The symbols used to denote these parameters are listed below.

- d, diameter of thread
- p, thread spacing
- h, maximum displacement of thread axis normal to plane of cloth (crimp height)
- θ, angle of thread axis to plane of cloth (weave angle in radians)
- l, length of thread axis between the planes through the axes of consecutive cross-threads (modular length)

- c, crimp (fractional)
- $D = d_1 + d_2$

Suffixes $_1$ and $_2$ to the above parameters represent warp and weft threads respectively. In the above figure projection of yarn axis parallel and normal to the cloth plane gives the following equations:

$$c_1 = \frac{l_1}{p_2} - 1 \qquad [9.1]$$

$$p_2 = (l_1 - D\theta_1)\cos\theta_1 + D\sin\theta_1 \qquad [9.2]$$

$$h_1 = (l_1 - D\theta_1)\sin\theta_1 + D(1 - \cos\theta_1) \qquad [9.3]$$

Three similar equations are obtained for the weft direction by interchanging suffix from $_1$ to $_2$ or vice-versa.

$$c_2 = \frac{l_2}{p_1} - 1 \qquad [9.4]$$

$$p_1 = (l_2 - D\theta_2)\cos\theta_2 + D\sin\theta_2 \qquad [9.5]$$

$$h_2 = (l_2 - D\theta_2)\sin\theta_2 + D(1 - \cos\theta_2) \qquad [9.6]$$

$$d_1 + d_2 = h_1 + h_2 = D \qquad [9.7]$$

In all there are seven equations connecting 11 variables. If any four are known then the equations can be solved and the rest can be determined. These fundamental relationships can be used by fabric designers to decide the specification of fabrics according to their end use.

9.5 High performance fabric

Industrial textiles are specially designed and engineered structures. Unlike ordinary traditional clothing and furnishing fabrics, industrial textiles are generally used for various high performance or heavy duty applications. Synthetic fibres offer high strength, elasticity, uniformity, chemical resistance, flame resistance and abrasion resistance. In fact flexibility, elasticity and strength are simultaneously found in some of the textile materials that no other industrial product can provide. The development of exceptionally strong high performance fibres widened the area of applications of industrial textiles. High performance fibres offer special properties due to the demands of the respective application. These demands cover properties such as high strength, high elongation, high modulus and resistance to heat, chemical and environmental attack. Glass fibre, carbon fibre and aramid fibre are among the best known high performance fibres used in production of various speciality applications under high performance fabrics.

Carbon fibres containing high strength-to-weight and high stiffness-to-weight ratio enabled production of fabrics which are thermally and electrically conductive and exhibit excellent fatigue resistance. Fabrics woven from aramid and other high performance yarns are used for ballistic protection both for civilian and military personnel. These fabrics produced from Kevlar offer unmatched resistance to bullet, fragments, cuts, stabs and abrasion while offering light weight, high strength and comfort. Blast resistant fabrics produced from high performance para-aramid fibre display excellent dimensional stability over a wide range of temperature for a prolonged period. There are several soft as well as hard body armour products now being developed using woven fabrics from Kevlar. The applications are ballistic vest and helmet, racing helmet, ballistic blanket and electronic housing protection.

9.6 Yarn preparation for high quality fabric

To ensure high productivity and economic efficiency in a weaving mill, good warp preparation is indispensable. Faultless warps are an essential precondition for utilizing assets in the best possible way and achieving the fabric quality demanded by the market.

Yarn preparation for weaving depends on fundamental understanding of the yarn to be processed and the knowledge of stresses to which the yarn would be subjected to during weaving. Modern weaving machines have placed increased demands on warp preparation due to faster weft insertion and use of different weft insertion devices. High efficiency is crucial to ensuring economic production. It is unrealistic to assume that a high quality warp can be produced with an inferior quality yarn. On the other hand, it is possible to produce an inferior quality warp from a high quality yarn, and to avoid this, a number of important points should be kept in mind when making warps. For example, a knot in the weaving room can cause a warp stoppage and possibly a fault in the fabric. For this reason a correct weaver's knot should be used for every broken end. Nowadays the use of mobile splicers can be recommended in weaving to mend broken ends which may cause faults in the fabric. Yarn preparation during warping and sizing is crucial for both loom shed efficiency and fabric quality.

9.6.1 Warping

In warping, hundreds of yarns drawn from individual packages lie parallel to one another, and are wound over a drum. During this process a preliminary assessment of yarn quality can be made on the basis of stoppage records or analysis. This is especially important with bought-in yarns which are utilized without being inspected on receipt. For good warps and economy in the subsequent processes the stoppage value of the order of 5 per 10^7 metres of ring spun spliced warp yarn is considered as satisfactory in the warping room. The following are some of the measures that can be taken to minimize stoppages:

- prevention of fly by regular cleaning – no weaving machine stoppage due to oversized fly;
- creeling of cylindrical packages with the same unwinding direction – uniform unwinding direction avoids collision of balloons;
- avoidance of lost warp ends – no stoppages at the sizing machine. This is accomplished through good training of operators and regular maintenance of the warping machine, e.g. correct adjustment of the stopping distance and correctly functioning stop motions, etc.

When winding the yarn sheet onto the warp beam, care must be taken to ensure uniform distribution of the yarns. The beam must not have any excessively high or sloping edges; it must be completely cylindrical. For warping of synthetic yarns various measures like use of chemicals, ionization of air or humidification of air can be used to eliminate static charge. Special tension rollers need to be used between creel and warper while warping heavy industrial yarns to maintain desired thread tension.

9.6.2 Sizing

During sizing the warp yarn is temporarily coated with a protective layer of adhesive. It gives the warp yarn the resistance necessary to sustain weaving stresses on the loom. If the sizing machine is correctly set and the correct sizing agent has been chosen, the strength of the yarn is improved and its hairiness reduced. At the same time the sizing process also reduces yarn extensibility, which has a major impact on the warp breakage during weaving. In the case of ring and OE yarns, this reduction should not be more than 25% of the breaking extension of the parent yarn. A modern sizing installation for spun yarns should be equipped with pre-wetting attachment, two size boxes depending on the yarn cover factor of the squeeze rolls, wet splitting arrangement with separate drying, tension regulation system, regulation of squeezing pressure, regulation of residual moisture, measurement and regulation of size application, constant winding tension and after waxing device. Pre-wetting results in 25–30% saving of sizing agent. With this system, size application is restricted to the yarn surface and it offers uniform coating and better size–fibre interaction, which have a positive impact on the weaving process. Compared to conventionally sized warps, pre-wetted warps exhibit better weavability and reduced warp stoppages. An appropriate choice of sizing agent and optimization of the size recipe and process parameters have a major impact on the weaving performance of the warp yarns. The sizing machine should not be stopped at all during running. All possible measures should be taken to run the machine at uniform speed. Stretch of warp should be minimized and controlled accurately to preserve residual elongation in the yarn to sustain weaving stress. A balance between size penetration, size coating, add-on, yarn hairiness, residual yarn elongation and yarn abrasion resistance is essential to achieve high weaving efficiency. For instance, warp beams are often not filled to their full capacity. Over the years, additional warp changes cause extra costs which can be avoided by appropriate planning and working methods. The use of the right transport apparatus, knotting machines, drawing-in equipment, etc. can have a considerable impact on weaving room output.

Filament warp yarns can be made weavable by one of the three different means, i.e. sizing, twisting and intermingling. In all the three alternatives, cohesion between the neighbouring filaments of the multifilament yarn is generated which holds the fibres together and reduces separation and filamentation during weaving. In the case of twisting as well as intermingling, the yarn's physical structure changes, whereas sizing is the only process which improves the weavability of the yarn without disturbing the structure and surface characteristics of the warp yarns. Both twisting and intermingling deteriorate some of the mechanical properties of the yarn particularly when the filaments are very stiff and brittle. However the choice of a particular process is largely dependent on the end use application, process cost and quality of the fabric to be produced. For sizing filament yarn single end sizing principle is most suitable to prevent yarn flattening and filament sticking. The important task in filament sizing is control and monitoring of warp tension as these yarns are highly susceptible to extension.

9.7 Weaving systems

Weaving machines are known according to the weft insertion systems being employed on the loom. Weft insertion with a shuttle is the oldest weaving system in which weft is inserted by a shuttle that traverses back and forth across the loom width. Since the weight of the shuttle is several thousand times greater than the weight of the weft to be inserted in a pick, it is considered as an inefficient process and has become obsolete. Alternatively, other weft insertion systems have been developed and they are running successfully in industry. The most popular shuttleless weaving machines are air jet, water jet, rapier and projectile machine.

9.7.1 Air jet weaving

In air jet weaving system, the weft yarn is inserted into the warp shed by a blast of compressed air coming out of a nozzle. Normally the air velocity in tandem and main nozzles exceeds sonic velocity and provides high initial acceleration. Subsequently as the air expands freely, relay nozzles are used to maintain high air velocity across the shed. A profiled reed is also used to guide the air stream and to separate the weft yarn from the warp. The flow of air during air jet insertion is unsteady, turbulent and either incompressible or compressible depending on the velocity. The transfer of weft in air jet insertion takes place due to the propelling force generated by friction between the air and the yarn surface. The amount of propelling force generated during weft insertion is given by:

$$F = 0.5C_f\, \rho\, (U - V)^2\, \pi d\, l$$

where C_f = skin friction coefficient, ρ = air density, U = air velocity, V = weft velocity, d = yarn diameter, l = yarn length in air.

The propelling force is directly proportional to the square of the relative velocity between the air and weft yarn. This force also increases with the increase of yarn diameter. Skin friction coefficient depends on surface characteristics of the yarn. The air jet weaving machine offers the highest weft insertion rate among all shuttleless weaving machines. Because of high productivity, these machines are mostly used for the mass production of standard fabrics such as sheeting, denim, terry towel, glass fabrics, institutional clothing material and tyre cord. The air jet weaving system can process natural, synthetic, spun and filament yarn for production of a wide range of styles. Textured yarns in the weft direction are preferred as they generate very high propelling force. Monofilament yarns are not suitable for air jet weaving as they have smooth surface and lack enough friction between air and yarn for propagation in the shed. In general the suitability of a yarn for pneumatic insertion depends on the count, twist and structure of the yarn and it is independent of the fibre material. Since the machine works at very high speed the quality of yarn and the slashing quality have to be of very high standard, failing which there would be significant loss in production and efficiency. Air jet weaving machines are also used for manufacturing of tent fabrics, airbags, parachutes, etc.

9.7.2 Water jet weaving

In water jet weaving, the weft yarn is drawn through the warp shed by means of a highly pressurized stream of water. The tractive force is provided by the relative velocity between filling yarn and water jet coming out of a nozzle. This drag force can be affected by the viscosity of the water and roughness and length of the filling yarn; higher viscosity causes higher forces. The drag force accelerating the weft can be written as:

$$D_f = 0.5\ \rho_w\ C_f\ \pi\ d\ L\ V_r^2$$

where ρ_w = water density, C_f = drag coefficient, d = diameter of weft, L = length of weft and V_r = velocity of jet relative to weft. The basic principle of weft insertion with water jet is similar to that of air jet as both systems use a fluid to carry the weft yarn. However, one prerequisite for water jet weaving is that the yarn has to be wettable so that it can develop tractive force. In a water jet system, the propulsive zone is elongated as the water jet is more coherent due to viscosity and surface tension of water. Since the wet moving element is heavier, the probability of weft yarn to entangle with the warp line is very meagre. The weaving system is advantageous in terms of energy requirement, noise level and the jet is broken into droplets which create very little turbulence to disturb the weft yarn. However, the droplets spread in the shed and wet most part of the warp which restricts the use of this machine for the warp sized with water soluble adhesives. Therefore, water jet weaving is normally restricted to filament weaving. Modern water jet looms have a speed of about 1500 ppm, the maximum reed width can go up to 3 m and weft insertion rate can go as high as 2000 mpm. Light weight synthetic apparel cloths, tent/tarpaulin fabrics, inter-linings and canopy fabrics and high density air bag fabrics are made on these looms.

9.7.3 Rapier weaving

In this type of weaving a flexible or rigid solid element called a rapier is used to insert the weft yarn across the shed. The rapier head picks up the weft yarn and carries it across the shed. After reaching the destination the rapier head returns empty to pick up the next filling yarn, which completes the cycle. The conventional grippers are redesigned to ensure better clamping of the yarn and prevent rubbing of warp yarns. A rapier machine could be of single or double rapier type. The single rapier is normally a rigid rapier which carries the weft yarn from one end, passes it across the weaving machine and returns back empty. Therefore half the traverse time is wasted and loom width can be maximum up to the length of the rapier which requires more space per unit reed space. However, this has only one advantage that it can handle the weft yarn which is otherwise difficult to control as there is no yarn transfer from rapier to rapier. In the case of a double rapier system, the transfer of yarn takes place at the centre of the loom resulting in only half of the rapier movement being used for weft insertion. A double rapier machine can be either rigid or flexible which makes the difference in space requirement.

Rapier weaving machines are known for their versatility. These looms can weave very light fabrics of 20 gsm to the heaviest fabric of the order of 5000 gsm. The gripper heads can take a wide range of yarn count ranging from 5 to 1000 tex. It can manage successfully up to 16 different weft yarns enabling the weaver to weave any kind of fancy fabric along with an electronic jacquard. Apart from fancy and furnishing fabrics, rapier machine can easily handle filament yarns for manufacturing technical textiles. This is because of the fact that the rapier system of weft insertion exerts minimum stress on the weft yarn. The stress in weft yarn increases with increase in machine speed and it also depends on the elastic modulus of the yarn. Contrary to other shuttleless weaving systems, the speed of the rapier weaving machine is limited far more by the properties of the filling yarn than those of the warp. In the latest machines rapiers are made of composite materials and the rapier guide is eliminated. These machines are used for making automotive fabrics, fabrics for aircraft defence industries, heavy filter cloth and lightweight sports wear.

9.7.4 Projectile weaving

Projectile weaving machines use a projectile or a gripper miniature shuttle to insert the filling yarn across the machine. The gripper grips the end of the weft yarn presented to it and is projected across the warp shed. The projectile does not have to carry the weft package with it and it is therefore much lighter compared with the shuttle. The force needed to accelerate the projectile is also less and the picking mechanism is obviously lighter. However the mass of the projectile is heavy enough to be unaffected by minor obstructions in the warp shed. Since the mass of the projectile is much lower than that of the conventional shuttle, the speed can be increased substantially. The acceleration of the gripper can be increased by a factor of about 7 which offers advantage in terms of productivity and space. This unique weft insertion system uses the torsion bar picking system in which the strain energy is stored by twisting the torsion bar prior to the picking and it is released during the acceleration of the projectile by a toggle action. The projectile glides through the shed in a rake shaped guide. On its arrival at the other end, it is received in a specially designed unit and then conveyed back to its original position. The size of the projectile is small both longitudinally and in transverse direction compared with the shuttle size. The time required for it to pass through a given point is less and also the warp shed need not open too much for easy departure of the gripper. Therefore, a tighter loom timing can be accommodated to take the advantage of increased loom speed or larger fabric width. Projectile weaving practically allows the use of any type of yarn: cotton, wool, mono or multifilament, polypropylene ribbon and even hard fibers like jute and linen.

It is widely used for manufacturing cotton felts, agro-textiles, geotextiles, conveyor belts, cinema theatre screens, tarpaulins, paper machines, clothing and tyre cord.

9.7.5 Multi-phase weaving

The multiphase weaving machine is one in which several phases of the working cycle take place at any instant such that several filling yarns can be inserted simultaneously. In this more than one shed is formed at a time. The multiphase weaving system at present can weave 190 cm width with 69 m of fabric per hour. The weft is inserted continuously without interruption with an even pull off speed of around 20–25 m/s thus the stress on yarn is reduced. The system is more suitable for harsher bast fibres and cottons but unsuitable for weaving of continuous filament yarns. They have the added problem of stopping the loom in the event of weft break in any of the sheds. As four sheds operate simultaneously the system is very complicated with many small parts operating together. The machine can weave plain, 2/1, 3/1 and 2/2 weaves; and warp density is limited to a maximum of 45 ends per cm. Because of these drawbacks these looms are not commercially popular. It weaves fabrics of limited variety but at a substantially faster speed (about 5500 mpm) than any other conventional high-speed weaving machine.

9.7.6 Circular weaving

In circular weaving machines the warp is circular and there are continuously circulating shuttles running around the periphery in a wave or ripple shed. Circular fabrics are tubular fabrics of varying diameter without a lateral fold or edge. Tubular fabrics woven on flat weaving machines have a folded edge as they are joined at selvedges. In this the shuttles require a continuous motion across the shed and cannot leave the shed. On circular weaving machines a ripple shed is formed in which the warp is divided into segments which forms a shed with small heddle frames. An automatic shuttle change mechanism is used to remove the empty shuttle at a particular spot in the shed and a reserve shuttle is inserted. Drop wires pressing the filling yarns towards the fell of the fabric perform the beat-up operation. The machine is used for production of tubular fabrics for special applications such as woven sacks, tubes, medical textiles, etc.

9.7.7 Three dimensional weaving and composites

Three dimensional (3D) woven fabrics are fabricated by modifying the conventional weaving mechanisms. Harnesses with multi-eye heddles are used to arrange the warps into three sections in plane form for weaving convenience. Mainframe and flanges are interlaced by a set of warps moving to and fro as a joint. Weft passes through the clear warp sheds separated by multi-eye heddles to form the 3D woven fabrics in plane form. The differential feeding length between the warp yarns gives rise to extra friction, and therefore hairiness may occur. In order to reduce this friction the warps are passed through the tensioner and weight with ceramic eyes individually between the creel and weaving loom. The thickness of the central portion of the flattened fabrics is different from the side portions. Therefore the cloth roller cannot be used to take up the flattened fabrics. The fabric is clipped and pulled by a pair of rollers set in front of the loom as a take-up device.

The technology is used for the production of only speciality industrial fabrics such as for making preforms for construction, automotive, ballistic and various industrial uses; for marine applications such as carbon fibre preforms for high performance powerboats; in medical technology (artificial veins, arteries, orthopaedic tubes); lightweight construction (reinforced section in automotive engineering and aeronautics); pipeline construction; in sports like shinguards for soccer, protective headgear for skydiving, high speed water sports, etc. Preforms made by 3D weaving provide several important advantages in composite fabrication. The most important advantage of this material is seen in manufacturing thick composites, owing to a significantly reduced labour time, when multiple layers of 2D fabric plies are replaced by one or a few 3D plies to achieve the required thickness in a composite structure. It is obvious to expect that the processing advantages of thick 3D woven preforms come at the expense of reduced conformability. In fact 3D preforms appear to be better than the most conformable 2D fabrics. The flexural, tensile and compressive stiffness and strength are better in laminates made from 3D preforms than those made from comparable 2D woven or even knitted fabrics. This is mainly due to the absence of in-plane crimp of yarns in the materials.

Woven composites have proved ideal for security applications, where a high level of protection is expected from the lightest possible components. New areas of application are under development. In transport applications and vehicle construction, in particular, composites have major advantages. The lower weight results in a higher payload with lower fuel consumption. To meet the high standards required, fabrics woven from yarns containing appropriate special fibres and with sufficiently strong constructions are needed. Special criteria for the composite can be fulfilled with specific materials, such as appropriate synthetic fibres. Materials of this kind are usually designed on an interdisciplinary basis by specialists in various fields. State-of-the-art computer analysis with the finite-element method allows the properties of the fabric to be reliably predicted. Depending on the application, the component is built with different materials. In most cases, the fabric inlays perform important functions. The combination of different raw materials and fabrics with the matrices gives the desired properties.

The fibres used in the production of fabrics for composite materials are mainly inorganic and modified synthetic fibres, such as glass and carbon fibres, para-aramids, high-strength PE fibres, etc. For optimal take-up of forces by the fibres, the yarns are mainly of the untwisted multifilament type. However, spun yarns with a matrix in the yarn are now also being used. The design of the fabric is also dictated by the application. They are not standard fabrics produced in long production runs with unchanged settings. Exact reproducibility must therefore be assured.

9.7.8 Multi-directional weaving

Multi-directional weaving enables placement of fibres and yarns in various directions to obtain the required weave architecture and physical and mechanical properties. Fibre type, direction, spacing and volume fraction are key variables to achieve specified strength, modulus, density, electrical and thermal and many other transmission characteristics of the fabrics. Applications requiring multi-directional woven structures usually are those where extremes in temperature and highly stressed states are encountered. Various high strength, high modulus and high temperature resistant fibrous materials in tow or yarn forms are used in weaving. Fibres and filaments used to develop speciality weaving architectures include quartz, zirconia, silicon carbide, carbon, graphite, tungsten and impregnated yarns. Various fibres can also be woven into the same preform (hybrid weaves). Composite preforms can be woven with fibres oriented in three directions, as with orthogonal (mutually perpendicular) or polar (cylindrical) constructions. In addition, fibres may be oriented in 4-, 5-, 7- or 11- directions, which are referred to as multi-directional woven constructions. These woven structures are used either as preforms or as impregnated components for fabrication of fibre reinforced composites.

9.7.9 Jacquard

Grosse Webereimaschinen GmbH, Germany, and Stäubli developed the UNISHED and the UNIVAL 100 jacquard technology with a different concept. Although the principle of shed formation of these two machines is different, but they have a common goal to reduce the number of jacquard engine parts. The shed formation in the UNISHED is achieved using leaf springs. Each leaf spring is connected to a heddle that controls one warp end. The leaf springs, which are controlled by actuators, control the bottom shed as well as the top shed. The configuration of the jacquard head and the individual control of each heddle or warp end allow the heddles to be set vertically. These settings eliminate the need for harness cords, magnets, hooks, pulleys, springs and the gantry. This results in lower building and air-conditioning costs. The jacquard head is mounted directly on the side frames of the weaving machine, thus making quick style change (QSC) possible in jacquard weaving, as it is easy to exchange the entire jacquard head, including the heddles.

9.8 Production of some speciality fabrics

Woven fabrics with special features are now used in several applications. With advancement in manufacturing technology and invention of new high performance fibres, the use of industrial fabrics is increasing in agriculture, civil engineering, protection and safety, automotive industry and transportation, storage and packaging, medical and ecological sectors, sports and recreation, electronics and instrumentation, etc. Some of the technical textiles have replaced conventional textile materials and interestingly many technical textiles have replaced building materials and metals mainly because of their low weight, high tenacity and resistance to chemicals and corrosion. The production of industrial textiles requires high tech weaving machines such as projectile, rapier and air jet weaving machines with auxiliary attachments for specific purposes. Only a few examples are discussed in this chapter because of space constraints.

9.8.1 Airbag fabric

Airbag is one of the most important safety devices used in vehicles such as aircraft, motorcars and para-gliders. It is installed inside the vehicle in front of a seated occupant to provide protection against injury arising due to collision with the fixed portion of the vehicle body during an accident. Therefore the airbag must inflate and provide a cushion for the occupant immediately after the collision. The material which inflates and provides the cushion is typically a woven textile fabric. For better performance of the airbag, the fabric has to meet certain performance requirements such as low air permeability, high bursting strength, high tear resistance, good packability and good edgecombing properties. In order to achieve these multifarious characteristics the fabric must be designed carefully from the selection of the fibre material till final finishing. The main requirements in airbag fibre materials are high strength, heat stability, good ageing characteristics, energy absorption, coating adhesion and functionality inextreme hot and cold conditions. The most widely used yarn in airbag manufacture is nylon 66 yarn at a denier ranging from 420 to 840. Nylon 6, nylon 46 and polyester multifilament yarns are also used.

Airbags are made of compact plain woven fabric. Normally a thread density of about 18–21 threads per cm are chosen for both warp and weft direction to weave the fabric. Initially conventional rapier looms were used to manufacture the fabric. Subsequently high production water jet weaving machines are also being used successfully. The basic requirement of a weaving machine to produce airbag fabric is its ability to weave high thread density so that a compact structure can be made to provide low air permeability. In some situations to compensate for the lower weave density achievable on available weaving machines, weaving can be performed using yarns having high breaking tenacities so as to provide improved strength in the final fabric despite the lighter weave construction. Multifilament yarns for warp may require sizing with some synthetic binders such as polyvinyl alcohol, polystyrene and polyacetates to enhance the mechanical integrity of the flat filaments during weaving. Although these sizing compounds are typically effective in enhancing the mechanical integrity of the high tenacity yarns, such sizing also tends to enclose yarn oils which may not be compatible with polymeric compounds used for coating the fabric prior to its formation into an airbag structure. Therefore it is necessary to eliminate the sizing compound as well as the enclosed yarn oils by the scouring and drying of the fabric prior to making any coating operation.

9.8.2 Tyre cord

The tyre is a complex technical component and performs a variety of functions. It has to cushion, dampen, assure good directional stability, and provide long-term service. The most important characteristic of a tyre is that it should be capable of transmitting strong longitudinal and lateral forces in order to assure optimal and reliable road holding qualities. The pneumatic tyre is a rubber/textile composite. Cotton has been used as reinforcement in tyres for a long time. Continuous filament rayon began to be used for tyres in the 1930s. Research subsequently led to high tenacity variants and much needed improvements in fibre rubber adhesion. Normally the fibres used for tyre cords are high tenacity (above 6 g/den) filament yarns of nylon 6 and nylon 66, polyester and viscose, etc. While HT viscose and nylon were preferred earlier, they have now been replaced by polyester fibre which has lower creep under load and better heat resistance. Cords comprising the breaker or belt layers, however, use high modulus fibres, e.g. para-aramid (Kevlar), glass or steel. However, it is now realized that viscose is better than nylon in a high-speed impact. Polyester loses advantage of strength above 150°C. At 160°C, polyester shrinks by 2% in length, nylon by −4% and viscose by just 0.1%, Viscose is again the fibre of choice in radial-ply tyre casing. In the technical information literature of Michelin tyres, relative properties of tyre cord materials are compared, reporting that the worldwide consumption of textile fibres in tyres is more than 744 million tonnes and fibre use share is 57% Kevlar, 24% polyester, 19% nylon.

Tyre cord is a warp dominant textile structure. Normally the warps, with a density of 6–13 threads per cm, are kept in parallel and only one weft thread per cm is used. Specially twisted, high strength filament yarns of polyester, polyamide, aramide or rayon are used for the warp. The weft material is usually a cotton or core spun yarn. Due to the low weft density the productivity of a machine weaving tyre cord is extremely high. Weaving machines with different weft insertion systems are used, depending on the type of fabric. Normally for tyre cord production, machines with working widths of 190 and 220 cm are used. To achieve long yardages all weaving is done from a modern creel unit and the fabric is wound into large rolls on a digressive batch winder. Instead of being fed from beams, the warp is fed directly from bobbins placed on creels which are accounted for by the fact that the number of warp yarns in the cord fabric is comparatively small and the warp is not sized. Instead of being wound onto the take-up roller the finished cord fabric is wound onto a special out-built stand mounted outside the loom area. This is done for the reason that the cord fabric is very thick, and the rolls of fabric are very large, thus necessitating greater overall dimensions of the loom and rendering its maintenance very difficult. Some mechanisms on looms are simplified; instead of temples used in standard looms to control the normal fabric width, the cord looms are provided with lamellar limiters. There are two healds in the shedding motion. The main plies of the carcass are manufactured from a dense cord fabric (distance between warp yarns 0.24–0.39 mm). Intermediate plies of looser cord fabric with a distance between warp yarns of 0.52–0.61 mm are laid between the main plies and the breaker. The two upper layers of the tyre carcass are called the breaker; it is intended for safely joining the elastic carcass with the stiff thread. The breaker plies are made from a cord fabric with a low count warp, the distance between warp threads being 1.29–1.36 mm. The plies of the breaker cord fabric are laid over the other at an angle of 45°.

Tyre cord fabric is a skeletal structure which holds the uniformed rubber mass of the tyre. The essential properties of this fabric are high tensile strength, less extensibility and adhesion compatibility with rubber and rubber chemicals. In tyre manufacturing technology, the tyre cord warp sheet (fabric) plays a major role. The overall strength and ability to bear load by the tyre depends strongly on the nature of the cord. The tyre cord should have high tenacity (usually above 6 g/den), high cut-through resistance, good impact resistance, good flex fatigue resistance, good thermal stability, capability to strongly bond with the rubber, low elongation and low moisture regain, high grip and rolling resistance, shock resistance, dimensional stability and elastic recovery.

9.8.3 High performance light weight foldable stretcher fabric

The stretcher forms an essential item in the inventory of any army. Based on extensive research and the design requirements of the stretcher, the fabric has been woven using nylon 66 yarn; Denier of yarn: 500; No. of plies in yarn: Single; No. of filaments per ply: 140; Tenacity of yarn: 40 cN/tex; Texturized yarn. This fabric has got excellent mechanical properties and also offers resistance to bacteria, mildew growth, fungus, water (especially sea water), and corrosion. It is 60 per cent lighter than canvas fabric presently being used. This fabric has numerous other defence applications. It has all-weather capabilities, takes less drying time and offers ruggedness, strength, endurance, excellent abrasion resistance, good tear and puncture resistance, extreme fade resistance, etc. The fabric can be used for making combat uniforms, high altitude and winter clothing, tents, hovercraft, uppers of jungle boots, harnesses, covers, luggage, web equipment, ground sheets and parachutes. Areal density: 272 gsm; breaking load (5 cm × 20 cm strip, tensile): 220 kg × 180 kg; Tear load (warp): >6524 kg.

Years ago, stretch fabrics were used exclusively in sportswear. Nowadays, they also provide added comfort in leisurewear and working apparel. The distinctive feature of clothing made from stretch fabrics is its high degree of wear comfort. Special yarns in the warp or weft, and occasionally in both directions, make the fabric elastic. It adapts to the wearer's movements and does not go baggy where it is subjected to high tensile stress, e.g. at the elbows, knees, and seat. The degree of comfort depends on the fabric construction and on how the garment is made up.

A fabric's elasticity is dictated by the yarn used. Originally, it was highly elastic, texturized continuous filament yarns which gave fabrics used for sportswear their stretchability. Today, it is mainly elastane threads covered with staple fibres of cotton, wool, or man-made fibres. Elastane yarns of different fineness are used, depending on the fabric and the degree of stretch required. Yarns with elastane ensure a defined degree of stretch matched to the garment and the wearer, snap-back, dimensional stability, and maintenance of stretch for the entire lifetime of the garment. Garments are considered comfortable if they have the stretch values of about 18% in the warp or weft direction in menswear and 20% in ladies' wear.

To produce warp-elastic fabrics, corresponding adaptations have to be made during production of the warp itself. As a rule, warps consisting of elastic yarns are sectionally warped. With a high-speed warping creel, the warp can be produced with a constant and uniform tension. The warp is sized from the warping beam. In this way, the elasticity of the yarn is blocked for the weaving process, and the warp can be woven almost like a 'normal' warp. 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 density of warp and weft have to be defined accordingly: if the values chosen are too high, the elasticity may, in extreme cases, be blocked.

Elastic yarns can be woven on rapier and projectile weaving machines. Both 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 well 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. It results a uniform, reproducible stretch over the entire warp length.

9.8.4 Glass fibre fabrics for PCB

Almost all devices, machines and vehicles which are powered, controlled or regulated by electricity contain printed circuit boards (PCB). These boards, which serve as carriers for the circuits, are reinforced with fabrics made of glass fibre yarns. They have to meet exceptionally high standards of quality. The fabric must be dimensionally stable, i.e. it must not exhibit any elongation in either warp or weft. The surface must be uniform and the texture should be uniform in both the warp and weft direction. The fabric surface must not exhibit any broken filaments, because broken and projecting filaments may cause the printed circuit to malfunction.

All of the glass fibre yarns used are endless multifilament yarns consisting of many individual endless threads, known as fibrils or filaments. To facilitate weaving the yarn usually has a protective twist. This makes the thread more compact and the fibrils less susceptible to damage. However, so-called 'zero-twist' yarns are now being used increasingly to ensure that the synthetic material penetrates the fabric layer efficiently in production of the printed circuits. The filaments in these yarns are parallel, and therefore much more susceptible to damage and breakage. In the production of such fabrics, especially those made of untwisted glass fibre yarns, rapier weaving machines have crucial advantages as regards weft insertion. Conductive glass fibre fabrics are commonly woven on air-jet weaving machines, because weft insertion without any mechanical components minimizes wear of the fibrils. But the open thread structure of the 'zero-twist' yarns makes weaving problematic. Rapier weaving machines have the advantage that the open-thread yarns are securely gripped by the yarn clamps and can be inserted in the shed without any individual filaments being missed.

9.8.5 E-textiles

Electronic textiles (e-textiles) are fabrics that have electronics and interconnections woven into them, with physical flexibility and size that cannot be achieved with existing electronic manufacturing techniques. These textile structures may enable sensors and other electronic devices to be distributed over large areas in an economical manner. Some commercial electrotextile products like fabric-based heating systems, flexible keypads and keyboards, fabrics with integrated sensors, etc., have already been developed. Research in electronic textiles is currently being carried out in many diverse disciplines. It is envisioned that the preliminary research in these areas will pave the way for the development of fully integrated electronic textiles with integrated circuits, devices, and power sources, etc., built into the textile structures. Textile substrates with conducting components (fibres, yarns, etc.) are being used for the development of electrical and electronic devices and systems in applications where flexibility and conformability are of importance. Some of the research that is being carried out in this area has been applied to develop commercial products for civilian and military applications.

Applications of textile-based circuitry include a row and column fabric keyboard, an electrical dress, a musical jacket incorporating an e-broidered keypad and fabric buses, and a musical ball with e-broidered pressure sensors. One of the most significant recent developments in the application of conducting threads to electronics has been the attempt to form networks of conducting threads in a fabric by weaving. Great strides have been made in the last decade towards truly wearable unobtrusive electronic functionality into textiles. In the future electronic devices, including power supply and some level of information processing, will be built into the textile structures at various levels of fibres, yarns and fabrics. Additionally, electroactive polymer materials in some form may also be incorporated into textiles to incorporate active components.

9.8.6 Geotextiles

A geotextile is defined as any permeable textile material that is used with foundation, soil, rock, earth, etc. to increase stability and decrease wind and water erosion. A geotextile may be made of synthetic or natural fibres. In contrast, a geo-membrane is a continuous membrane-type liner or barrier. Geo-membranes must have sufficiently low permeability to control migration of fluid in a constructed project, structure or system. A geotextile is designed to be permeable to allow the flow of fluids through it and a geomembrane is designed to restrict the fluid flow.

Geotextiles have historically been made of natural plant fibre; modern geotextiles are usually made from a synthetic polymer (such as polypropylene, polyester, polyethylenes and polyamides) or a composite of natural and synthetic material. Plant fibre-based erosion control geotextiles are subject to decomposition and have a limited shelf life before their inherent durability suffers. The synthetic polymers have the advantage of not decaying under biological and chemical processes, but being a petrochemical-based product they use non-renewable resources in their construction, and cause environmental pollution in their manufacture and use, and have associated health risks.

Geotextiles can be woven, knitted or non-woven. Different fabric composition and construction are suitable for different applications. The non-woven geotextile is an arrangement of fibres either oriented or randomly patterned in a sheet, resembling felt. These geotextiles provide planar water flow in addition to stabilization of soil. Typical applications include access roads, aggregate drains, asphalt pavement overlays and erosion control.

Woven geotextile looks like burlap. It is a fabric made of two sets of parallel strands systematically interlaced to form a thin, flat fabric. The strands are of two kinds – slit film which is flat, or monofilaments which are round. The way these two sets of yarns are interlaced determines the weave pattern that in turn determines the best application for that woven fabric. Weave patterns come in a virtually unlimited variety that do affect some properties of the fabric. Woven geotextiles are generally preferred for applications where high strength properties are needed, but where filtration requirements are less critical and planar flow is not a consideration. These fabrics reduce localized shear failure in weak subsoil conditions, improving construction over soft subsoil and providing access to remote areas through separation.

Woven monofilament geotextile fabrics provide immediate and long term solutions for most drainage and filtration applications. The combination of high strength and excellent hydraulic characteristics make monofilament the fabric of choice behind bulkheads and under riprap. Percent open area, a property most often associated with 100% monofilament geotextiles, offers both water and particles a direct path through the geotextile. Woven geotextile fabrics are produced by weaving high tenacity yarns in an orderly pattern on large industrial looms. The high tensile strength of the order of about 200 kN/m allows the material to accommodate large stresses during installation and while in service without failure. Woven structures provide high abrasion resistance which makes the material resistant to the installation process and to sand abrasion in the surf zone. Woven geotextiles have a low capacity for elongation and consequently cannot accommodate large strains without failure. This is countered by the high tensile strength of the material, but it may lead to problems if the material is required to reshape during deployment or when in service. Woven geotextiles have a relatively low angle of friction between both the seabed and against other geotextiles, which may affect the stability of the structure as the units will be more likely to slide off one another.

9.9 Future outlook in weaving

The principle of interlacing yarns to make a woven fabric has not changed since time immemorial. However, there have been dramatic changes in the equipment used in weaving. In today's competitive market, low-cost manufacturing of quality woven fabrics is important for survival. Despite some gains, in particular by knitted fabrics, weaving will continue to be the predominant method of fabric formation, due to the advantages of structural stability of woven fabric. Weaving machine manufacturers are finding new, faster and better ways to produce woven cloth. Over the years, electronics have increased the processing speed, flexibility and reliability of weaving machines. Multiprocessors are now used to control, monitor and communicate functions. Modern control systems are capable of generating production statistics, efficiency calculations and a variety of other data which can be retrieved from the machine via an interface. Fabric parameters, patterns, colours and control functions can be input at the communication panel on the machine. Although the speed of weaving machines has increased dramatically, the weft insertion rates and loom productivity of single-phase projectile, air-jet and flexible rapiers are expected to increase further. It is also expected that there will be major improvements in multiphase weaving as such improvements may not be possible for single-phase machines due to physical limitations. However, research programmes are under way to further improve the performance of single-phase weaving machines. For example, pneumatic beat-up is being studied as a replacement for the traditional reed in air-jet weaving. In pneumatic beat-up, compressed air is used to push the filling yarn into the cloth fell. Weaving productivity and flexibility have been substantially improved with the introduction of the quick style change system, the off-loom take-up system, inverter drives, filling feeders, electronic let-off and take-up, automatic filling repair and new monitoring systems. Innovations to further increase productivity and flexibility are expected to continue, and may include automatic warp stop repair, automatic fabric doffing, automatic filling supply systems, etc.

With the ever-expanding fields of application of high-performance industrial fabrics, weaving machines will continue to be modified to meet the requirement of their production. Future machines would be wider and stronger to produce a wide range of industrial fabrics. One area with great potential for improvement is the manufacture of weaving machines for complex three-dimensional shapes. As industrial textiles penetrate into almost every industry in the world, 3D woven fabric structures are gaining importance. As of today, no 3D weaving machines are commercially available. However, this is expected to change as the market share of 3D fabrics increases. New fabric development will be a key factor in survival and success of the weaving industry in the years to come.

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10

Advances in coloration of polyester textiles

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10.1 Evolution of dyeing of polyester

Polyester fibre [poly (ethylene terephthalate) (PET)] offered considerable difficulties in dyeing when it was first produced by the Imperial Chemical Industries (ICI) in 1947. Since polyester has no reactive groups such as those present in cellulose (hydroxy groups) and protein (amino groups) fibres it had no affinity for water-soluble dyes, like direct, acid and basic dyes that were being extensively used for coloration of textiles at that time. Only one major class of dyestuff proved to be practical for dyeing light shades on unmodified polyester: disperse dyes – a nonionic dye class. These dyes were originally developed by Ellis in 1923 for the dyeing of cellulose acetate fibres.

The first systematic study of the dyeing of polyester (polyethylene terephthalate) was carried out by Waters[1] in 1950. From the diffusion coefficient and saturation values of four disperse dyes dyed at 85°C and 100°C, this investigator concluded that even though disperse dyes have an affinity for polyester the 'slow diffusion is the cause of the poor dyeability of polyester'. In order to achieve deep shades, the dyebath temperature must be as high as possible.

In a subsequent study, Lyle, Iannarone, and Thomas[2] observed that disperse (acetate) and vat dyes on polyester, when applied at 250°F (121°C), gave an excellent penetration generally not obtained at 212°F (100°C). Remington[3] pointed out that the problem in dyeing polyester fibre results from the compactness of the structure, which prevents dyes from diffusing through it rapidly. Dye molecules can be induced to travel rapidly from the dyebath to the interior of the fibre by means of carriers, use of high temperature, or by forming the final dye molecules within the fibre.

Schroeder and Remington[4] were the first to propose the mechanism of dyeing of polyester fibres with disperse dyes. According to these investigators, the dye is sorbed from its solution by the polyester fibre and a constant partition between the concentration of dye in water and the concentration of the dye in fibre is maintained until equilibrium, thereby confirming the solid solution mechanism. These investigators further stated that since it is difficult to say whether the dye is uniformly solubilised in fibre or not (since the fibre contains crystalline and amorphous portions), the use of the term 'solid solution' is not appropriate.

A detailed investigation[5] of the stability, dyeing, and fastness properties of a range of disperse dyes on polyester fibre showed that it can be treated for 2 h at temperatures up to 160°C in the pH range 2.8–7.0 without reducing its toughness factor. Optimum dyeing conditions were obtained between 130 and 140°C.[6]

From the studies on the solubilities of the dye in water and fibre, rates of desorption from dyed fibres, heats of dyeing, diffusion coefficients, and activation energies, Patterson and Sheldon[7] concluded that in the dyeing of polyester with disperse dyes the dissolution of the dye molecules in H_2O is followed by the diffusion of single dye molecules inside the fibre structure. The rate process depended on the spontaneous appearance at a suitable position in the non-crystalline regions of a hole large enough to accommodate the dye molecule.

In another similar work Glenz[8,9] concluded that polyester molecules are bound together by relatively strong forces which must be loosened by the penetrating dye. Moreover, if the dye is to diffuse, it must detach itself from the site at which it is adsorbed and be anchored to a neighbouring site, with a velocity determined by the affinity of the dye for the fibre, the relative size of the intermicellar spacing and the dye molecule, the changes in energy and in geometry. To increase the diffusion rate, either the temperature must be raised or the energy of activation must be lowered, as by the addition of a carrier. According to Garrido[10] the activation energy of dyeing calculated from the rates of dyeing with CI Disperse Red 15 at 70, 80, 85, 90, and 95°C using the Arrhenius equation, is about 70 kcal/mole for the dyeing of polyester fibre with disperse dyes. These pioneering studies formed the basis of the further development of dyeing of polyester.

10.2 Disperse dyes

The first ever 'Disperse Dye' SRA Orange 1 was synthesized by Holland Ellis for the British Celanese Ltd in 1923. However, the Gold Medal of the Society was given to Baddiley and Shepherdson for introducing 'Duranol' dyes in 1924, much before the invention of polyester fibres.[11]

When polyester was introduced Duranol dyes and other such dyes were there to dye it. These dyes being simple, nitro, azo and anthraquinone dyes were found to have low sublimation fastness and those based on anthraquinone backbone were found to fade by NO_x gases found in the urban environment.

The first tasks of development of suitable disperse dyes for the dyeing of polyester were to modify the then available dyes to improve their sublimation and gas fume fading properties. The sublimation fastness was achieved by introducing additional groups in the dye molecules to increase their molecular weight and the deficiency of gas fume fading was rectified by protecting the easily reducible amino groups in the anthraquinone based disperse dyes.[12] Subsequently, disperse dyes were developed to meet the specific requirements of polyester such as 'alkali clearing' dyes and the dyes having low thermo-migration and high wet fastness. The forerunners among the 'alkali clearable' dyes were the di-ester-side group containing Dispersol PC dyes that could be 'reduction cleared' without a reducing agent to remove the superficially surface adhering dye, thereby reducing the pollution load of the effluent.[13] These dyes have also been exploited in the 'discharge' printing of polyester fabrics where the dye from the alkali printed portion of the printed design can be easily washed with hot aqueous alkali solution.[14] In another approach similar results can be achieved by dyeing with thiophene-based disperse dyes, where the dye molecule is ruptured on treatment with alkali breaking the bond between the azo and the thiophene group, producing almost colourless easily washable by-products.[15–16] Recently, Koh[17] has developed alkali-clearable azohydroxypyridone disperse dyes containing a fluorosulfonyl group. The alkali-clearability is imparted by the hydrolysis of fluorosulfonyl residues and ionisation of azohydroxypyridone structure under alkaline condition.

Dyes with low thermo-migration propensity and unique wet fastness that were researched by ICI were introduced for the dyeing of polyester in 1975.[18] These dyes such as CI Disperse Red 356 and 367 are based on benzodifuranone chromophoric backbone. Additionally, they are extremely bright with good build-up. Dyes dyeable from an alkaline medium have also been developed to cater to the needs of polyester- cellulosic blend dyeing. The traditional classification of disperse dyes on the basis of sublimation characteristics (i.e. A,B,C,D or E,SE,S) and concomitant energy levels (Low, Medium, High) has undergone considerable change. The first such change occurred when the concept of 'Rapid Dyeing' was introduced in the 1980s, where the 'on-tone' dyeing and the compatibility of dyes based on their concentration-based exhaustion behaviour was desirable. This led to the emergence of multi-dye formulated RD dyes and single-dye based compatible trichromatic dyes.[19] In more recent times, dyes are being classified on the basis of end-use, such as dyes for automotive fabrics having very high light fastness or dyes for sportswear and heavy-duty work-wear having the highest level of wash fastness, or for that matter, luminous disperse dyes for high-visibility garments used by traffic controlling personnel. As far as home-textiles are concerned one can use compatible dyes with good levelling properties and reasonable fastness. There are various minor classifications that have not yet found their place in shade cards such as dyes suitable for 'Solvent Dyeing' and 'SCFE dyeing'.

The disperse dyes (erstwhile Cellulose Acetate Dyes) were originally introduced as pastes that had problems of settling down and crust formation. Subsequently spray drying was introduced where a nicely ground mixture of a dispersing agent and the dye were spray dried to produce self-dispersible powders. Automation of the dyeing process again led to the production of easily 'pumpable' dyes in the form of liquid dyes. In the production of dyes besides their easily dispersability and pourability, the particle size is of paramount importance since the solubility of the dye is directly proportional to the particle size and hence its ultimate exhaustion of polyester. A typical dye may have particle sizes varying from 0.1 to 1 micron possibly with some nanoparticles. Studies on the crystalline structure of disperse dyes has indicated that they are polymorphic and the different crystal forms have different saturation value. However, prolonged dyeing at high temperature results in the conversion of all meta-stable forms to the stable form, hence the original difference in the crystal forms of disperse dyes does not affect the ultimate dye uptake.[20,21]

A new range of micro-encapsulated disperse dyes having regulated release of disperse dyes was developed in 1970 and used for creating snow-like flecked effect on fabric by printing.[22] Thereafter magnetic micro-encapsulated dyes were introduced for the Thermosol dyeing of polyester in specially designed machines.[23] Recently, polyurea microcapsules (PMs) having disperse dyes for Thermosol and high temperature exhaust dyeing have been produced that can dye polyester without any auxiliary chemical and the exhausted dye bath can be reused for dyeing.[24]

In another recent study, dispersed dyeing having temporary solubilising groups, that do not require the use of dispersing agents, have been used for the dyeing of polyester.[25] In this study, precursors of vinylsulphone dyes having aminophenyl-4-(β-sulphatoethylsulphone) groups that impart water solubility to dye have been synthesised and dyed onto polyester. The β-elimination reaction of the sodium sulphate group during dyeing produces the vinylsulphone form of the dye and this in turn may be partly hydrolysed to the hydroxyethylsulphone form, both of which are sparingly soluble, during the dyeing process. The optimum application pH for the dyeing of polyester in the absence of a dispersing agent has been found to be between pH 5 and 6 at which the hydrolysis rate of the dyes is moderate. These and similar precursors of vinysulphone dyes have been used for the single bath dyeing of polyester-cotton blends. Where the vinylsulphone form of the dye covalently reacts with cotton and is also sorbed by polyester as a disperse dye.[26] This approach of synthesizing dual function disperse-reactive dyes that can dye various fibres singly or in blends is being pursued by several investigators.[27]

10.3 Theory of dyeing with disperse dyes

As stated above the dyeing of polyester with disperse dyes was perceived as the distribution of the dye molecules between the dye bath and polyester fibre such that at equilibrium the concentration of the dye in the polyester fibre is linearly proportional to the concentration of the dye remaining in the dye bath according to Nernst Isotherm. The ratio of the concentration of dye in fibre to the concentration of the dye remaining in the dye bath represents the Nernst distribution coefficient. This coefficient was taken as a measure of the affinity of the particular dye for a particular polyester fibre assuming it to be a homogeneous inert solvent in which dye molecules could dissolve.

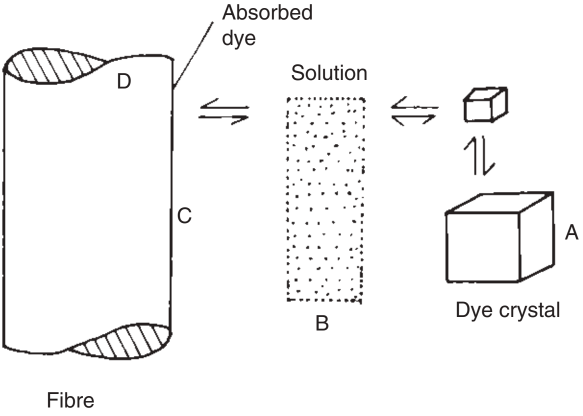
However, subsequent studies on the differently pretreated polyester fibres having complex morphological structures showed that the dye distribution in the fibre was different for fibres having different morphology even though it had the same basic chemical structure.[28–30] These observations led to the closer examination of the state of the dye in the dispersion, particle size and crystal structures, morphology of the fibre, its previous history and changes during dyeing, and diffusion in fibre.

While deliberating on the state of the dye in the dye bath McDowell[31] postulated that the dyeing of polyester fibres with disperse dyes takes place from dilute solution of dye in the presence of a suspension of dye particles. As the dye molecules are sorbed by the fibre from solution, more dye passes into solution from suspension in order to maintain the concentration of the solution, which is in equilibrium with a definite concentration of dye on the surface of the fibre. As dyeing proceeds and these molecules are taken up from solution by the fibre, the dye remaining in suspension in the form of much larger particles dissolves slowly and is taken up by the fibre until equilibrium is reached as shown in Fig. 10.1. When equilibrium is reached, the following subsidiary equilibria are established.

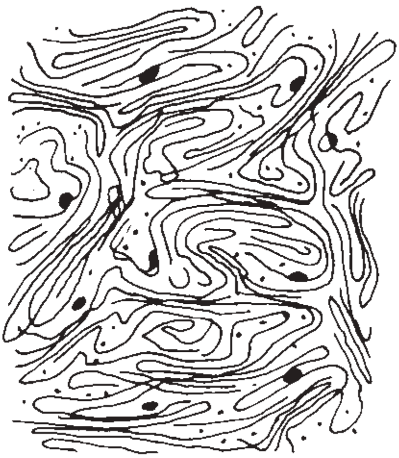
I. Dyeing dispersion in bath ⇔ Dye dissolved in the bath
II. Dye dissolved in the bath ⇔ Dye dissolved in the fibre
III. Dye dissolved in the fibre ⇔ Dye diffused in the fibre

Theoretical studies of the equilibrium adsorption of dyes showed that two types of isotherms are obtained, viz. (1) Isotherm indicating Langmuir type adsorption of dyes, and (2) Isotherm indicating constant partition ratio up to the saturation point.

From the studies of Patterson and Sheldon[7] it was concluded that in the dyeing of polyester with disperse dyes the diffusion of single dye molecules inside the fibre structure takes place. Moreover, the rate process depended on the spontaneous appearance at a suitable position in the non-crystalline regions of a hole large enough to accommodate the dye molecule. These



10.1 Schematic of the dyeing process.



10.2 Pore model of dye diffusion.

findings have led to the postulation of Free Volume Theory of diffusion of dyes into thermoplastic fibres that is applicable to the disperse dye polyester fibre system.[32] According to this theory the dyestuff is attracted from solution to the fibre surface and remains there until sufficient thermal energy has been supplied to the system to allow the dyestuff to diffuse into the fibre through the transient holes, the formation of which is a result of the onset of segmental motion of the fibre. Thus at and above the glass transition temperature (Tg) of the fibre the dyestuff diffuses into the fibre by 'jumping' from one site to another (Fig. 10.2).

Below the glass transition temperature, the polymer molecules are relatively motionless and very little, if any, diffusion of dyestuff into the fibre takes place. Once the Tg is reached, sufficient energy exists in the fibre causing some segments in the polymer to move. These segments vibrate, but no net translational motion of the centre of the molecule occurs. When a polymer chain comes in contact with a chain having no dye molecule, the dyestuff can interchange between these two chains and thus diffuse through the polymer.

In the free volume theory, the activation energy of dyeing is defined as the energy required to form a free volume around the dye which can accommodate the dyestuff and permit a location change of the incorporated dye molecule. The activation energy is not constant but is a variable with a maximum value at the Tg, decreasing with increasing temperature. The purpose of the solvent, such as water, according to the free volume theory, is to transport the dye from solution to the fibre surface and then to act as plasticiser. The mode of action of the plasticiser in dyeing is to lower the energy of activation. The plasticiser is sorbed into the fibre and weakens the intermolecular attractive forces. Due to weakening of these forces, the plasticiser energy needed to permit rotational and vibrational motion of the chain segments is reduced, thus lowering the Tg of the fibre. The concentration of the plasticiser in the fibre is more important than the chemical structure of the plasticiser.[33]

In this theory of diffusion of disperse dyes into polyester fibre considerable importance has been given to the Tg of the fibre and it is assumed that irrespective of the dye used the dye-diffusion starts at Tg. The 'energy effects', that is, the intermolecular forces between the dye and the fibre and geometric dimensions, that is, size and shape of the diffusing molecule, have not been considered.

Gulrajani and Saxena[34] have indicated that practically no diffusion of the dye starts at the Tg of the fibre. The diffusion of the dye starts at a temperature T_D which is at a higher temperature than Tg, so that,

$$T_D = Tg + \Delta T_{Dye}$$

ΔT_{Dye}, the difference between ΔT_D and Tg, has been attributed to the 'energy effects' as well as 'geometric properties' of the dyes. The value of ΔT_{Dye} is different for different dyes. The observation that the plasticisers such as water and other organic chemicals reduce the Tg of the fibre was further investigated by Mitsuishi and coworkers.[35] These investigators observed that presence of the dye in the fibre lowers the Tg in a similar manner as the plasticisers and is proportional to the concentration of the dye in the fibre. The lowering of Tg by the dye is influenced not only by the molecular structure of the dyes but also the dye-polymer interactions. This observation shows that the Tg of the fibre goes on changing during dyeing.

Most of the investigators support the hypothesis that a sorption of disperse dyes on polyester follows a linear relationship between dye in the bath and dye on the fibre and dye diffusion takes place by the segmental motion of the polymer chains as postulated in the Free Volume theory. However some workers[36,37] obtained Langmuir types of sorption isotherms on equilibrium dyeing of disperse dyes on polyester fibres. Such curves are associated with processes in which the dye is attached to the sites on the surfaces of crystallites or to the sites on the molecular chains in the amorphous region.

It is reported that the sorption isotherms depend on the presence of dispersing agents, the dyeing temperature, and the dye structure and fibre types.[38] Generally, sorption isotherms of disperse dyes on polyester fibres have been reported as Nernst-type linear distribution isotherms in the presence of a constant concentration of dispersing agent.[29] However, in the absence of a dispersing agent, the sorption isotherms of disperse dyes on polyester fibres have more complex shapes. It has been reported that a dual-mode sorption model that is composed of both Nernst and Langmuir sorption models, or a more complex sorption model which has one Nernst type model and several Langmuir sorption models, may be more appropriate.[39]

Nakamura *et al.*[40] while investigating the sorption isotherms and dyeing rates of purified disperse dyes on polyester microdenier fibres from aqueous medium obtained isotherms that are curved and can be described in terms of the dual-mode sorption model: Nernst-type partitioning and Langmuir sorption isotherms. However, this dual-model also depends on the dye structure and on the dyeing temperature. Therefore, the selection of the sorption isotherm model for polyester disperse dyeing systems depends on dyeing and material conditions.

While investigating the diffusion of disperse dyes into microfibres and conventional polyester fibres, Park *et al.*[38] observed that the simple Langmuir sorption isotherm fits well to the experimental sorption isotherms obtained at high dyeing temperatures. The correlation is, however, better for microfibres than for conventional fibres. These findings of Park *et al.* have been very recently confirmed by Dhouib *et al.*[41] According to these researchers the most important parameters for dye saturation on the fibre are temperature, dye size and volume of accessible domains able to receive dye molecules. This volume is very dependent on fibre crystallinity. Both fibre surface area and dyeing temperature have a second-order effect. The temperature has more influence on fibres having poor accessibility to the dye.

10.4 Effect of fibre structure on dyeing

10.4.1 Heat setting

In the production of polyester fibre, variations in crystallinity, orientation of the crystalline, paracrystalline and amorphous regions of the fibre may occur during the post-spinning drawing stage and the heat-setting processes. These changes in the physical structure of the fibre affect the dyeability of the fibre. Several attempts have been made to establish qualitative and quantitative correlation between the dye diffusion and morphology of polyester fibre. Marvin[42] was the first to show that over a range of setting temperatures the uptake of disperse dyes by heat-set polyester initially decreased, as the temperature of pre-heating was raised giving minima in the range 140°C to 180°C. However, at higher temperatures the dye uptake increased with temperature and was greater than that of the untreated control sample. These observations of Marvin have been confirmed by many other workers.

The anomalous dye uptake of heat-set polyester has been explained by Dumbleton *et al.*[43] on the theory that the diffusion of dye depends on its segmental mobility in the amorphous regions and also on the size and size distribution of the crystallites. Moreover, it is also influenced by the number of crystalline sites and the orientation of the amorphous phase within its fine structure. Some workers have observed that the porosity of the fibre, that is, the number, size and size distribution of pores within the matrix, can also affect dye uptake.[44–47] In a comprehensive study[48] of the effect of polyester fibres heat-set in slack and taut condition on the diffusion behaviour of disperse dyes, it has been proposed that dye diffusion in heat-set polyester is controlled by two factors: (1) the volume of the accessible region, represented by the amorphous volume per crystal; and (2) the tortuosity of the path of diffusion of dye into the fibre that is dependent on the orientation of the amorphous region and the type of coupling between the amorphous and the crystalline region. Donze *et al.*[49] have suggested that adequate shrinkage must be allowed during heat-setting of polyester fabrics to smooth out the structural differences caused by variations of the tension applied to the yarns during mechanical textile processes.

On dyeing of polyester heat-set at temperature between 160°C to 220°C with disperse dyes at 130°C Gacèn *et al.*[50] observed that the fibre structure becomes more compact, thereby showing that supplementary setting of polyester takes place in the dye bath at 130°C. This effect is more pronounced in fabrics heat-set at relatively low temperatures. These findings contradict the earlier finding of Lipp-Symonowicz[51] that treatment of polyester fibres in water at 130°C decreases the molecular orientation of polymer chains in the surface layers of the fibre. However, both these studies show that some further setting of the polyester takes place during dyeing.

10.4.2 Texturing

Texturing of polyester filament yarns not only disturbs the orientation of the polymer chains and the crystallinity of the yarn but it also modifies its cross-section resulting in uneven dye sorption by the yarn thereby producing barré dyeing. Clements[52] devised a method of evaluating the dye uniformity of false-twist pin-textured polyester yarns produced from fully drawn feed yarns. According to this investigator, the textured yarn dyeability is not very sensitive to the texturing parameters, and only a serious lack of drawback of proper process control can account for very high dye variance of some commercial yarns.

From a study of the dyeability of poly (ethylene terephthalate) yarn textured at different temperatures and different contact times Gupta, Kumar and Gulrajani[53] have concluded that the degree of crystallinity and the size of crystallites are the controlling factors of dye uptake. Moreover, the temperature of texturing determines the crystallinity and the crystal size distribution in the textured samples. Their findings have been supplemented by the observations of Goldin.[54] According to this investigator the nonuniformity of dyeing textured yarn is related to the shape of the primary heater response curve in texturing. According to Miller, Southern and Ballman[55] the variable dyeability of textured yarn that is dependent on yarn crystallite size and crystalline content can be attributed to dye path tortuosity of disperse dyes in textured polyester fibres.

In a comprehensive study of the response of textured yarn properties to process variables in relation to barré, McGregor and coworkers[56] have concluded that the rate of dyeing is not very sensitive to texturing variables, and the control of the heater temperatures should be within ±2°F (1°C) to get barré free dyeings and the feed yarn should be uniform. In a subsequent study,[57] they have reported that differences in feed-yarn orientation propagate though texturing and modify almost all the textured yarn properties. Such effects can be comparable in magnitude with those of large changes in texturing variables, and they influence some of the crimp, shrinkage, and tensile properties of the yarns even more than they modify the dyeing responses. However, the information on feed yarn variation is lost on high-temperature dyeing.

Navrati[58] has proposed a mathematical model to predict disperse dye barréness attributable to differences in draw ratio and texturing temperature of polyester fibres. It is claimed that the use of dyeing simulation will be useful to optimize dye formulations and dye usage. In an another study[59] it is proposed that determination of crimp contraction force variations is an effective way of detecting potential nonuniform dyeing behaviour of textured yarns. When the coefficient of variations in crimp contraction force and percentage tension instability were >5%, barré appeared more frequently in textured yarn fabrics so that a strict tension control during draw texturing is necessary to avoid barré problems.[60] Lawson-Hemphill has developed Textured Yarn Tester that employs dynamic testing of crimp and can be used for determination of dyeability properties of polyester textured yarns.[61] ASTM standard D 6774-02 titled 'Standard Test Method for Textured Yarns Using a Dynamic Textured Yarn Tester' specifies the use of this tester.

10.5 Dyeing procedures

10.5.1 Exhaust dyeing

A conventional dyeing cycle has three main phases, namely, the sorption phase, the diffusion and levelling phase and the after-treatment phase. The levelling phase that is about 45 min to 60 min takes care of the uneven sorption of the dye during the sorption phase. This phase is a drain on energy and productivity. For the dyeing of polyester it was soon realized that unlike natural fibres the fibre plays an active role in dyeing. Hence the rate of sorption of dye suddenly jumps above the Tg of the fibre when the segmental motion sets in, giving rise to rapid diffusion of the dye into the fibre. This necessitated the need to work out a differential heating up procedure for the dyeing of polyester. In doing so it was observed that if the sorption of the dye onto fibre is regulated during the first phase of dyeing then the need for a levelling phase is reduced or even eliminated in some cases. This gave birth to the Rapid Dyeing of polyester.[62–67]

The rapid dyeing of polyester, based on the differential heating rate from 60°C to 130°C, resulted in considerably shortening the dyeing time with the result that new rapid dyeing dyes and machines had to be developed. Every dye manufacturer came out with their own heating up procedure and set of dyes that was suitable for that procedure. Over time, the situation has improved thanks to the introduction of programmable microprocessor, attached to the dyeing machines that could carry out different kinds of dyeing protocols from its stored memory.

A further development in the dyeing of polyester is that many companies have produced dedicated software suitable for their own range of dyes such as the Optidye P of DyeStar for Dianex CC dyes. These software claim to optimize various parameters of dyeing and reduce the auxiliary consumption. BASF has developed its own integrated polyester dyeing system 'dyexact XP', which enables precise control of the dyeing process.[68] The essential core product of dyexact XP range, Basojet XP, has been designed to cater for all 100% polyester exhaust dyeing, of which 70–80% can be processed with this product alone, in combination with normal pH control. According to BASF, Basojet XP, the basis of dyexact XP range, is an effective levelling and disposing agent with excellent anti-oligomer property suitable for high temperature dyeing of polyester with disperse dyes. It offers a large number economic and ecological advantages such as procontrol and high levels of process reliability.

Besides these some dye-bath exhaustion monitoring software based on Flow Injection Analysis (FIA) methods to monitor the dyeing of polyester, cellulose acetate and cotton have been developed. These methods avoid some of the problems of direct spectrophotometric dye-bath measurement of dye concentrations. Using FIA methods successfully monitored the disperse dyeing of polyester yarns and the individual exhaustion characteristics of three mixed dyes can be carried out.

10.5.2 Continuous dyeing

A process for continuous dyeing of polyester by padding the fabric with disperse dyes and curing the padded, dried fabric at 180–220°C for 45–180 s was developed and patented by du Pont in 1953.[69] This process which is called 'Thermosol Dyeing' was licensed for use by industry for the dyeing of polyester-cellulosic blended fabrics in the late 1950s. Since then the process is being mainly used for dyeing of polyester blends on continuous dyeing ranges (CDRs).

Numerous studies have been carried out on the optimization of the degree of fixation as a function of the concentration of the padding bath and of the temperature and time of heat fixation in the Thermosol dyeing of polyester fibres. It is reported that the rate of diffusion of dye into polyester is doubled for a 10°C temperature increase.[70]

The use of dyes having good sublimation fastness is recommended. However, it has been observed that the higher the sublimation fastness of the dye, the higher the temperature required for its levelling and the higher the operating temperature required in the dyeing; hence, the choice of dyes employed in mixtures is important for attaining maximum dye buildup.[71] From the studies on the Foron S and SE dyes of Sandoz (now Clariant) Somm and Gerber[72] have surmised that the diffusion coefficients of dyes with low sublimation fastness are greater than those with high sublimation fastness but during dyeing the former are absorbed through vapour phase migration while the latter are absorbed by direct contact.

Attempts have also been made to dye both cotton and polyester with vat dyes. Vat dyes generally give different shades on polyester; however, some of the dyes were found to give reasonable good shades.[73] In a recent study it has been reported that colour depth of vat dyes increased by adding urea in the padding solution.[74] The use of auxiliary chemicals in the padding bath to increase the diffusion and uptake of disperse dyes has been extensively investigated. Since the Thermosol dyeing of polyester proceeds by first dissolving the dye on the surface layer at low temperature followed by its diffusion into fibre at high temperature, those compounds that have high solubilising capacity and melt during curing can increase the dye uptake.[75] Many nonionic surfactants have been recommended as accelerants for intensifying the colour and yield of disperse dyes applied by Thermosoling process. Their mechanism of action has been recently reviewed by Manian and Etters.[76] According to these authors nonionic surfactants may act as fixation accelerants by accelerating the rate of dye dissolution in the auxiliary melt. At high surfactant concentrations, dye retention in surfactants may adversely affect dye fixation.

Decheva *et al.*[77–79] on the basis of their intensive study have recommended the use of caprolactam as an additive in the padding bath for its intensifying effect. According to these investigators the solubilising and dispersing effect of caprolactam, its chemical inertness toward disperse dyes, its non-detrimental effect on colour fastness and fibre properties, its ability to decrease the temperature and time of dyeing, and its positive effects on fixation and other properties of a wide variety of disperse dyes make it an ideal intensifier for use in Thermosol dyeing of polyester fibres. The use of caprolactam results in lowering the Thermosol temperature by 10°C and Thermosoling duration by 15 s. In a later study Dusheva and Aleksandrova[80] have stated that the presence of caprolactum enhances the effect of temperature on the supramolecular structure of polyester by increasing segment mobility of the macromolecular chain in the non-crystalline regions, and facilitates the relaxation and crystallization processes so that a supramolecular structure of higher micro-heterogeneity and, correspondingly, better accessibility of the non-crystalline area of the fibre is created. These changes facilitate the formation of new crystalline aggregates under the effect of disperse dyes. Caprolactam also decreases the oligomer content on the fibre surface and creates an energetically more uniform surface which promotes sorption. The rate of dyeing increases 1.5-fold.

While investigating the effect of orientation of the fibre on the rate of dyeing it was observed that rate of Thermosol dyeing was much greater in partially elongated than in fully elongated fibres.[81] On the other hand it was observed that the orientation of the fibre decreases with increasing Thermosoling temperature.[82] Moreover, the fixation of disperse dyes on polyester fibres in Thermosol dyeing decreases with increasing crystallinity of the fibres.[83] However, on Thermosol dyeing, three types of crystalline aggregates are formed, that is, aggregates containing only polymer molecules, those containing predominately polymer molecules but incorporating some dye molecules, and those the recrystallization of which has been influenced by the dye molecules incorporated in the crystal lattice.[84]

10.6 New methods of dyeing

10.6.1 Non-aqueous dyeing

Organic solvent dyeing

Dyeing of polyester from aqueous medium generates substantial effluent that needs to be disposed of after proper remediation treatment. Attempts were made during the 1970s to replace water with organic solvent for the exhaust as well as continuous dyeing of polyester. Of the various solvents investigated perchloroethylene and trichloroethylene were found to be promising. The economics of the process depended on the recovery of the solvent (~95%) from the exhausted dye bath after dyeing.

Exhaust dyeing of polyester from perchloroethylene with disperse dyes results in higher dyeing speeds due to faster diffusion, better levelling and migration and better oligomer removal. However, the exhaustion of the dye is low and addition of auxiliary solvents such as DMF, methanol and benzyl alcohol in the presence of 1% water in the dye bath increased it to almost 100%.[85–87] These auxiliary solvents and water have been reported to lower the Tg of the fibre and also act as solvents for the dye.[88]

In another study it is postulated that in solvent dyeing of polyesters with disperse dyes, diffusion and partition coefficients are controlled through choice of the solubility parameters of the solvent. If a solvent is selected that has a solubility parameter close to that of polyester the diffusion coefficient will be high and the partition coefficient will be low. If a solvent is selected with a very different solubility parameter from that of the polymer, the diffusion coefficient will be low while the partition coefficient will be high.[89]

In a recent study by Kim, Son and Lin,[90] the adsorption and solubility properties of disperse dyes on polyester from 29 solvent were examined. They observed that the dye adsorptions in alkane media were much higher than those in other non-aqueous systems. From the results of the relationship between the adsorption and the solubility of disperse dyes, it was concluded that the dye adsorptions onto polyester were linearly and inversely proportional to the dye solubilities in non-aqueous media. In a subsequent study with ten different dyes dyed from pentane Kim and Son[91] confirmed their previous observation about the relation between dye sorption and its solubility. While investigating the interaction of polyester with various solvents it was observed that some of the solvents modified the physical structure of the fibre resulting in higher dye uptake.[92] This observation led to a series of studies on the dyeability of solvent pretreated polyester at or below 100°C.[93–97] Weigmann *et al.*[93] have thoroughly investigated the effect of DMF on polyester and proposed that the treatment of polyester with DMF at high temperature results in the swelling of the fibre that leads to the formation of crystallites within the swollen structure, which, depending on the size and stability of the crystallites, can be stabilized to form voids upon removal of the interacting medium. A rigid pore mechanism of dye diffusion operates in this structure as opposed to the free volume mechanism of diffusion of dyes in thermally treated polyester yarns. In a later study[94] these investigators have claimed that the solvent treatments of polyester yarn, which increase dyeability, do not change the dye-diffusion mechanism and the significant increase in dye-diffusion coefficient resulting from the solvent treatment is attributable to increased segmental mobility in noncrystalline domains of the treated fibre. The increased amount of dye is believed to be held in voids in the fibre structure formed during solvent treatment. Pretreatment in DMF also resulted in a lowering of tensile strength and initial modulus, whereas subsequent dyeing caused further reduction in extensibility.[95]

Moore and Weigmann[96] while studying the effect of pretreatment of polyester fibres with CH_2Cl_2 found that this pretreatment led to greater dye penetration, due either to residual CH_2Cl_2 in the yarn or to solvent-induced structural changes occurring in the yarn during pretreatment. The literature on solvent-induced modifications of polyester structure, properties and dyeability has been reviewed;[97] however, no commercially successful process had been adopted at the time of writing.

10.6.2 Dyeing in supercritical carbon dioxide

A process of dyeing from supercritical carbon dioxide ($scCO_2$) was patented by Schollmeyer *et al.*[98] in 1990 with a claim that when a polyester knitted fabric is dyed with the disperse dyes from supercritical CO_2 at 130°C and 250 bar pressure the dyeings were more brilliant, had a 20–40% increase in depth of dyeing, and were comparable in fastness properties to those produced by the conventional Thermosol process. This process offers a number of ecological and economic advantages, such as, no treatment of wastewater, no drying, improved dye utilization, no addition of chemicals, no reductive after-treatments, shorter dyeing times, and no restrictions on location because of availability of water.[97]

Various studies have indicated that $scCO_2$ does not damage or modify the fibre during dyeing provided it is properly heat-set preferably at a temperature that is 30°C higher than the dyeing temperature. The Tg of the fibre is not significantly altered in $scCO_2$ hence the dying should be carried out at 90°C to 140°C as in the case of conventional HT-HP dyeing. Higher temperature should be used for darker shades.[100]

During the $scCO_2$ dyeing of polyester disperse dyes are dissolved into the supercritical phase, transported to the fibre and adsorbed onto the surface. Finally, the dye molecules diffuse into the CO_2-swollen polymer matrix, where they are held mainly by dispersion forces. On reducing the pressure after dyeing, the CO_2 molecules escape from the fibres while the dye molecules are retained. This dyeing mechanism was suggested by Saus *et al.*[101] and subsequently confirmed by Tabata *et al.*[102] $ScCO_2$ has a density and dissolvability similar to liquids, but viscosity and diffusion properties similar to gases.

Suitability of disperse dyes, that have been developed for dyeing from an aqueous medium, for dyeing from $scCO_2$ has been extensively investigated.[100,103] Generally solubility is low for all dyes and is between 10^{-4} and 10^{-7} mol dye/mol CO_2 under the dyeing condition of 120–140°C and 300 bar pressure which is similar to that in water. Moreover, the dye uptake in CO_2 is nearly comparable to conventional aqueous dyeing but not to organic solvent dyeing.[102] It has been observed that changes in the temperature and pressure result in significant colour differences in terms of colour yield and hue. During dyeing, the dyes seem to compete for accessible regions of the fibre where the dyes with the lowest molecular weight have the highest mobility resulting in higher dye uptake compared with the higher molecular weight dyes. This causes differences in colour with slight variation in temperature and pressure of dyeing, especially when mixtures of dyes are used.[104] Keeping the non-linear exhaustion behaviour of the dyes in $scCO_2$, a new colour matching system has been developed.[100]

First dyeing machine with a capacity to dye 4 bobbins of 2 kg yarn each was constructed by Jasper GmbH & Co in 1991 and installed by Amann & Sŏhne GmbH & Co. However, there was need to improve the technology. Later on UHDE Hochdrucktechnik GmbH of Germany made a pilot plant having improved technology that also has some shortcomings.[100] A commercial-scale 1000-litre supercritical dyeing machine has been designed, for treating 300 kg polyester while recycling all dye and 96% of the CO_2 by van der Karaan.[105] An economic analysis showed that, although the purchase cost for a supercritical machine is higher (k€ 500) than for an aqueous machine (k€ 100), the operating cost is lower (0.35 instead of € 0.99 per kg polyester). This is due to the higher rate of dyeing and by the simpler dye formulations that can be used in $scCO_2$. The overall result is a 50% lower process cost for the supercritical process.

10.6.3 Dyeing from alkaline medium

Dyeing of polyester from an alkaline medium offers an opportunity to dye polyester cellulosic blends by a single bath single stage process. Most of the disperse dyes are adversely affected when heated in an alkaline bath; however, some select dyes have been found to be stable in an alkaline dye bath. It has been observed that the majority of disperse dyes are sensitive to the water hardness and the residual impurities present in the fibre when dyed in alkaline medium. Moreover the pH of the dye bath shifts towards neutral during dyeing.[106] In order to overcome these problems of dyeing in an alkaline medium a special auxiliary chemical such as Diaserver AD-95 (DyStar) that has many functions (e.g. in stabilizing dyestuffs, sequestering agents, buffering, and dissolving oligomers) must be used. Optimal conditions for attaining higher *K/S* values for alkali stable Dianix AD dyes of DyStar have been worked out to be 130°C for 45 min in the presence of 2% Diaserver AD-95.[107]

The alkaline dyed polyester showed increased values of specific breaking stress and elongation, but lower abrasion resistance than the acid dyed yarns. The results of the extraction of oligomers showed that the virgin and the acid dyed polyester samples possessed higher oligomer content, whereas the oligomer content in the alkaline dyed polyester was lower. The measured colour intensity of the samples dyed with the Dianix AD dyes in an alkaline medium was slightly lower than that of the acid dyed samples.[108]

10.7 Dyeing of chemically modified polyester fibres

10.7.1 Basic-dyeable polyester

Chemical modification of PET polyester permits a substantial change in its dyeability without any significant change in their physicomechanical properties. Of the various methods of modification, incorporation of 2–3 mol % of sodium salt of 5-sulphetoisophthalic acid into the basic PET polymer to impart basic dyeabily has been commercially successful and various anionically modified fibres have been introduced in the market. The possibility of dyeing with cationic dyes entails the following advantages compared with normal disperse dyeing: (a) dyestuff costs are lower; (b) shades are more brilliant; (c) reduction clearing step is eliminated; and (d) sublimation fastness of the dyeings is high. There are some problems that need to be looked into, such as: (a) light fastness of the cationic dyes; (b) levelling and reproducibility of the dyeings due to very high affinity of the dyes for these fibres; and (c) hydrolysis of the fibre during dyeing.[109]

Since these fibres are prone to hydrolysis during dyeing they are dyed at 120°C in the presence of 2–6 g/L of sodium sulphate to protect the fibre.

It is postulated that the addition of salt prevents the exchange of sodium ions of the fibre with the hydrogen ions that is the critical step in the hydrolysis of the fibre.[110]

The cationic dyes form electrovalent bonds with the sulphonic acid and carboxyl groups of the fibre and the amount of dye sorbed by the fibre is dependent on the number and accessibility of these groups. The accessibility of the anionic groups is a function of both the morphology and temperature of dying. X-ray diffraction data showed that the crystalline regions of these fibres are formed of segments of unaltered poly (ethylene terephthalate); the modified polyester segments remained in the noncrystalline regions. The degree of crystallinity of the modified fibres of similar thermal history is 10% lower than that of the unmodified fibres and the density and orientation of noncrystalline regions in the modified fibres is lower than in the nonmodified fibres.[111] Ingamells, Lilou and Peters[112] have reported that the accessibility of the sulfonate groups in the fibres is greatly improved by plasticisation and is independent of the size of the exchanging ion. Since the fibre structure limits the accessibility of anionic centres so the sorption of the dye is not in stoichiometric proportion to the dye sites.

Pal, Gandhi and Kothari[113] produced cationic dyeable polyester (CDPET) having different amounts of dimethyl ester of 5-sulfoisophthalic acid (DMS) salt through melt blending of normal polyester and cationic dyeable polyester chips. The presence of DMS salt disturbs the structure of CDPET fibre. The dyeability of both disperse dyes and cationic dyes on CDPET improves with increase in DMS salt content. The proper amount of DMS salt in CDPET is important to get a fibre with good dyeability as well as satisfactory mechanical properties. The mechanical properties of textured CDPET with more than 1.5 mol % DMS salt decrease rapidly, indicating the limit of increase in DMS salt in CDPET fibre.

10.7.2 Easy-dyeable polyester

A large number of processes for the modification of polyester by incorporating a comonomer or copolymer into the PET so as to make it dyeable at or below 100°C have been patented over 40 years.[114–117] Such fibres are collectively termed as easy-dyeable polyesters. Such polyester fibres have low crystallinity and low Tg. Due to their having low Tg the segmental motion of polymer chains in the dye-accessible regions sets in at lower temperature thereby allowing the dye to diffuse at temperature below boiling. Dyeing properties of two recently introduced polyester fibres, that is, an easy-dyeable polyester (EDP) fibre and polytrimethylene terephthalate (PTT) fibre, has been investigated by Kim, Son and Lin.[118] EDP is manufactured by polymerizing terephthalic acid with a mixture of polyethylene glycol and normal ethylene glycol. In the case of polyethylene glycol, the degree of polymerization is 500–1000. This approach for EDP fiber is to relax the compact structure of the fiber molecules, to improve its hydrophilicity and finally to reduce its dyeing temperature.[115] In addition, PTT is produced by polymerizing terephthalic acid with 1,3-propandiol instead of ethylene glycol to increase mobility and flexibility of the polymer molecular chains and to make it easy for disperse dye to penetrate into the fibre substrates. They found that the standard affinities of EDP and PTT were a little higher than those of PET and the activation energy of EDP and PTT was lower than that of PET thereby indicating that these fibres can be dyed at lower temperatures than PET.

One approach to produce deep-dyeable polyester involves the production of polyester from the PET/SiO_2 nanocomposites. The TEM photographs show that the SiO_2 nanoparticles get dispersed in the PET matrix at a size level of 10–20 nm. The DSC results indicated that the SiO_2 nanoparticles acted as nucleating agent, promoting the crystallization of the PET matrix from melt but inhibiting the crystallization from the glassy state, owing to the 'crosslink' interaction between the PET and SiO_2 nanoparticles. Dyeing of such fibres gives deeper dyeings.[119]

10.7.3 Surface modification of fibres

For the past 25 years, studies are being pursued on the surface modification of polyester to enhance their dyeability and depth of colour by exposing them to plasma,[120] UV laser[121] and vacuum UV radiations[122,123] in different gaseous atmospheres. Four approaches are being pursued to get deeper colours on polyester, namely: (a) optical effect due to nano-roughening of the fibre surface that modifies the reflectance of light from the surface; (b) changes in the morphology of the exposed surface; (c) creation of additional functional groups; and (d) anti-reflective film coating of the surface.[124]

Raffaele-Addamo *et al.*[120] observed an increase in colour depth upon dyeing plasma treated polyester fabrics. This has been attributed to optical effects caused by the plasma-induced increase of surface roughness that decreases the fraction of light reflected from treated surfaces with respect to smoother surfaces. Other effects such as increased surface area and modifications of the partition equilibrium of the dye between the dyeing bath and the macromolecular surface may also play a role.

It is reported[121] that exposure of polyester fabrics to UV laser causes regular ripples perpendicular to the axis of the fibre. The amorphous regions of the surface as well as the number of carboxyl groups increase after UV laser treatment. A greater depth of shade was achieved on treated fabrics compared with untreated fabrics dyed with the same amount of disperse dye. This is due to the scattering of light caused by ripples on the fibre surface, and greater dye uptake by the amorphous regions on the surface of laser irradiated PET fabrics.

10.8 References

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