3

Technical yarns

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3.1 Introduction

Technical yarns are produced for the manufacture of technical textiles. They have to meet the specific functional requirements of the intended end-use. This may be achieved through special yarn production techniques or through the selection of special fibre blends or a combination of both. This chapter describes the yarn production technologies that are applicable to technical yarns and discusses the structures and properties of the yarns that may be produced using these technologies.

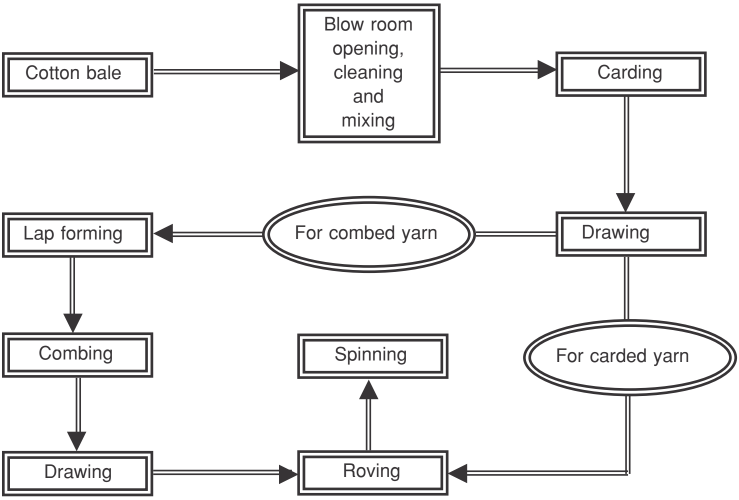
3.2 Staple fibre yarns

3.2.1 Ring spinning

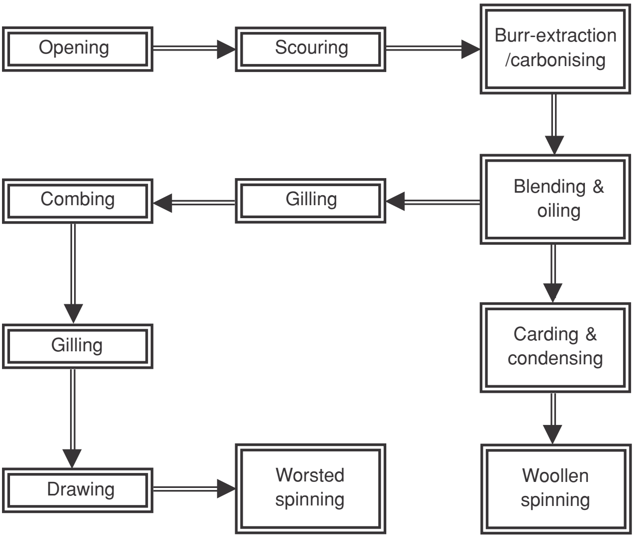
Ring spinning is currently the most widely used yarn production method. Initially developed in America in the 1830s, its popularity has survived the emergence of much faster spinning technologies. In addition to the superior yarn quality, ring spinning is extremely versatile. It is capable of producing yarns with wide ranges of linear density and twist from a great variety of fibre materials. It is also used for doubling and twisting multifold and cabled yarns.

Fibre materials must be properly prepared before they can be used on the ring spinning machine. The preparation processes are dependent on the fibre material. Figures 3.1 and 3.2 illustrate the typical process routes for cotton and wool. The ultimate objectives of the many preparation processes are to produce a feed material for the final spinning process that is clean, even, homogeneous and free from fibre entanglement. The fibres must also be in the preferred orientation.

On the ring spinning machine, the feed material is attenuated to the required linear density by a drafting system, typically a roller drafting system with three lines of rollers. The drafted fibre strand is then twisted by the ring spindle illustrated in Fig. 3.3.



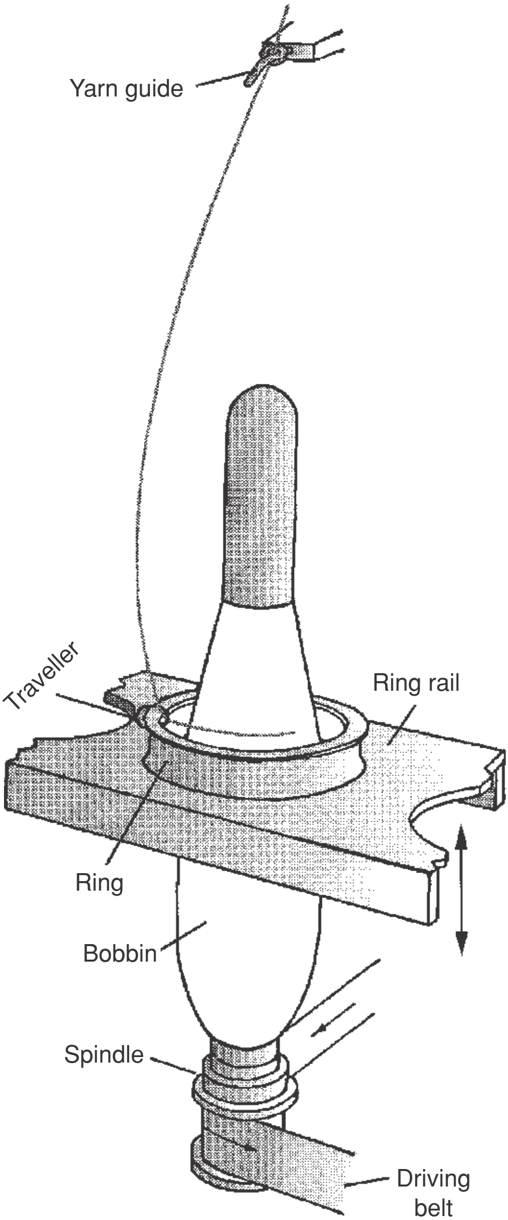
3.1 Production of ring-spun cotton yarn.



3.2 Production of wool yarn.

The yarn leaving the front rollers is threaded through a yarn guide (the lappet), which is located directly above the spindle axis. The yarn then passes under the C-shaped traveller onto the bobbin. The bobbin is mounted on the spindle and rotates with the spindle. When the bobbin rotates, the tension of the yarn pulls the traveller around the ring. The traveller rotational speed, the spindle rotational speed and the yarn delivery speed follow Equation 3.1:

$$N_t = N_s - \frac{V_d}{\pi D_b} \tag{3.1}$$



3.3 Ring spindle.

where N_t is the traveller rotational speed (rpm), N_s is the spindle rotational speed (rpm), V_d is the yarn delivery speed ($\mathrm{m\,min^{-1}}$) and D_b is the bobbin diameter (m).

During production, the bobbin rail moves up and down to spread the yarn along the length of the bobbin so that a proper package can be built. The movement of the ring rail is quite complicated, but the aim is to build a package that is stable, easy to unwind and contains the maximum amount of yarn. As the yarn is wound on the bobbin, the bobbin diameter increases steadily during production. The spindle speed and the yarn delivery speed are normally kept constant, it is therefore obvious from Equation 3.1 that the traveller speed increases during production.

Each rotation of the traveller inserts one full turn in the yarn, so the twist inserted in a unit length of yarn can be calculated by Equation 3.2:

$$t = \frac{N_t}{V_d} \tag{3.2}$$

where t is the yarn twist (turns m^{-1}).

Because the traveller speed is not constant, the twist in the yarn also varies. However, because this variation is usually very small, it is commonly ignored and the twist is simply calculated from the spindle speed, Equation 3.3:

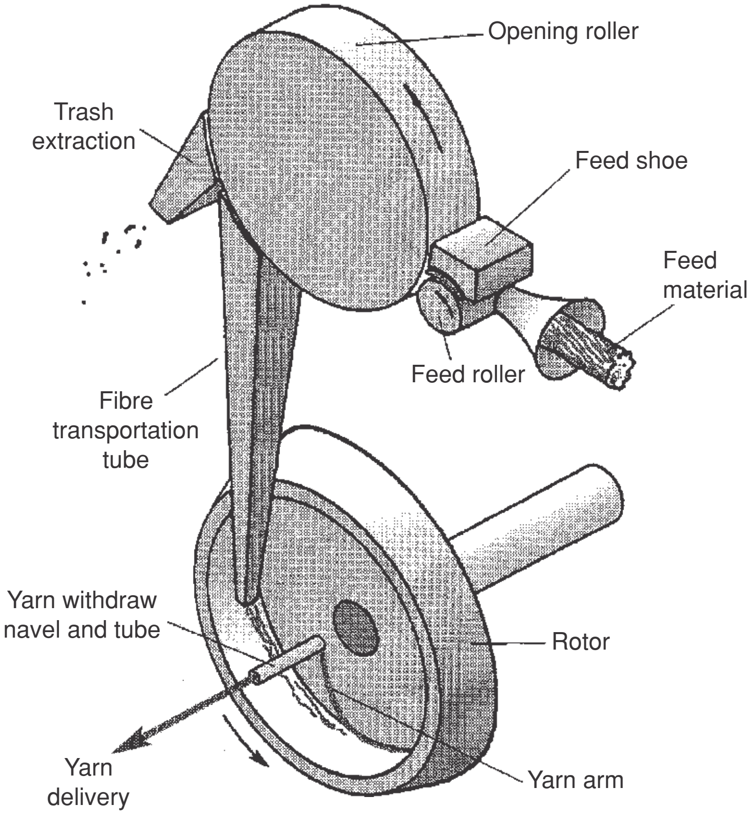
$$t = \frac{N_s}{V_d} \tag{3.3}$$

As can be seen from Equation 3.3, for a given yarn twist, the higher the spindle speed the higher the yarn delivery speed. A spindle speed of up to 25 000 rpm is possible, although speeds of between 15 000 and 20 000 rpm are more usually used. The spindle speed is restricted by the traveller speed, which has an upper limit of around 40 m s^{-1}. When the traveller speed is too high, the friction between the traveller and the ring will generate too much heat, which accelerates the wear on the traveller and the ring and may also cause yarn damage. The yarn between the yarn guide and the traveller rotates with the traveller and balloons out owing to centrifugal force. The tension in the yarn increases with the rotational speed of the yarn balloon. When the spindle speed is too high, the high yarn tension will increase the yarn breakage. The traveller speed and the yarn tension are the two most critical factors that restrict the productivity of the ring spinning system. The increasing power cost incurred by rotating the yarn package at higher speeds can also limit the economic viability of high spindle speeds. For the same traveller linear speed, using a smaller ring allows a higher traveller rotational speed and increases delivery speed. A smaller ring also reduces yarn tension, as the yarn balloon is also smaller. However, a smaller ring leads to a smaller bobbin which results in more frequent doffing.

Ring-spun yarns have a regular twist structure and, because of the good fibre control during roller drafting, the fibres in the yarn are well straightened and aligned. Ring spun yarns therefore have excellent tensile properties, which are often important for technical applications.

The ring spinning system can be used for spinning cover yarns where a core yarn, spun or filament, is covered by staple fibres. This can provide yarns with a combination of technical properties. For example, a high strength yarn with good comfort characteristics may be spun from a high strength filament core with natural fibre covering. Other technical yarns, such as flame-retardant and antistatic yarns can also be made by incorporating flame-retardant and electricity conductive fibres.

The main limitation of the ring spinning system is the low productivity. The other limitations are the high drafting and spinning tensions involved. These high tensions can become a serious problem for spinning from fibres such as alginate fibres that have low strength.



3.4 Rotor spinning principle.

3.2.2 Rotor spinning

The productivity limitation of the ring spinning system was recognised long before the commercial introduction of rotor spinning in 1967. In ring spinning, the twist insertion rate is dependent on the rotational speed of the yarn package. This is so because of the continuity of the fibre flow during spinning. Numerous attempts have been made since before the end of the 19th century, particularly since the 1950s, to introduce a break into the fibre flow so that only the yarn end needs to be rotated to insert twist. Very high twisting speeds can thus be achieved. In addition, by separating twisting from package winding, there will be much more flexibility in the form and size of the yarn package built on the spinning machine. This increases the efficiency of both the spinning machine and of subsequent processes. Rotor spinning was the first such new technology to become commercially successful and it is the second most widely used yarn production method after ring spinning.

The principles of rotor spinning are illustrated in Fig. 3.4. The fibre material is fed into an opening unit by a feed roller in conjunction with a feed shoe. The feed material is usually a drawn sliver. An opening roller is located inside the opening unit and is covered with carding wire, usually saw-tooth type metallic wire. The surface speed of the opening roller is in the region of 25–30 $\mathrm{m\,s^{-1}}$, approximately 2000 times the feed roller surface speed. This high speed-ratio enables the fibres to be opened up into a very thin and open fibre flow. The fibres are taken off the opening roller by an air stream with a speed about twice that of the opening roller. The fibres are carried by the air stream, through the fibre transportation tube, into the spinning rotor. The air speed in the transportation tube increases, owing to the narrowing cross-section of the tube, as the air reaches the exit point inside the rotor. This ensures that the fibres are kept aligned along the airflow direction and as straight as possible. The exit angle of the fibres from the transportation tube is at a tangent to the rotor wall and the surface speed of the rotor is faster than the exit air speed, so the fibres emerging from the transportation tube are pulled into the rotor, keeping the fibres aligned in the direction of the fibre flow. The centrifugal force generated by the rotor forces the fibres into the rotor groove. Because of the high surface speed of the rotor, only a very thin layer of fibres, usually one or two fibres in the cross-section, is deposited in the rotor when the rotor passes the fibre exit point of the transportation tube. Many such layers of fibres are needed to make up the yarn. This doubling up of the fibres in the rotor is called back doubling.

The tail of the yarn arm inside the rotor is thrown against the rotor groove because of the centrifugal force. The yarn arm rotates with the rotor and each rotation of the yarn arm inserts one full turn in the yarn. As the yarn is withdrawn continuously through the navel and tube, the contact point of the yarn arm with the rotor groove must move around the rotor. Because the yarn arm is rotating axially, the fibres in the rotor groove are twisted into the yarn. The machine twist of the yarn can be calculated by Equation 3.4:

$$t = \frac{N_y}{V_d} \tag{3.4}$$

where t is the yarn twist (turns m^{-1}), N_y is the rotational speed of the yarn arm (rpm) and V_d is the yarn delivery speed ($\mathrm{m\,min}^{-1}$).

The following relationship exists between the yarn arm speed, the rotor speed and the yarn delivery speed, Equation 3.5:

$$(N_y - N_r)\pi D = V_d \tag{3.5}$$

where D is the diameter of rotor groove.

The relative speed between the yarn arm and the rotor is normally very small in comparison with the rotor speed and the machine twist of the yarn is commonly calculated by Equation 3.6:

$$t = \frac{N_r}{V_d} \tag{3.6}$$

The back-doubling ratio β is equal to the ratio of the rotor speed to the relative speed between the yarn arm and the rotor, Equation 3.7:

$$\beta = \frac{N_r}{N_y - N_r} = \frac{N_r}{V_d}\pi D = t\pi D \tag{3.7}$$

Because there is no need to rotate the yarn package for the insertion of twist, rotor spinning can attain much higher twisting speeds than ring spinning. The rotor speed can reach 150 000 rpm. The roving process needed in ring spinning is eliminated in rotor spinning, further reducing the production cost. The package can be much larger, with fewer knots in the product and with a more suitable form for subsequent processes.

Because the yarn is formed in an enclosed space inside the rotor, trash particles remaining in the fibres can accumulate in the rotor groove. This leads to a gradual deterioration of yarn quality and in severe cases yarn breakage. The cleanliness of fibres is more critical for rotor spinning than for ring spinning. In order to improve the cleanliness of the fibres, a trash extraction device is used at the opening roller.

As the twist in the yarn runs into the fibre band in the rotor groove, inner layers of the yarn tend to have higher levels of twist than outer layers. Fibres landing on the rotating fibre band close to the yarn tail, or directly on the rotating yarn arm when the yarn arm passes the exit of the transportation tube, tend to wrap around the yarn instead of being twisted into the yarn. These wrapping fibres are characteristic of rotor-spun yarns.

Rotor-spun yarns usually have lower strength than corresponding ring-spun yarns because of the poorer fibre disposition in the yarn. This is the result of using an opening roller to open up the fibres, of transporting the fibres by airflow, and of the low yarn tension during yarn formation. The wrapping fibres also lead to a rougher yarn surface. Rotor yarns have better short term evenness than ring-spun yarns because of the back-doubling action.

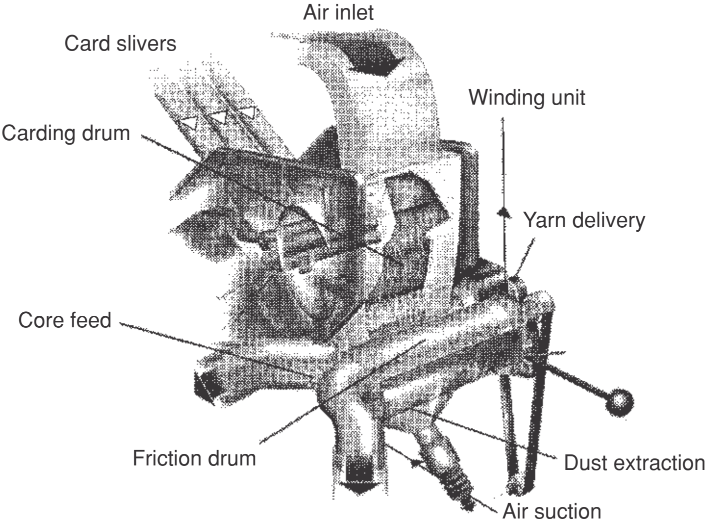
The main advantage of rotor spinning is the high production rate. However, because of the lower yarn strength, rotor spinning is limited to medium to course yarn linear densities. It is also limited to the spinning of short staple fibre yarns.

3.2.3 Friction spinning

Friction spinning is an open end spinning technique. Instead of using a rotor, two friction rollers are used to collect the opened-up fibres and twist them into the yarn. The principle is shown in Fig. 3.5.

The fibres are fed in sliver form and opened by a carding roller. The opened fibres are blown off the carding roller by an air current and transported to the nip area of two perforated friction drums. The fibres are drawn onto the surfaces of the friction drums by air suction. The two friction drums rotate in the same direction and because of the friction between the fibre strand and the two drum surfaces, twist is inserted into the fibre strand. The yarn is withdrawn in the direction parallel to the friction drum axis and delivered to a package forming unit. The friction drum diameter is much larger than the yarn diameter. The diameter ratio can be as high as 200. A high twisting speed can thus be achieved by using a relatively low speed for the friction drums. Owing to the slippage between the drum surface and the yarn end, the yarn takes up only 15–40% of the drum rotation. Nevertheless, a high production speed, up to 300 m min^{-1}, can be achieved. For a finer yarn the twist insertion rate is higher with the same drum speed so the delivery speed can be practically independent of yarn linear density.

Because the yarn is withdrawn from the side of the machine, fibres fed from the machine end away from the yarn delivery tend to form the yarn core while fibres fed from the machine end closer to the yarn delivery tend to form the sheath. This characteristic can be conveniently exploited to produce core–sheath yarn structures. Extra core components, filaments or drafted staple fibres, can be fed from the side of the machine while the fibres fed from the top of the machine, the normal input, form the sheath.



3.5 DREF 2 friction spinner.

Unlike ring or rotor spinning machines that are produced by many manufacturers around the world, friction spinning machines are only currently made by Dr. Ernst Fehrer AG of Austria. The diagram shown in Fig. 3.5 is the DREF 2 machine that has recently been upgraded to DREF 2000. The company also produces the DREF 3 machine that has an extra drafting unit on the side of the machine for feeding drafted staple fibres as a core component.

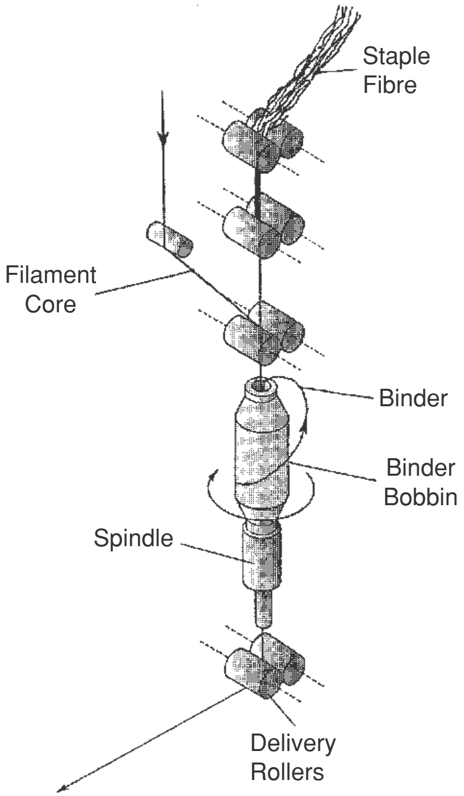
The fibre configuration in friction-spun yarns is very poor. When the fibres come to the friction drum surface, they have to decelerate sharply from a high velocity to almost stationary. This causes fibre bending and disorientation. Because of the very low tension in the yarn formation zone, fibre binding in the yarn is also poor. As a result, the yarn has a very low tensile strength and only coarse yarns, 100 tex and above, are usually produced.

The main application of friction spinning is for the production of industrial yarns and for spinning from recycled fibres. It can be used to produce yarns from aramid and glass fibres and with various core components including wires. The yarns can be used for tents, protective fabrics, backing material, belts, insulation and filter materials.

3.2.4 Wrap spinning

Wrap spinning is a yarn formation process in which a twistless staple fibre strand is wrapped by a continuous binder. The process is carried out on a hollow spindle machine as illustrated in Fig. 3.6. The hollow spindle was invented by DSO 'Textil' in Bulgaria. The first wrap spinning machine was introduced in the 1979 ITMA.

The staple roving is drafted on a roller drafting system similar to those used on ring frames and is passed through a rotating hollow spindle that carries a binder bobbin. The rotation of the hollow spindle and the bobbin wraps the binder around the staple strand.



3.6 Wrap spinning principle.

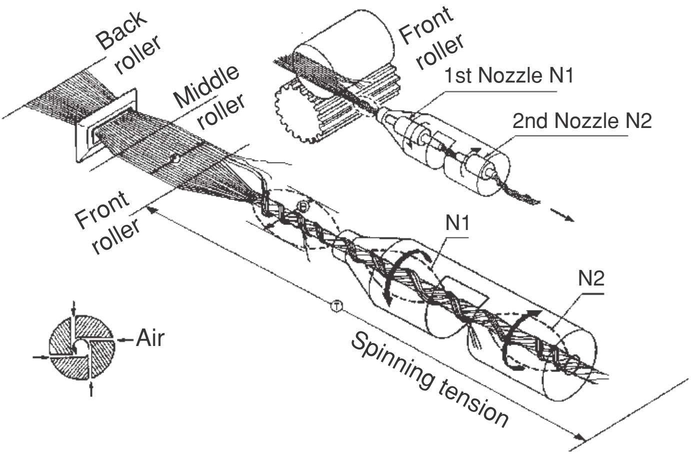
To prevent the drafted staple strand falling apart before it is wrapped by the binder, false twist is usually generated in the staple strand by the spindle. To introduce the false twist, the staple strand is not threaded through the hollow spindle directly. It is wrapped around either a twist regulator at the bottom of the spindle or part of the spindle top. The false twist also allows the staple strand to be compacted before the binder is wrapped around it. This improves the yarn strength.

Two hollow spindles can be arranged one above the other to wrap the staple strand with two binders in opposite directions. This is used to produce special effect yarns with a more stable structure. Real twist may also be added to the yarn by passing the wrapped yarn onto a ring spindle, usually arranged directly underneath the hollow spindle.

Core yarns, mostly filaments, can be added to the feed. This can be used to provide extra yarn strength or other special yarn features. An example is to use this method to spin alginate yarns. Alginate fibres are very weak and cause excessive breakages during spinning without the extra support of core filaments.

A variety of binders can be used to complement the staple core or to introduce special yarn features. For example, a carbon-coated nylon filament yarn can be used to produce yarns for antistatic fabrics. Soluble binders can be used for making yarns for medical applications.

Wrap spinning is highly productive and suitable for a wide range of yarn linear densities. Yarn delivery speeds of up to 300 m min^{-1} are possible. Because the binder is normally very fine, each binder bobbin can last many hours, enabling the pro-



3.7 Murata jet spinner.

duction of large yarn packages without piecing. Because the staple core is composed of parallel fibres with no twist, the yarn has a high bulk, good cover and very low hairiness. The main limitation of wrap spinning is that it is only suitable for the production of multicomponent yarns. The binder can be expensive, increasing the yarn cost.

3.2.5 Air-jet spinning

Air-jet spinning technology was first introduced by Du Pont in 1963, but it has only been made commercially successful by Murata since 1980. Du Pont used only one jet, which produced a low strength yarn. The Murata system has two opposing air jets, which improves the yarn strength. The twin-jet Murata Jet Spinner is illustrated in Fig. 3.7. Staple fibres are drafted using a roller drafting system with three or four pairs of rollers. The fibres are then threaded through the twin-jet assembly. The second jet N_2 has a higher twisting torque than the first jet N_1. Immediately after leaving the front drafting rollers, the fibres in the core of the yarn are twisted in the twist direction of N_2. The fibres on the edges of the drafted ribbon are twisted by the weaker N_1 and wrap around the core fibres in the opposite direction. Because the jet system is located between the front drafting rollers and the yarn delivery rollers, neither of which rotates around the axis of the yarn, the twist inserted by the jets is not real twist and after the yarn passes through the jet system, the core fibres become twistless. The yarn strength is imparted by the wrapping of the edge fibres. Because of the small jet dimensions, very high rotational jet speeds are possible. Although twist efficiency is only 6–12% because of the twist resistance of the yarn, delivery speeds of up to 300 m min^{-1} are possible. In a further development by Murata the second jet is replaced with a pair of roller twisters. The principle of yarn formation is similar to the twin-jet system. The new machine, the roller-jet spinner, is capable of delivery speeds of up to 400 m min^{-1}. However, the yarn has a harsher handle.

Air-jet spinning is used mainly for spinning from short staple fibres, especially cotton and polyester blends. The vortex spinner, the latest addition to the Murata jet spinner range, was shown in ITMA 99 for spinning from 100% cotton.

The air-jet system can be used to produce core–sheath yarn structures by feeding the core and sheath fibres at different stages of the drafting system. Fibres fed in from the back of the drafting system tend to spread wider under the roller pressure and form the sheath of the yarn while fibres fed in nearer to the front tend to form the yarn core. Filament core can also be introduced at the front drafting roller. Two spinning positions can be combined to produce a two-strand yarn that is then twisted using the usual twisting machinery.

Air-jet yarns have no real twist, therefore they tend to have higher bulk than ring and rotor yarns and better absorbency. They are more resistant to pilling and have little untwisting tendency. Because the yarn strength is imparted by the wrapping fibres, not the twisting of the complete fibre strand, air-jet yarns have lower tensile strength than ring and rotor yarns. The system is only suitable for medium to fine yarn linear densities as the effectiveness of wrapping decreases with the yarn thickness. The rigid yarn core of parallel fibres makes the yarn stiffer than the ring and rotor yarns.

3.2.6 Twistless spinning

Numerous techniques have been developed to produce staple yarns without twisting so that the limitations imposed by twisting devices, notably the ring traveller system, can be avoided and production speed can be increased. Because of the unconventional yarn characteristics, these techniques have not gained widespread acceptance commercially, but they do offer an alternative and could be exploited to produce special products economically.

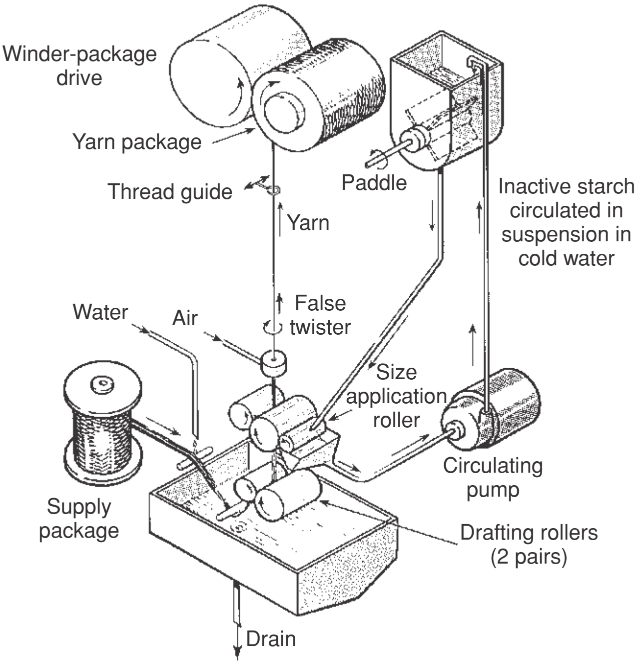
Most of these twistless methods use adhesives to hold the drafted staple fibre strand together. They can produce low linear density yarns at a high speed. The adhesives may later be removed after the fabric is made and the fibres are then bound by the interfibre forces imposed by fabric constraints. This type of yarn has high covering power due to the untwisted yarn structure. However, these processes mostly involve additional chemicals and require high power consumption. The yarns can only be used for fabrics that offer good interfibre forces.

As an example, the TNO twistless spinning method is shown in Fig. 3.8. In the system shown here, the roving is drafted under wet conditions, which gives better fibre control. An inactive starch is then applied to the drafted roving, which is also false twisted to give it temporary strength. The starch is activated by steaming the package that is then dried. The later version of TNO twistless system replaces the starch with PVA (polyvinyl alcohol) fibres (5–11%), which melt at above 80 °C to bind the staple fibres. This is also known as the Twilo system.

Another twistless spinning method is the Bobtex process, which can produce high strength yarns for industrial/leisure fabrics, such as tents, workwear and sacks. In this process, staple fibres (30–60%) are bonded to a filament core (10–50%) by a layer of molten polymer (20–50%). Production speeds of up to 1000 m min^{-1} can be achieved. The process can use all types of staple fibres including waste fibres.

3.2.7 Ply yarn

Single yarns are used in the majority of fabrics for normal textile and clothing applications, but in order to obtain special yarn features, particularly high strength



3.8 TNO twistless yarn production method.

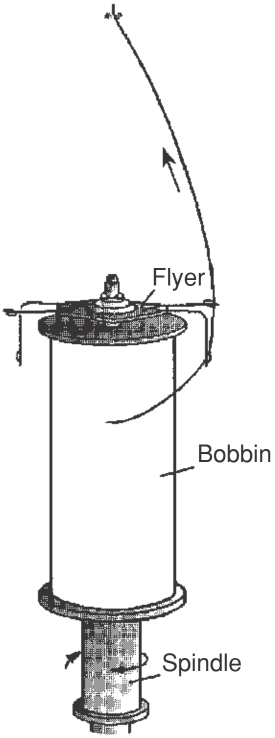
and modulus for technical and industrial applications, ply yarns are often needed. A folded yarn is produced by twisting two or more single yarns together in one operation, and a cabled yarn is formed by twisting together two or more folded yarns or a combination of folded and single yarns.

The twisting together of several single yarns increases the tenacity of the yarn by improving the binding-in of the fibres on the outer layers of the component single yarns. This extra binding-in increases the contribution of these surface fibres to the yarn strength. Ply yarns are also more regular, smoother and more hard wearing. By using the appropriate single yarn and folding twists, a perfectly balanced ply yarn can be produced for applications that require high strength and low stretch, for example, for tyre cords.

A typical process route of a ply yarn involves the following production stages:

1. single yarn production
2. single yarn winding and clearing
3. assembly winding: to wind the required number of single yarns as one (doubling) on a package suitable for folding twisting
4. twisting
5. winding

Twisting can be carried out in a two-stage process or with a two-for-one twister. In the two-stage process, the ring frame is used to insert a low folding twist in the first stage and an up-twister to insert the final folding twist in the second

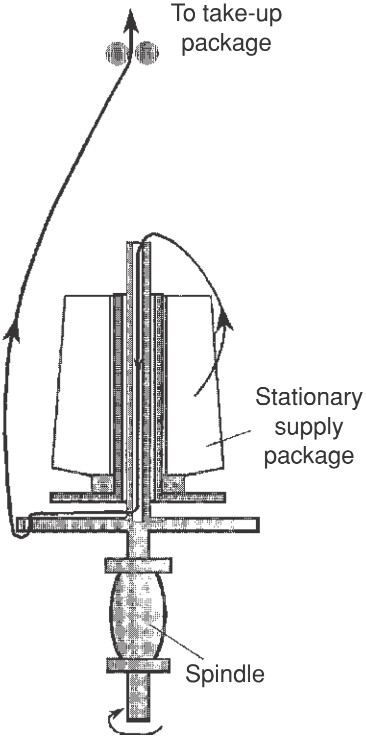


3.9 The up-twister.

stage. The ring frame uses a low twist to enable higher delivery speeds. A suitable package is formed on the ring frame for the over-end withdrawal of yarn on the up-twister. Figure 3.9 shows the principle of the up-twister. The supply package rotates with the spindle while the yarn is withdrawn over the package end from the top. The free-rotating flyer is pulled around by the yarn and inserts twist in the yarn.

The two-for-one twister is illustrated in Fig. 3.10. The supply yarn package is stationery. After withdrawal from the package, the yarn is threaded through the centre of the spindle and rotates with the spindle. Each rotation of the spindle inserts one full turn in the yarn section inside the spindle centre and also one turn in the yarn section outside the yarn package (the main yarn balloon). The yarn therefore gets two turns for each spindle rotation. If the supply package is rotated in the opposite direction of the spindle, then the twisting rate will increase by the package rotational speed. The Saurer Tritec Twister is based on this principle. In the Tritec Twister, the package rotates at the same speed as the spindle, but in the opposite direction, so each spindle rotation inserts three twists in the yarn. The package is magnetically driven.

The production of a ply yarn is much more expensive than the production of a single yarn of equivalent linear density. Not only does the ply yarn production require the extra assembly winding and twisting processes, but the production of the finer component single yarn is also much more expensive.



3.10 The two-for-one twister.

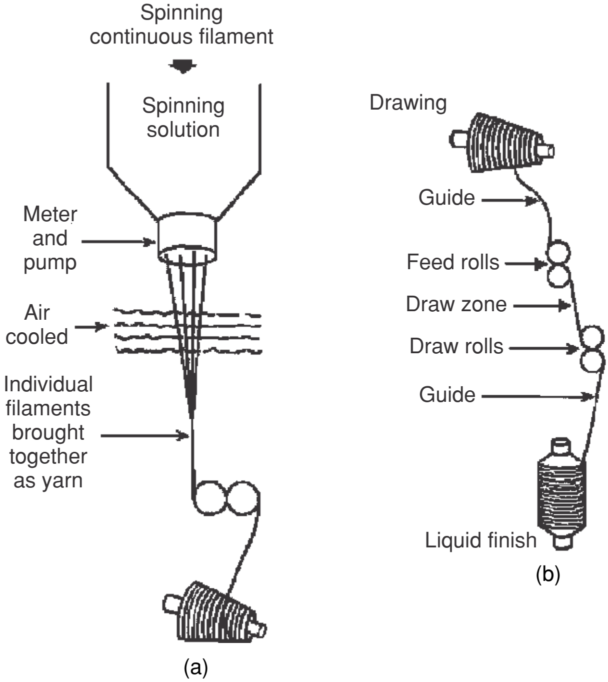
3.3 Filament yarns

3.3.1 Definitions

A filament yarn is made from one or more continuous strands called filaments where each component filament runs the whole length of the yarn. Those yarns composed of one filament are called monofilament yarns, and those containing more filaments are known as multifilament yarns. For apparel applications, a multifilament yarn may contain as few as two or three filaments or as many as 50 filaments. In carpeting, for example, a filament yarn could consist of hundreds of filaments. Most manufactured fibres have been produced in the form of a filament yarn. Silk is the only major natural filament yarn.

According to the shape of the filaments in the yarn, filament yarns are classified into two types, flat and bulk. The filaments in a flat yarn lie straight and neat, and are parallel to the yarn axis. Thus, flat filament yarns are usually closely packed and have a smooth surface. The bulked yarns, in which the filaments are either crimped or entangled with each other, have a greater volume than the flat yarns of the same linear density.

Texturing is the main method used to produce the bulked filament yarns. A textured yarn is made by introducing durable crimps, coils, and loops along the length of the filaments. As textured yarns have an increased volume, the air and vapour permeability of fabrics made from them is greater than that from flat yarns.



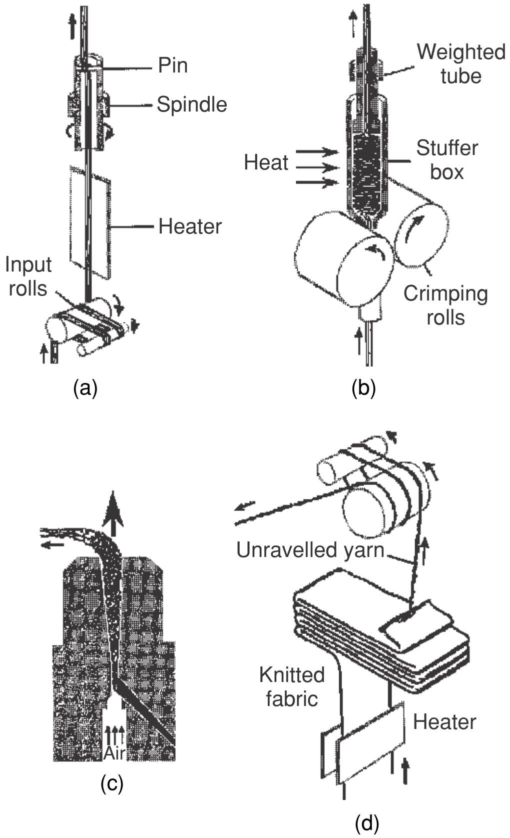
3.11 (a) Melt spinning process, (b) drawing process.

However, for applications where low air permeability is required, such as the fabrics for air bags, flat yarns may be a better choice.

3.3.2 Manufacture of filament yarns

Most manufactured fibres are extruded using either melt spinning, dry spinning, or wet spinning, although reaction spinning, gel spinning and dispersion spinning are used in particular situations. After extrusion, the molecular chains in the filaments are basically unoriented and therefore provide no practical strength. The next step is to draw the extruded filaments in order to orient the molecular chains. This is conventionally carried out by using two pairs of rollers, the second of which forwards the filaments at approximately four times the speed of the first. The drawn filaments are then wound with or without twist onto a package. The tow of filaments at this stage becomes the flat filament yarn. Figure 3.11 shows the melt spinning process and the subsequent drawing process.

For many applications, flat filament yarns are textured in order to gain increased bulkiness, porosity, softness and elasticity in some situations. Thermoplastic filament yarns are used in most texturing processes. The interfibre bonds break and reform during the texturing process. A filament yarn is generally textured through three steps. The first step is to distort the filament in the yarn so that the interfibre bond is broken. Twisting or other means are used to distort the filaments within a yarn. The second step is to heat the yarn, which breaks bonds between polymers, allowing the filaments to stay crimped. The last step is to cool the yarn in the distorted state to enable new bonds to form between the polymers. When the yarn is untwisted



3.12 Principles of main texturing methods: (a) false twist, (b) stuffer box, (c) air-jet, (d) knit-de-knit.

or otherwise released from its distorted state, the filaments remain in a coiled or crimped condition.

There are many methods for yarn texturing, including false-twist, air-texturing, knit-de-knit, stuffer box and gear crimp. Among these, the false-twist is the most popular method. Figure 3.12 shows the principles of the main methods of yarn texturing.

3.3.3 Filament technical yarns

There have been many types of filament yarns developed for technical applications, such as reinforcing and protecting. The reinforcing technical yarns have either high modulus, high strength, or both. Yarns for protecting applications can be resistant to safety hazards such as heat and fire, chemical and mechanical damage. There are many types of technical filament yarns used in various applications, it is only possible, therefore, to list just a few yarns here that are popularly used in the development of some technical textile products.

3.3.3.1 Aramid filament yarns

Aramid fibre is a chemical fibre in which the fibre-forming substance is a long chain synthetic polyamide where at least 85% of the amide linkages are attached directly to two aromatic rings. Nomex and Kevlar are two well-known trade names of the aramid fibre, owned by Du Pont. Aramid fibres have high tenacity and high resistance to stretch, to most chemicals and to high temperature. The Kevlar aramid is well known for its relatively light weight and for its fatigue and damage resistance. Because of these properties, Kevlar 29 is widely used and accepted for making body armour. Kevlar 49, on the other hand, has high tenacity and is used as reinforcing material for many composite uses, including materials for making boat and aircraft parts. The Nomex aramid, on the other hand, is heat resistant and is used in making fire fighters' apparel and similar applications.

Aramid yarns are more flexible than their other high performance counterparts such as glass and Kevlar, and thus are easier to use in subsequent fabric making processes, be it weaving, knitting, or braiding. Care should be taken, though, as aramid yarns are much stronger and much more extensible than the conventional textile yarns, which could make the fabric formation process more difficult.

3.3.3.2 Glass filament yarns

Glass is an incombustible textile fibre and has high tenacity too. It has been used for fire-retardant applications and also is commonly used in insulation of buildings. Because of its properties and low cost, glass fibre is widely used in the manufacture of reinforcement for composites. There are different types of glass fibres, such as E-glass, C-glass, and S-glass. E-glass has very high resistance to attack by moisture and has high electrical and heat resistance. It is commonly used in glass-reinforced plastics in the form of woven fabrics. C-glass is known for its chemical resistance to both acids and alkalis. It is widely used for applications where such resistance is required, such as in chemical filtration. The S-glass is a high strength glass fibre and is used in composite manufacturing.

Glass filament yarns are brittle compared with the conventional textile yarns. It has been shown that the specific flexural rigidity of glass fibre is $0.89\,\mathrm{mN\,mm^2\,tex^{-2}}$, about 4.5 times more rigid than wool. As a result, glass yarns are easy to break in textile processing. Therefore, it is important to apply suitable size to the glass yarn to minimise the interfibre friction and to hold the individual fibres together in the strand. Dextrinised starch gum, gelatine, polyvinyl alcohol, hydrogenerated vegetable oils and non-ionic detergents are commonly used sizes.

When handling glass fibres, protective clothing and a mask should be worn to prevent skin irritation and inhalation of glass fibres.

3.3.3.3 Carbon filament yarns

Carbon fibres are commonly made from precursor fibres such as rayon and acrylic. When converting acrylic fibre to carbon, a three-stage heating process is used. The initial stage is oxidative stabilisation, which heats the acrylic fibre at 200–300 °C under oxidising conditions. This is followed by the carbonisation stage, when the oxidised fibre is heated in an inert atmosphere to temperatures around 1000 °C. Consequently, hydrogen and nitrogen atoms are expelled from the oxidised fibre, leaving the carbon atoms in the form of hexagonal rings that are arranged in oriented fibrils. The final stage of the process is graphitisation, when the carbonised filaments are heated to a temperature up to 3000 °C, again in an inert atmosphere. Graphitisation increases the orderly arrangement of the carbon atoms, which are organised into a crystalline structure of layers. These layers are well oriented in the direction of fibre axis, which is an important factor in producing high modulus fibres.

Like the glass yarns, most carbon fibres are brittle. Sizes are used to adhere the filaments together to improve the processability. In addition to protecting operatives against skin irritation and short fibre inhalation, protecting the processing machinery and auxiliary electric and electronic devices needs to be considered too, as carbon fibre is conductive.

3.3.3.4 HDPE filament yarns

HDPE refers to high density polyethylene. Although the basic theory for making super strong polyethylene fibres was available in the 1930s, commercial high performance polyethylene fibre was not manufactured until recently. Spectra, Dyneema, and Tekmilon are among the most well-known HDPE fibres. The gel spinning process is used to produce the HDPE fibre. Polyethylene with an extra high molecular weight is used as the starting material. In the gel spinning process, the molecules are dissolved in a solvent and spun through a spinneret. In solution, the molecules which form clusters in the solid state become disentangled and remain in this state after the solution is cooled to give filaments. The drawing process after spinning results in a very high level of macromolecular orientation in the filaments, leading to a fibre with very high tenacity and modulus. Dyneema, for example, is characterised by a parallel orientation of greater than 95% and a high level of crystallinity of up to 85%. This gives unique properties to the HDPE fibres. The most attractive properties of this type of fibre are: (1) very high tenacity, (2) very high specific modulus, (3) low elongation and (4) low fibre density, that is lighter than water.

HDPE fibres are made into different grades for different applications. Dyneema, for example, is made into SK60, SK65 and SK66. Dyneema SK60 is the multipurpose grade. It is used, for example, for ropes and cordage, for protective clothing and for reinforcement of impact-resistant composites. Dyneema SK65 has a higher tenacity and modulus than SK60. This fibre is used where high performance is needed and maximum weight savings are to be attained. Dyneema SK66 is specially designed for ballistic protection. This fibre provides the highest energy absorption at ultrasonic speeds.

Table 3.1 compares the properties of the above mentioned filament yarns to steel.

3.3.3.5 Other technical yarns

There have been many other high performance fibres developed for technical applications, among which are PTFE, PBI, and PBO fibres.

PTFE (polytetrafluoroethylene) fibres offer a unique blend of chemical and temperature resistance, coupled with a low fraction coefficient. Since PTFE is virtually chemically inert, it can withstand exposure to extremely harsh temperature and chemical environments. The friction coefficient, claimed to be the lowest of all fibres, makes it suitable for applications such as heavy-duty bearings where low relative speeds are involved.

PBI (polybenzimidazole) is a manufactured fibre in which the fibre-forming substance is a long chain aromatic polymer. It has excellent thermal resistance and a good hand, coupled with a very high moisture regain. Because of these, the PBI

Table 3.1 Comparison of filament yarn properties

Yarns	Density ($g\,cm^{-3}$)	Strength (GPa)	Modulus (GPa)	Elongation (%)
Aramid – regular	1.44	2.9	60	3.6
Aramid – composite	1.45	2.9	120	1.9
Aramid – ballistic	1.44	3.3	75	3.6
E Glass	2.60	3.5	72	4.8
S Glass	2.50	4.6	86	5.2
Carbon HS	1.78	3.4	240	1.4
Carbon HM	1.85	2.3	390	0.5
Dyneema SK60	0.97	2.7	89	3.5
Dyneema SK65	0.97	3.0	95	3.6
Dyneema SK66	0.97	3.2	99	3.7
Steel	7.86	1.77	200	1.1

Table 3.2 High performance fibres

Fibre	Density ($g\,cm^{-3}$)	Tenacity ($mN\,tex^{-1}$)	Elongation (%)	Regain (%)
PTFE	2.1	0.9–2.0	19–140	0
PBI	1.43	2.6–3.0	25–30	15
PBO	1.54	42	2.5–3.5	0.6–2.0

fibre is ideal for use in heat-resistant apparel for fire fighters, fuel handlers, welders, astronauts, and racing car drivers.

PBO (polyphenylenebenzobisoxazole) is another new entrant in the high performance organic fibres market. Zylon, made by Toyobo, is the only PBO fibre in production. PBO fibre has outstanding thermal properties and almost twice the strength of conventional *para*-aramid fibres. Its high modulus makes it an excellent material for composite reinforcement. Its low LOI gives PBO more than twice the flame-retardant properties of *meta*-aramid fibres. It can also be used for ballistic vests and helmets.

Table 3.2 lists some properties of these fibres.

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4

Technical fabric structures – 1. Woven fabrics

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4.1 Introduction

Technical textiles[1] are textile materials and products manufactured primarily for their technical performance and functional properties rather than their aesthetic or decorative characteristics. Most technical textiles consist of a manufactured assembly of fibres, yarns and/or strips of material which have a substantial surface area in relation to their thickness and have sufficient cohesion to give the assembly useful mechanical strength.

Textile fabrics are most commonly woven but may also be produced by knitting, felting, lace making, net making, nonwoven processes and tufting or a combination of these processes. Most fabrics are two-dimensional but an increasing number of three-dimensional woven technical textile structures are being developed and produced.

Woven fabrics generally consist of two sets of yarns that are interlaced and lie at right angles to each other. The threads that run along the length of the fabric are known as warp ends whilst the threads that run from selvedge to selvedge, that is from one side to the other side of the fabric, are weft picks. Frequently they are simply referred to as ends and picks. In triaxial and in three-dimensional fabrics yarns are arranged differently.

Woven technical textiles are designed to meet the requirements of their end use. Their strength, thickness, extensibility, porosity and durability can be varied and depend on the weave used, the thread spacing, that is the number of threads per centimetre, and the raw materials, structure (filament or staple), linear density (or count) and twist factors of the warp and weft yarns. From woven fabrics higher strengths and greater stability can be obtained than from any other fabric structure using interlaced yarns. Structures can also be varied to produce fabrics with widely different properties in the warp and weft directions.

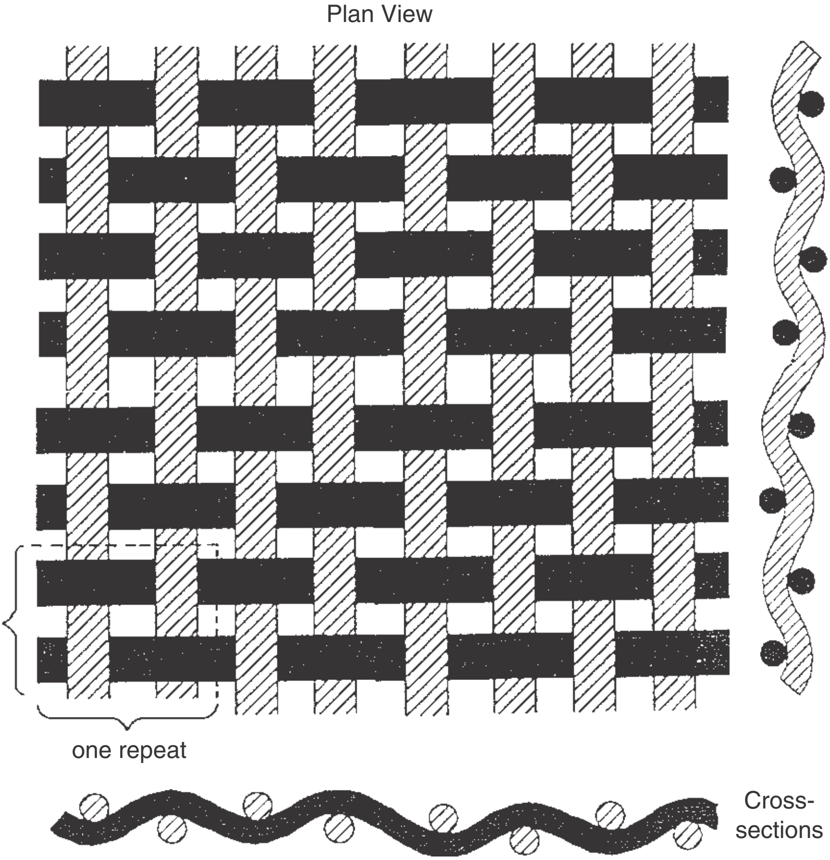
4.2 Weave structures

The number of weave structures that can be produced is practically unlimited. In this section basic structures, from which all other weave structures are developed, are discussed. Also briefly referred to are lenos, because of their importance in selvedge constructions, and triaxial fabrics, because they show simple structural changes which can affect the physical properties of fabrics. Most two-dimensional woven technical fabrics are constructed from simple weaves and of these at least 90% use plain weave. Simple cloth constructions are discussed in greater detail by Robinson and Marks[2] whilst Watson[3,4] describes a large variety of simple and complicated structures in great detail.

4.2.1 Plain weave

4.2.1.1 Construction of a plain weave

Plain weave is the simplest interlacing pattern which can be produced. It is formed by alternatively lifting and lowering one warp thread across one weft thread. Figure 4.1 shows 16 repeats (four in the warp and four in the weft direction) of a plain



4.1 Fabric woven with plain weave – plan view (4 × 4 repeats) and warp and weft cross-sections.

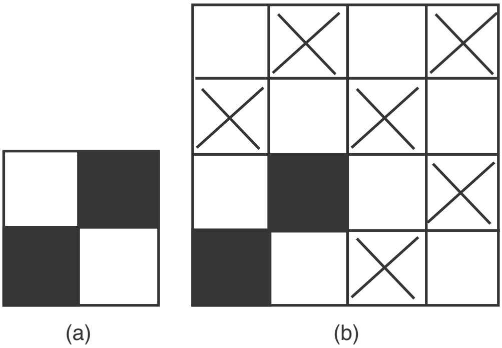
weave fabric in plan view and warp way and weft way cross-sections through the same fabric. The diagrams are idealized because yarns are seldom perfectly regular and the pressure between the ends and picks tends to distort the shape of the yarn cross-sections unless the fabrics are woven from monofilament yarns or strips of film. The yarns also do not lie straight in the fabric because the warp and weft have to bend round each other when they are interlaced. The wave form assumed by the yarn is called crimp and is referred to in greater detail in Section 4.4.3.

4.2.1.2 Constructing a point paper diagram

To illustrate a weave either in plan view and/or in cross-section, as in Fig. 4.1, takes a lot of time, especially for more complicated weaves. A type of shorthand for depicting weave structures has therefore been evolved and the paper used for producing designs is referred to as squared paper, design paper or point paper. Generally the spaces between two vertical lines represent one warp end and the spaces between two horizontal lines one pick. If a square is filled in it represents an end passing over a pick whilst a blank square represents a pick passing over an end. If ends and picks have to be numbered to make it easier to describe the weave, ends are counted from left to right and picks from the bottom of the point paper design to the top. The point paper design shown in Fig. 4.2(a) is the design for a plain weave fabric. To get a better impression of how a number of repeats would look, four repeats of a design (two vertically and two horizontally) are sometimes shown. When four repeats are shown the first repeat is drawn in the standard way but for the remaining three repeats crossing diagonal lines may be placed into the squares, which in the firsts repeat, are filled in. This method is shown for a plain weave in Fig. 4.2(b).

4.2.1.3 Diversity of plain weave fabrics

The characteristics of the cloths woven will depend on the type of fibre used for producing the yarn and whether it is a monofilament yarn, a flat, twisted or textured (multi-)filament yarn or whether it has been spun from natural or manufactured staple fibres. The stiffness of the fabrics and its weavability will also be affected by the stiffness of the raw materials used and by the twist factor of the yarn, that is the number of turns inserted in relation to its linear density. Very highly twisted yarns are sometimes used to produce special features in plain weave yarns. The resulting fabrics may have high extensibility or can be semiopaque.



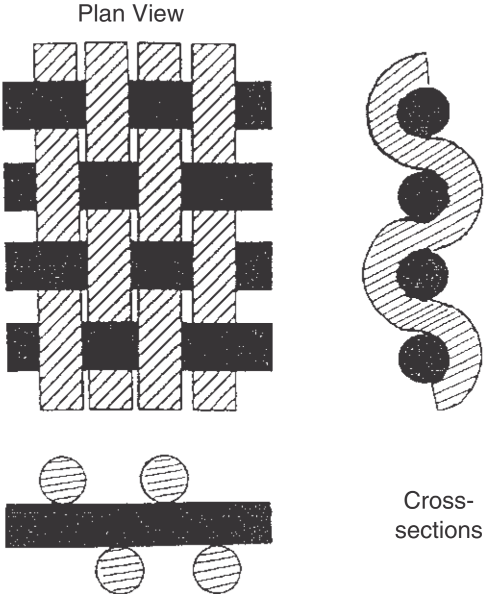
4.2 Point paper diagram of a plain weave fabric. (a) One repeat, (b) four repeats.

The area density of the fabric can be varied by changing the linear density or count of the yarns used and by altering the thread spacing, which affects the area covered by the yarns in relation to the total area. The relation between the thread spacing and the yarn linear density is called the cover factor and is discussed in Section 4.4. Changing the area density and/or the cover factors may affect the strength, thickness, stiffness, stability, porosity, filtering quality and abrasion resistance of fabrics.

Square sett plain fabrics, that is fabrics with roughly the same number of ends and picks per unit area and warp and weft yarns of the same linear densities are produced in the whole range of cloth area densities and cloth cover factors. Low area density fabrics of open construction include bandages and cheese cloths, light area density high cover factor fabrics include typewriter ribbons and medical filter fabrics, heavy open cloths include geotextile stabilization fabrics and heavy closely woven fabrics include cotton awnings.

Warp-faced plain fabrics generally have a much higher warp cover factor than weft cover factor. If warp and weft yarns of similar linear density are used, a typical warp faced plain may have twice as many warp ends as picks. In such fabrics the warp crimp will be high and the weft crimp extremely low. The plan view and cross-sections of such a fabric are shown in Fig. 4.3. By the use of suitable cover factors and choice of yarns most of the abrasion on such a fabric can be concentrated on the warp yarns and the weft will be protected.

Weft-faced plains are produced by using much higher weft cover factors than warp cover factors and will have higher weft than warp crimp. Because of the difference in weaving tension the crimp difference will be slightly lower than in warp-faced plain fabrics. Weft-faced plains are little used because they are more difficult and expensive to weave.



4.3 Plan view and cross-sections of warp-faced plain weave fabric with a substantially higher warp than weft cover factor.

4.2.2 Rib fabrics and matt weave fabrics

These are the simplest modifications of plain weave fabrics. They are produced by lifting two or more adjoining warp threads and/or two or more adjoining picks at the same time. It results in larger warp and/or weft covered surface areas than in a plain weave fabric. As there are fewer yarn intersections it is possible to insert more threads into a given space, that is to obtain a higher cover factor, without jamming the weave.

4.2.2.1 Rib fabrics

In warp rib fabrics there are generally more ends than picks per unit length with a high warp crimp and a low weft crimp and vice versa for weft rib fabrics. The simplest rib fabrics are the 2/2 warp rib and the 2/2 weft rib shown respectively in Fig. 4.4(a) and (b). In the 2/2 warp rib one warp end passes over two picks whilst in the 2/2 weft rib one pick passes over two adjoining ends. The length of the floats can be extended to create 4/4, 6/6, 3/1 or any similar combination in either the warp or weft direction. 3/1 and 4/4 warp ribs are shown in Fig. 4.4(c) and (d).

In rib weaves with long floats it is often difficult to prevent adjoining yarns from overlapping. Weft ribs also tend to be expensive to weave because of their relatively high picks per unit length which reduces the production of the weaving machine unless two picks can be inserted at the same time.

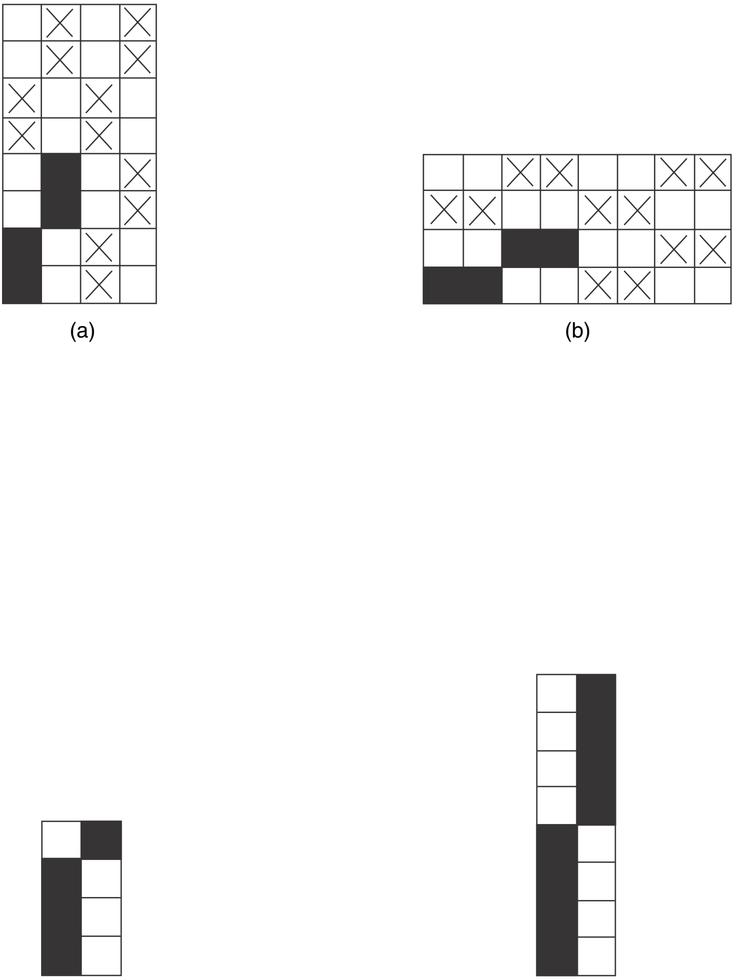
4.2.2.2 Matt fabrics (or hopsack)

Simple matt (or hopsack) fabrics have a similar appearance to plain weave. The simplest of the matt weaves is a 2/2 matt shown in Fig. 4.5(a), where two warp ends are lifted over two picks, in other words it is like a plain weave fabric with two ends and two picks weaving in parallel. The number of threads lifting alike can be increased to obtain 3/3 or 4/4 matt structures. Special matt weaves, like a 4/2 matt, shown in Fig. 4.5(b), are produced to obtain special technical effects. Larger matt structures give the appearance of squares but are little used because they tend to become unstable, with long floats and threads in either direction riding over each other. If large matt weaves are wanted to obtain a special effect or appearance they can be stabilized by using fancy matt weaves containing a binding or stitching lift securing a proportion of the floats.

Matt weave fabrics can be woven with higher cover factors and have fewer intersections. In close constructions they may have better abrasion and better filtration properties and greater resistance to water penetration. In more open constructions matt fabrics have a greater tear resistance and bursting strength. Weaving costs may also be reduced if two or more picks can be inserted at the same time.

4.2.3 Twill fabrics

A twill is a weave that repeats on three or more ends and picks and produces diagonal lines on the face of a fabric. Such lines generally run from selvedge to selvedge. The direction of the diagonal lines on the surface of the cloth are generally described as a fabric is viewed along the warp direction. When the diagonal lines are running upwards to the right they are ‘Z twill’ or ‘twill right’ and when they run in the opposite direction they are ‘S twill’ or ‘twill left’. Their angle and definition can be varied



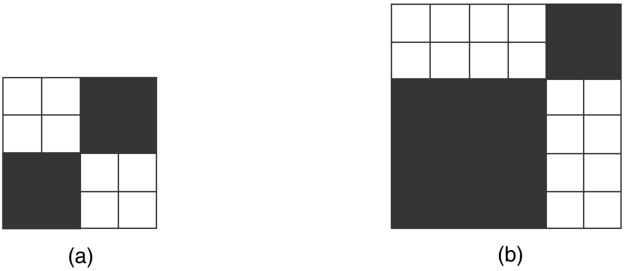
(a)

(b)

(c)

(d)

4.4 Rib fabrics. (a) 2/2 Warp rib (four repeats), (b) 2/2 weft rib (four repeats), (c) 3/1 warp rib (one repeat), (d) 4/4 warp rib (one repeat).



4.5 Matt fabrics. (a) 2/2 Matt, (b) 4/2 matt.

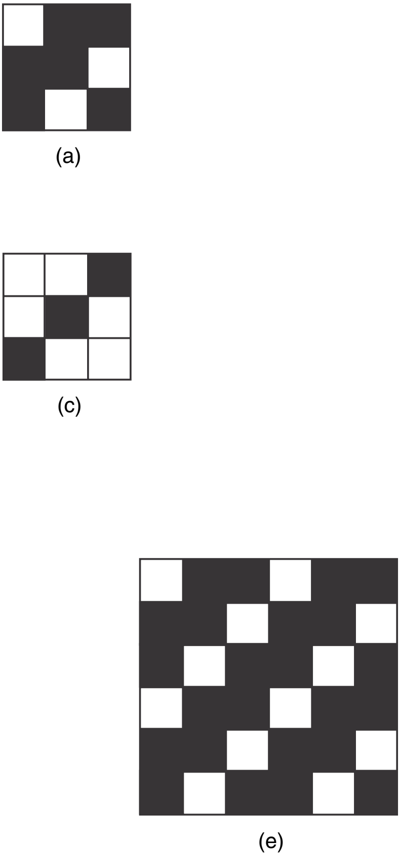
by changing the thread spacing and/or the linear density of the warp and weft yarns. For any construction twills will have longer floats, fewer intersections and a more open construction than a plain weave fabric with the same cloth particulars.

Industrial uses of twill fabrics are mainly restricted to simple twills and only simple twills are discussed here. Broken twills, waved twills, herringbone twills and elongated twills are extensively used for suiting and dress fabrics. For details of such twills see Robinson and Marks[2] or Watson.[3,4]

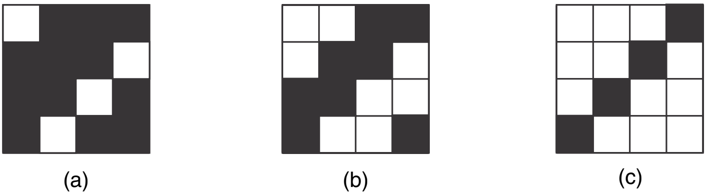
The smallest repeat of a twill weave consists of 3 ends × 3 picks. There is no theoretical upper limit to the size of twill weaves but the need to produce stable fabrics with floats of reasonable length imposes practical limits.

The twill is produced by commencing the lift sequence of adjacent ends on one pick higher or one pick lower. The lift is the number of picks which an end passes over and under. In a 2/1 twill, an end will pass over two picks and under one, whilst in a 1/2 twill the end will pass over one pick and then under two picks. Either weave can be produced as a Z or S twill. There are, therefore, four combinations of this simplest of all twills and they are illustrated in Fig. 4.6(a) to (d). To show how pronounced the twill line is even in a 3 × 3 twill, four repeats (2 × 2) of Fig. 4.6(a) are shown in Fig. 4.6(e) with all lifted ends shown in solid on the point paper. 2/1 twills are warp faced twills, that is fabrics where most of the warp yarn is on the surface, whilst 1/2 twills have a weft face. Weft-faced twills impose less strain on the weaving machine than warp-faced twills because fewer ends have to be lifted to allow picks to pass under them. For this reason, warp-faced twills are sometimes woven upside down, that is as weft-faced twills. The disadvantage of weaving twills upside down is that it is more difficult to inspect the warp yarns during weaving.

Twills repeating on 4 ends × 4 picks may be of 3/1, 2/2 or 1/3 construction and may have ‘Z’ or ‘S’ directions of twill. Weaves showing 4 × 4 twills with a Z twill line are shown in Fig. 4.7(a) to (c). As the size of the twill repeat is increased further, the number of possible variations also increases. In the case of a 5 × 5 the possible combinations are 4/1, 3/2, 2/3 and 1/4 and each of these can be woven with the twill



4.6 3 × 3 Twill weaves. (a) 2/1 Twill with Z twill line, (b) 2/1 twill with S twill line, (c) 1/2 twill with Z twill line, (d) 1/2 twill with S twill line, (e) four repeats of (a) (2/1 twill with a Z twist line).



4.7 4 × 4 Twill weaves. (a) 3/1 Twill with Z twill line, (b) 2/2 twill with Z twill line, (c) 1/3 twill with Z twill line.

4.8 5 × 5 Twill weaves. (a) 4/1 Twill with Z twill line, (b) 1/4 twill with Z twill line.

line in either direction. In Fig. 4.8(a) and (b) 4/1 and 1/4 twills with a Z twill line are shown.

4.2.4 Satins and sateens

In Britain a satin is a warp-faced weave in which the binding places are arranged to produce a smooth fabric surface free from twill lines. Satins normally have a much greater number of ends than picks per centimetre. To avoid confusion a satin is frequently described as a 'warp satin'. A sateen, frequently referred to as a 'weft sateen', is a weft-faced weave similar to a satin with binding places arranged to produce a smooth fabric free of twill lines. Sateens are generally woven with a much higher number of picks than ends. Satins tend to be more popular than sateens because it is cheaper to weave a cloth with a lower number of picks than ends. Warp satins may be woven upside down, that is as a sateen but with a satin construction, to reduce the tension on the harness mechanism that has to lift the warp ends.

To avoid twill lines, satins and sateens have to be constructed in a systematic manner. To construct a regular satin or sateen weave (for irregular or special ones see Robinson and Marks[2] or Watson[3]) without a twill effect a number of rules have to be observed. The distribution of interlacing must be as random as possible and there has only to be one interlacing of each warp and weft thread per repeat, that is per weave number. The intersections must be arranged in an orderly manner, uniformly separated from each other and never adjacent. The weaves are developed from a 1/× twill and the twill intersections are displaced by a fixed number of steps. The steps that must be avoided are:

(i) one or one less than the repeat (because this is a twill),
(ii) the same number as the repeat or having a common factor with the repeat (because some of the yarns would fail to interlace).

The smallest weave number for either weave is 5 and regular satins or sateens also cannot be constructed with weave numbers of 6, 9, 11, 13, 14 or 15. The most popular weave numbers are 5 and 8 and weave numbers above 16 are impracticable because of the length of floats. Weave numbers of 2 or 3 are possible for five-end weaves and 3 or 5 for 8-end weaves.

4.9 5-End weft sateen. (a) 5-end and two step sateen, (b) 5-end three step sateen.

4.10 5-End warp satin. (a) 5-end two step satin, (b) 5-end three step satin.

Figure 4.9(a) and (b) shows 5-end weft sateens with two and three steps, respectively. They have been developed from the 1/4 twill shown in Fig. 4.8(b). Mirror images of these two weaves can be produced. Five-end warp satins with two and three steps are shown in Fig. 4.10(a) and (b). It is the cloth particulars, rather than the weave pattern, which generally decides on which fabric is commercially described as a sateen or a satin woven upside down. Five-end satins and sateens are most frequently used because with moderate cover factors they give firm fabrics. Figure 4.11(a) and (b) shows 8-end weft sateens with three and five step repeats and Fig. 4.12 shows an 8-end warp satin with a 5 step repeat.

Satins and sateens are widely used in uniforms, industrial and protective clothing. They are also used for special fabrics such as downproofs.

In North America a satin is a smooth, generally lustrous, fabric with a thick close texture made in silk or other fibres in a satin weave for a warp-face fabric or sateen weave for a filling (weft) face effect. A sateen is a strong lustrous cotton fabric generally made with a five-harness satin weave in either warp or filling-face effect.

4.2.5 Lenos

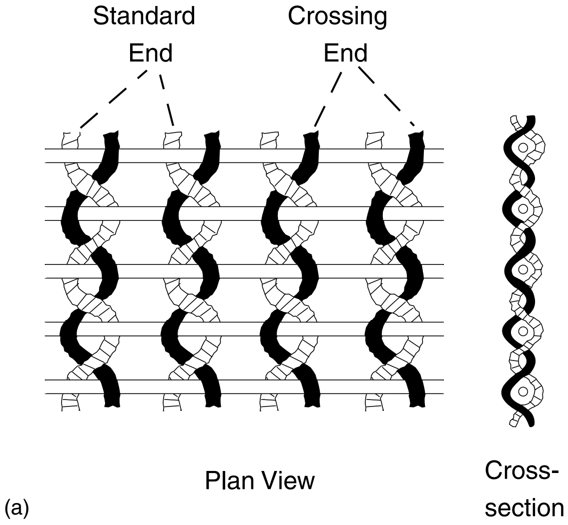
In lenos adjoining warp ends do not remain parallel when they are interlaced with the weft but are crossed over each other. In the simplest leno one standard end and

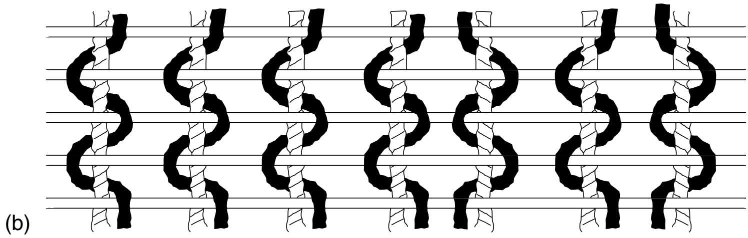
4.11 8-End weft sateen. (a) 8-end three step sateen, (b) 8-end five step sateen.

4.12 8-End five step warp satin.

one crossing end are passed across each other during consecutive picks. Two variations of this structure are shown in plan view and cross-section in Fig. 4.13(a) and (b).[4] Whenever the warp threads cross over each other, with the weft passing between them, they lock the weft into position and prevent weft movement. Leno weaves are therefore used in very open structures, such as gauzes, to prevent thread movement and fabric distortion. When the selvedge construction of a fabric does not bind its edge threads into position, leno ends are used to prevent the warp threads at each side of a length of cloth from slipping out of the body of the fabric. They are also used in the body of fabrics when empty dents are left in weaving because the fabrics are to be slit into narrower widths at a later stage of processing.

Leno and gauze fabrics may consist of standard and crossing ends only or pairs or multiples of such threads may be introduced according to pattern to obtain the required design. For larger effects standard and crossing ends may also be in pairs or groups of three. Two or more weft threads may be introduced into one shed and





4.13 (a) Leno with standard and crossing ends of same length (woven from one beam), (b) leno with standard and crossing ends of different length (woven from two beams).

areas of plain fabric may be woven in the weft direction between picks where warp ends are crossed over to give the leno effect. Gauze fabrics used for filtration generally use simple leno weaves.

Standard and crossing ends frequently come from separate warp beams. If both the standard and crossing ends are warped on to one beam the same length of warp is available for both and they will have to do the same amount of bending, that is they will have the same crimp. Such a leno fabric is shown in plan view and cross-section in Fig. 4.13(a). If the two series of ends are brought from separate beams the standard ends and the crossing ends can be tensioned differently and their crimp can be adjusted separately. In such a case it is possible for the standard ends to lie straight and the crossing ends to do all the bending. Such a fabric is shown in Fig. 4.13(b). This figure also shows that crossing threads can be moved either from the right to the left or from the left to the right on the same pick and adjoining leno pairs may either cross in the same or opposite directions. The direction of crossing can affect locking, especially with smooth monofilament yarns. When using two beams it is also possible to use different types or counts of yarn for standard and crossing ends for design or technical applications. The actual method of weaving the leno with doups or similar mechanisms is not discussed in this chapter.

When lenos are used for selvedge construction only one to four pairs of threads are generally used at each side and the leno selvedge is produced by a special leno mechanism that is independent of the shedding mechanism of the loom. The leno threads required for the selvedge then come from cones in a small separate creel rather than from the warp beam. The choice of selvedge yarns and tensions is particularly important to prevent tight or curly selvedges. The crimps selected have to take into account the cloth shrinkage in finishing.

4.2.6 Triaxial weaves

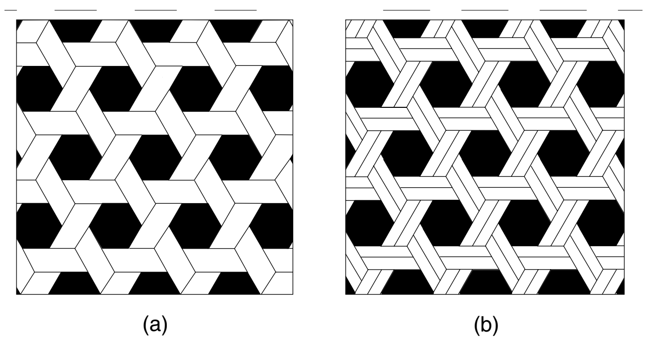
Nearly all two-dimensional woven structures have been developed from plain weave fabrics and warp and weft yarns are interlaced at right angles or at nearly right angles. This also applies in principle to leno fabrics (see Section 4.2.5 above) and to lappet fabrics where a proportion of the warp yarns, that is the yarns forming the design, are moved across a number of ground warp yarns by the lappet mechanism. The only exceptions are triaxial fabrics, where two sets of warp yarns are generally inserted at 60° to the weft, and tetra-axial fabrics where four sets of yarns are inclined at 45° to each other. So far only weaving machines for triaxial fabrics are in commercial production. Triaxial weaving machines were first built by the Barber-Colman Co. under licence from Dow Weave and have been further developed by Howa Machinery Ltd., Japan.

Triaxial fabrics are defined as cloths where the three sets of threads form a multitude of equilateral triangles. Two sets of warp yarn are interlaced at 60° with each other and with the weft. In the basic triaxial fabric, shown in Fig. 4.14(a), the warp travels from selvedge to selvedge at an angle of 30° from the vertical. When a warp yarn reaches the selvedge it is turned through an angle of 120° and then travels to the opposite selvedge thus forming a firm selvedge. Weft yarn is inserted at right angles (90°) to the selvedge. The basic triaxial fabric is fairly open with a diamond-shaped centre. The standard weaves can be modified by having biplane, stuffed or basic basket weaves, the latter being shown in Fig. 4.14(b). These modified weaves form closer structures with different characteristics. Interlacing angles of 75° to the selvedge can be produced. At present thread spacing in the basic weave fabric is limited to 3.6 or 7.4 threads per centimetre.

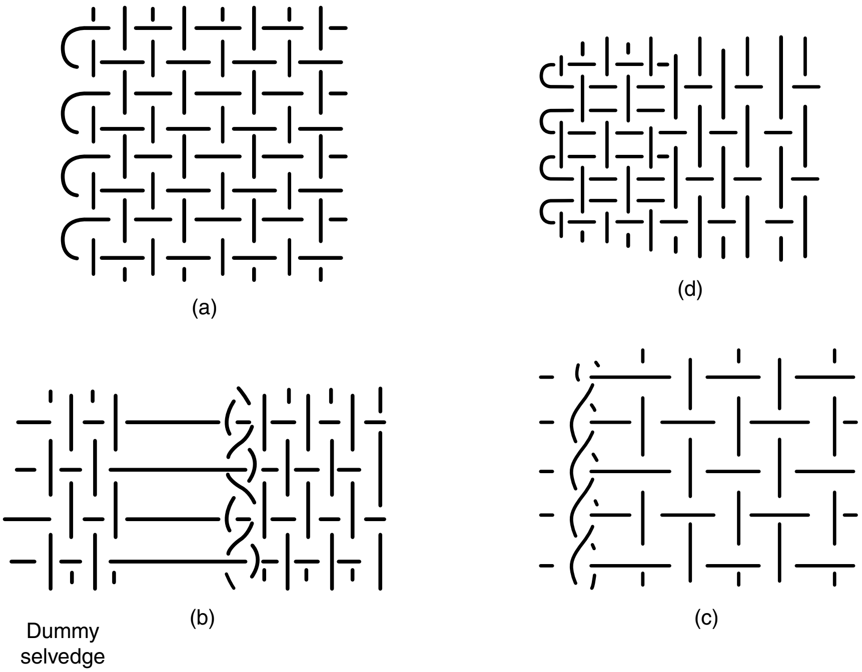
The tear resistance and bursting resistance of triaxial fabrics is greatly superior to that of standard fabrics because strain is always taken in two directions. Their shear resistance is also excellent because intersections are locked. They have a wide range of technical applications including sailcloths, tyre fabrics, balloon fabrics, pressure receptacles and laminated structures.

4.3 Selvedge

The selvedges form the longitudinal edges of a fabric and are generally formed during weaving. The weave used to construct the selvedge may be the same, or may differ from, the weave used in the body of the cloth. Most selvedges are fairly narrow but they can be up to 20-mm wide. Descriptions may be woven into the selvedge, using special selvedge jacquards, or coloured or fancy threads may be incorporated for identification purposes. For some end-uses selvedges have to be discarded but,



4.14 Triaxial fabrics (weaving machine: Howa *TRI-AX* Model TWM). (a) Basic weave, (b) basic basket weave.



4.15 (a) Hairpin selvedge – shuttle loom, (b) leno selvedge with dummy selvedge, (c) helical selvedge, (d) tucked-in or tuck selvedge.

whenever possible, selvedges should be constructed so that they can be incorporated into the final product so as to reduce the cost of waste.

In cloths woven on weaving machines with shuttles selvedges are formed by the weft turning at the edges after the insertion of each pick. The weft passes continuously across the width of the fabric from side to side. In cloths woven on shuttleless weaving machines the weft is cut at the end of each pick or after every second pick. To prevent the outside ends from fraying, various selvedge motions are used to bind the warp into the body of the cloth or edges may be sealed. The essential requirements are that the selvedges should protect the edge of the fabric during weaving and subsequent processing, that they should not detract from the appearance of the cloth and that they should not interfere with finishing or cause waviness, contraction or creasing. Four types of woven selvedges are shown in Fig. 4.15.

4.3.1 Hairpin selvedge – shuttle weaving machine

Figure 4.15(a) shows a typical hairpin selvedge which is formed when the weft package is carried in a reciprocating media, for example a shuttle. With most weaves it gives a good edge and requires no special mechanism. Frequently strong two-ply yarns are incorporated into the selvedge whilst single yarns are used in the body of the cloth because the edge threads are subjected to special strains during beat-up. To ensure a flat edge a different weave may be used in the selvedge from the body of the cloth. For twills, satins and fancy weaves this may also be necessary to ensure that all warp threads are properly bound into the edge. If special selvedge yarns are used it is important to ensure that they are not, by mistake, woven into the body of the fabric because they are likely to show up after finishing or cause a reduction in the tear and/or bursting resistance of industrial fabrics.

When two or more different weft yarns are used in a fabric only one weft yarn is being inserted at a time and the other yarn(s) are inactive until the weft is changed. In shuttle looms the weft being inserted at any one time will form a normal selvedge whilst the weft yarn(s) not in use will float along the selvedge. If long floats are formed in weaving, because one weft is not required for a considerable period, the floats may have to be trimmed off after weaving to prevent them from causing problems during subsequent processing. Whenever a pirn is changed, or a broken pick is repaired, a short length of yarn will also protrude from the selvedge and this has to be trimmed off after weaving.

Industrial fabrics with coarse weft yarn are sometimes woven with loop selvedges to ensure that the thread spacing and cloth thickness remains the same right to the edge of the cloth. To produce a loop selvedge a wire or coarse monofilament yarn is placed 3 or 4 mm outside the edge warp end and the pick reverses round the wire to form a loop. As the wire is considerably stiffer than a yarn it will prevent the weft pulling the end threads together during beat-up. The wire extends to the fell of the cloth and is automatically withdrawn during weaving. Great care is required to ensure that no broken-off ends of wire or monofilament remain in the fabric because they can cause serious damage to equipment and to the cloth during subsequent processing.

4.3.2 Leno and helical selvedges

In most shuttleless weaving machines a length of weft has to be cut for every pick. For looms not fitted with tucking motions the warp threads at the edges of the fabric have to be locked into position to prevent fraying. With some weft insertion systems the weft has to be cut only after every second pick and it is possible to have a hairpin selvedge on one side of the fabric and a locked selvedge on the second side. Leno and helical selvedges are widely used to lock warp yarns into position and these are shown in Fig. 4.15(b) and (c), respectively. When shuttleless weaving machines were first introduced there was considerable customer resistance to fringe selvedges but, in the meantime, it has been found that they meet most requirements.

With leno selvedges (see also Section 4.2.5) a set of threads at the edge of the fabric is interlaced with a gauze weave which locks round the weft thread and prevents ravelling of the warp. As the precut length of the picks always varies slightly, a dummy selvedge is sometimes used at the edge of the cloth as shown in Fig. 4.15(b). This makes it possible to cut the weft close to the body of the cloth resulting in a narrow fringe which has a better appearance than the selvedge from which weft threads of varying lengths protrude. It also has the advantage in finishing and coating that there are no long lengths of loose weft that can untwist and shed fly. Because of the tails of weft and because of the warp in dummy selvedges, more waste is generally made in narrow shuttleless woven fabrics than in fabrics woven on shuttle looms. For wide cloth the reverse frequently applies because there is no shuttle waste. Leno selvedges, sometimes referred to as 'centre selvedges', may be introduced into the body of the cloth if it is intended to slit the width of cloth produced on the loom into two or more widths either on the loom or after finishing.

Helical selvedges consist of a set of threads which make a half or complete revolution around one another between picks. They can be used instead of leno selvedges and tend to have a neater appearance.

4.3.3 Tucked-in selvedges

A tuck or tucked-in selvedge is shown in Fig. 4.15(d). It gives a very neat and strong selvedge and was first developed by Sulzer[5] Brothers (now Sulzer-Textil), Winterthur, Switzerland, for use on their projectile weaving machines. Its appearance is close to that of a hairpin selvedge and it is particularly useful when cloths with fringe selvedges would have to be hemmed. High-speed tucking motions are now available and it is possible to produce tucked-in selvedges even on the fastest weaving machines.

Tucked-in selvedges, even when produced with a reduced number of warp threads, are generally slightly thicker than the body of the cloth. When large batches of cloth with such selvedges are produced it may be necessary to traverse the cloth on the cloth roller to build a level roll. The extra thickness will also have to be allowed for when fabrics are coated. When tucked-in selvedges can be incorporated into the finished product no yarn waste is made because no dummy selvedges are produced but the reduced cost of waste may be counterbalanced by the relatively high cost of the tucking units.

4.3.4 Sealed selvedges

When fabrics are produced from yarns with thermoplastic properties the edge of a fabric may be cut and sealed by heat. The edge ends of fringe selvedges are frequently cut off in the loom and the edge threads with the fringe are drawn away into a waste container. Heat cutting may also be used to slit a cloth, in or off the loom, into a number of narrower fabrics or tapes.

For special purposes ultrasonic sealing devices are available. These devices are fairly expensive and can cut more cloth than can be woven on one loom. Whilst they can be mounted on the loom they are, because of their cost, more frequently mounted on a separate cutting or inspection table.

4.4 Fabric specifications and fabric geometry

Fabric specifications[6] describe a cloth but frequently need experience for correct interpretation. The most important elements are cloth width, threads per centimetre in the warp and weft directions, linear density (count) and type of warp and weft yarns (raw material, filament or staple, construction, direction of twist and twist factors), weave structure (see Section 4.2 above) and finish. From these, if the weaving machine particulars and finishing instructions are known, the cloth area density can be calculated.

It has been assumed that other cloth particulars, such as warp and weft cover factors, crimp, cloth thickness, porosity and drape, have either to be estimated or measured by various test methods. Peirce[7] showed that standard physical and engineering principles can be applied to textiles and cloth specifications can be forecast if the effect of interlacing the warp and weft threads and the distortion of the yarns caused thereby is allowed for.

4.4.1 Fabric width

The width of fabrics is generally expressed in centimetres and has to be measured under standard conditions to allow for variations which are caused by moisture and tension. It is necessary to know whether the cloth width required is from edge to edge or whether it excludes the selvedges. Before deciding on the weaving specifications of a fabric, allowance has to be made not only for shrinkage from reed width to grey width during weaving but also for contraction (if any) during finishing. If the cloth width changes, other parameters such as cloth area density and threads per centimetre, will be effected.

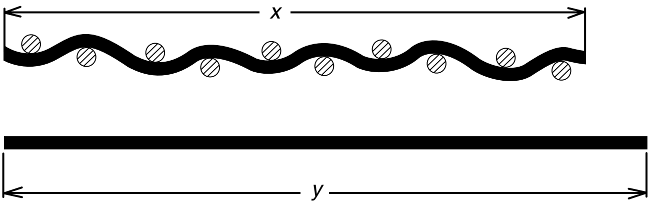
4.4.2 Fabric area density

The fabric area density is generally expressed in grams per square metre although sometimes it is reported as grams per linear metre. It is essential to specify whether the area density required is loomstate or finished. The loomstate area density depends on the weaving specification, that is, yarns, thread spacing and weave, and on any additives, such as size, which are used to improve the weaving process. During finishing the cloth area density is frequently altered by tension and chemical treatments or compressive shrinkage which affect cloth width and length, by the removal of additives needed in weaving and by substances added during finishing.

4.4.3 Crimp

The waviness or crimp[1] of a yarn in a fabric, shown in the cross-sections of Fig. 4.1, is caused during weaving and may be modified in finishing. It is due to the yarns being forced to bend around each other during beat-up. It depends on the warp and weft cover factors, which are described in Section 4.4.4, the characteristics of the yarns and the weaving and finishing tensions.

The crimp is measured by the relation between the length of the fabric sample and the corresponding length of yarn when it has been straightened after being removed from the cloth, as shown in Fig. 4.16, which, as drawn, is idealized and only applies to monofilament yarns. Multifilament and staple yarn will be deformed to some extent at intersections by the pressure exerted by the warp on the weft or vice versa depending on yarn particulars and cloth construction. It is most convenient to express crimp as a percentage, which is 100 divided by the fabric length and multiplied by the difference between the yarn length and the fabric length.



4.16 Crimp – relation of length of yarn in cloth to length of cloth. x is the width of sample, y is the length of yarn extracted from sample and percentage crimp = $(y - x)/x \times 100$.

Warp crimp is used to decide the length of yarn which has to be placed on to a warper's beam to weave a specified length of fabric. Allowance has to be made for stretching of the yarns during weaving which is generally low for heavily sized yarns but can be of importance when unsized or lightly sized warps are used. For fabrics woven on shuttleless weaving machines, the estimated weft crimp has to be adjusted for the length of yarn used to produce a selvedge and, sometimes, a dummy selvedge.

4.4.4 Cover factors

The cover factor[1] indicates the extent to which the area of a fabric is covered by one set of threads. For any fabric there are two cover factors: the warp cover factor and the weft cover factor. The cloth cover factor is obtained by adding the weft cover factor to the warp cover factor. The cover factors can be adjusted to allow for yarns of different relative densities – either because of the yarn structure or because of the raw material used.

The cover factors in SI units[8] are calculated by multiplying the threads per centimetre by the square root of the linear density of the yarn (in tex) and dividing by 10. The resultant cover factor differs by less than 5% from the cotton cover factor pioneered by Peirce[7] and expressed as the number of threads per inch divided by the square root of the cotton yarn count.

For any given thread spacing plain weave has the largest number of intersections per unit area. All other weaves have fewer intersections than plain weave. The likely weavability of all fabrics woven with the same weave and from similar yarns can be forecast from their cover factors. Plain weave fabrics with warp and weft cover factors of 12 in each direction are easy to weave. Thereafter weaving becomes more difficult and for cover factors of 14 + 14 fairly strong weaving machines are required. At a cover factor of 16 + 16 the plain structure jams and a very strong loom with heavy beat-up is needed to deform the yarns sufficiently to obtain a satisfactory beat-up of the weft. Some duck and canvas fabrics woven on special looms achieve much greater cover factors. Three cloths with cover factors of 12 + 12 are shown in Table 4.1. It shows how thread spacing and linear density have to be adjusted to maintain the required cover factor and how cloth area density and thickness are affected.

When widely varying cover factors are used for warp and weft, a high cover factor in one direction can generally be compensated by a low cover factor in the other direction. In Fig. 4.3, which shows a poplin-type weave, the warp does all the bending and the weft lies straight. With this construction warp yarns can touch because they bend around the weft and cloth cover factors of well above 32 can be woven fairly easily. Peirce calculated the original adjustment factors for a number of weave

Table 4.1 Comparison of fabrics with identical warp and weft cover factors woven with yarns of different linear densities (in SI units)

Cloth	Threads per cm		Linear density		Cover factor		Cloth weight[a] (g/m^2)	Thickness[b] (mm)
	n_1	n_2	N_1	N_2	K_1	K_2		
A	24	24	25	25	12.0	12.0	130	0.28
B	12	12	100	100	12.0	12.0	260	0.56
C	6	6	400	400	12.0	12.0	520	1.12

n_1 are warp threads, n_2 are weft threads, N_1 is the linear density of warp, N_2 is the linear density of weft, K_1 is the warp cover factor, K_2 is the weft cover factor.

[a] Allowing for 9% of crimp.

[b] Allowing 25% for flattening and displacement of yarns.

Table 4.2 Cover factor adjustment factors for weave structure

Weave	Adjustment factor[a]
Plain weave	1.0
2/2 weft rib	0.92
1/2 and 2/1 twills	0.87
2/2 matt	0.82
1/3, 3/1 and 2/2 twills	0.77
5 end satin and 5 end sateen	0.69

Source: Rüti[10].

[a] Multiply actual cover factor by adjustment factor to obtain equivalent plain weave cover factor.

structures. Rüti[9] published an adjustment factor that they found useful to establish whether fabrics with various weave structures can be woven in their machines and these are shown in Table 4.2. Sulzer have prepared graphs showing how easy or difficult it is to weave fabrics with different weave structures, thread spacings and linear densities in various types of weaving machines.

4.4.5 Thickness

Yarn properties are as important as cloth particulars when forecasting cloth thickness. It is difficult to calculate the cloth thickness because it is greatly influenced by yarn distortion during weaving and by pressures exerted on the cloth during finishing. It is also difficult to measure thickness because the results are influenced by the size of the presser feet used in the test instrument, the pressure applied and the time that has elapsed before the reading is taken. It is therefore essential to specify the method of measurement of thickness carefully for many industrial fabrics.

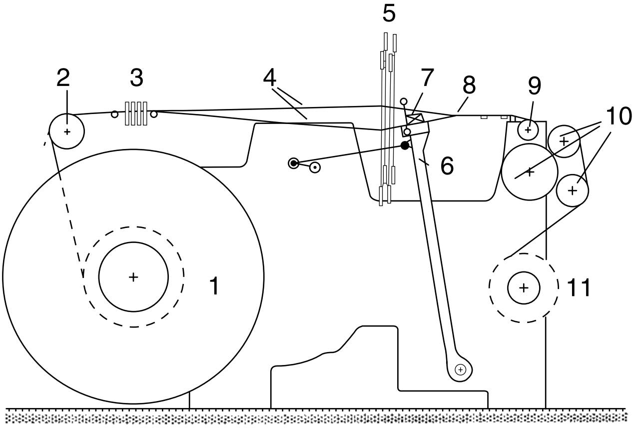
4.5 Weaving – machines (looms) and operations

Whilst the principle of weft interlacing in weaving has not changed for thousands of years, the methods used and the way that weaving machines are activated and controlled has been modified. During the last few decades of the 20th century the rate of change increased continuously and weft insertion rates, which control machine productivity, increased ten-fold from around 1950–2000 and they are likely to double again during the first five to ten years of the 21st century. The productivity of the weaver has increased even more and is likely soon to have increased a hundred-fold. Weaving, which used to be a labour-intensive industry, is now capital intensive using the most modern technology.

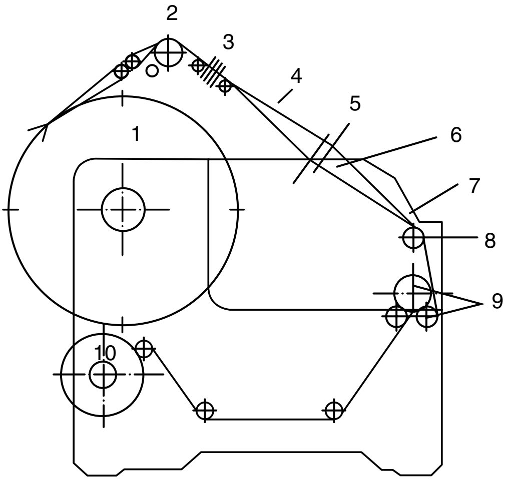
The essential operations in the weaving of a cloth are:

1. Shedding, i.e. the separation of the warp threads into two (or more) sheets according to a pattern to allow for weft insertion
2. Weft insertion (picking) and
3. Beating-up, i.e. forcing the pick, which has been inserted into the shed, up to the fell of the cloth (line where the cloth terminates after the previous pick has been inserted).

Provision has also to be made for the supply of warp and weft warp yarns and for the cloth, after weaving, to be collected. The warp yarn is usually supplied on warp beam(s) and the weft on pirn (shuttle looms only) or cones. A typical cross-section through a shuttle weaving machine[10] showing the main motions, together with the arrangement of some ancillary motions, is shown schematically in Fig. 4.17. Most single phase machines, irrespective of their weft insertion system, use similar motions and a nearly horizontal warp sheet between the back rest(2) and the front rest(9). Although this is the most common layout, other successful layouts have been developed. One of these, for an air jet,[11] is shown in Fig. 4.18 and an interesting double-sided air jet with two vertical warp lines back to back is being developed by Somet.[12]



4.17 Schematic section through Rüti shuttle weaving machine (machine motions and parts shown in *italics*). 1, *Weaver's beam* holding warp yarn (controlled by *let-off*); 2, *back rest* guiding yarn and controlling warp tension; 3, *drop wires* of *warp stop motion*; 4, shed formed by top and bottom warp sheet; 5, *healds* controlled by *shedding motion (crank, cam or dobby)* (Jacquard shedding motions do not use healds); 6, *sley* carrying *reed* and *shuttle*. It reciprocates for beat-up. (In many shuttleless machines the weft insertion system and the reed have been separated); 7, *shuttle* carrying the *pirn*; 8, fell where cloth is formed; 9, *front rest* for guiding cloth; 10, *take-up motion* controlling the pick spacing and cloth wind-up; 11, cloth being wound on to *cloth roller*.



4.18 Schematic section through Elitex air jet weaving machine (machine motions and parts shown in *italics*). 1, *Weaver's beam* holding warp yarn (controlled by *let-off*); 2, *back rest* guiding warp yarn; 3, *drop wires* of *warp stop motion*; 4, shed formed by top and bottom warp sheet; 5, *healds* controlled by *cam shedding motion*; 6, *weft insertion area* (the reed for beating-up located in this area is not shown); 7, fell where cloth is formed; 8, *front rest* for guiding cloth; 9, *take-up motion* controlling the pick spacing and cloth wind-up; 10, cloth being wound on to *cloth roller*.

Weaving machines can be subdivided into single phase machines, where one weft thread is laid across the full width of the warp sheet followed by the beat-up and the formation of the next shed in preparation for the insertion of the next pick, and multiphase machines, in which several phases of the working cycle take place at any instant so that several picks are being inserted simultaneously. Single phase machines are further subdivided according to their weft insertion system, whilst multiphase machines are classified according to their method of shed formation. The classification of weaving machines is summarized in Table 4.3.

In this chapter the details of the different types of weaving machines and their functions can only be outlined and the most important points highlighted. Weaving machines and their operation are described and discussed by Ormerod and Sondhelm.[13]

For the successful operation of a weaving machine good warps are essential. Warp preparation is, therefore, discussed in Section 4.5.1. This is followed by shedding in Section 4.5.2, weft insertion and beating-up in Section 4.5.3 and other motions used on machines in Section 4.5.4. The importance of machine width is considered in Section 4.5.5.

4.5.1 Warp preparation

The success of the weaving operation depends on the quality of the weaver's beam presented to the weaving machine because each fault in the warp will either stop the machine and require rectification, or cause a fault in the cloth, which is woven from it.

Before most fabrics can be woven a weaver's beam (or beams) holding the warp yarn has to be prepared. For very coarse warp yarns or when very long lengths of

Table 4.3 Classification of weaving machines

Single-phase weaving machines

Machines with shuttles (looms):
  - Hand operated (hand looms)
  - Non-automatic power looms (weft supply in shuttle changed by hand)
  - Automatic weaving machines
    - shuttle changing
      rotary batteries, stack batteries, box loaders or
      pirn winder mounted on machine (Unifil)
    - pirn changing

Shuttleless weaving machines:
  - Projectile
  - Rapier
    - rigid rapier(s)
      single rapier, single rapier working bilaterally
      or two rapiers operating from opposite sides of machine
    - telescopic
    - flexible
  - Jet machines
    - air (with or without relay nozzles)
    - liquid (generally water)

Multiphase weaving machines

Wave shed machines:
  - Weft carriers move in straight path
  - Circular weaving machines (weft carriers travel in circular path)

Parallel shed machines (rapier or air jet)

filament can be woven without modification of the warping particulars, a separate cone creel placed behind each weaving machine can be used economically. It improves the weaving efficiency by avoiding frequent beam changes but requires a large amount of space. For most yarns, especially sized yarns, it is more economical to prepare a weaver's beam and use it in the weaving machine.

The object of most warp preparation systems is to assemble all ends needed in the weaving machine on one beam and to present the warp with all ends continuously present and the integrity and elasticity of the yarns as wound fully preserved. Before this can be done the yarns have first to be wound on to a cone, then rewound on to a warper's beam and finally sized before the weaver's beam is made. The purpose of warp sizing is to apply a protective coating to the yarn to enable it to withstand the complex stresses to which it is subjected in the weaving machine. Some coarse ply yarns and some strong filament yarns can be woven without being sized.

Details of the various warp preparation processes are described by Ormerod and Sondhelm.[14]

4.5.2 Shedding

Irrespective of whether cloth is woven on an ancient handloom or produced on the most modern high speed multiphase weaving machine a shed has to be formed before a pick can be inserted prior to beat-up and cloth formation. The shed must be clean, that is slack warp threads or hairy or taped ends must not obstruct the passage of the weft or of the weft carrier. If the weft cannot pass without obstruction either the machine will stop for rectification, a warp end may be cut or damaged or a faulty weave pattern may be produced.

4.5.2.1 Shedding in single phase machines

In most single phase weaving machines, before pick insertion commences, an upper and a lower warp sheet is formed and the lifting pattern is not changed until the weft thread has been inserted across the full width of the warp. The shedding mechanism is used to move individual ends up or down in a prearranged order governed by the weave pattern. To maintain a good separation of the ends during weaving and avoid adjoining ends from interfering with each other the ends in each warp sheet can be staggered but in the area of weft insertion an unobstructed gap through which the weft can pass has to be maintained. The shedding mechanism chosen for a given weaving machine depends on the patterns that it is intended to weave on it. Most shedding mechanisms are expensive and the more versatile the mechanism the greater its cost. On some weaving machines there are also technical limitations governing the shedding mechanisms that can be fitted.

When crank, cam (or tappet) or dobby shedding is used, ends are threaded through eyes in healds that are placed into and lifted and lowered by heald frames. All healds in one heald frame are lifted together and all ends controlled by it will therefore lift alike. The weave pattern therefore controls the minimum number of healds required. To prevent overcrowding of healds in a heald frame or to even out the number of ends on a heald frame, more than one frame may lift to the same pattern. To weave a plain fabric, for example, 2, 4, 6, or 8 heald frames may be used with equal numbers of frames lifting and lowering the warp on each pick. Crank motions are generally limited to 8 shafts, cams to 10 or 12 and dobbies to 18 or 24. When the necessary lifting pattern cannot be obtained by the use of 24 shafts a Jacquard shedding mechanism, in which individual ends can be controlled separately, has to be used.

The crank shedding mechanism is the simplest and most positive available. It can only be used to weave plain weave. It is cheap, simple to maintain and in many high speed machines increases weft insertion rates by up to 10%. This mechanism has not been used as much as would be expected because of its lack of versatility. It is however particularly useful for many industrial fabrics that, like the majority of all fabrics, are woven with plain weave.

Cam or tappet shedding motions on modern high speed machines use grooved or conjugate cams because they give a positive control of the heald shafts. Negative profile cams are, however, still widely used especially for the weaving of fairly open fabrics of light and medium area density. The cam profile is designed to give the necessary lifting pattern to healds in the sequence required by the lifting plan which is constructed from the weave structure.

The third method of controlling heald shafts is by dobby and its main advantage is that there is practically no limit to the size of pattern repeat that can be woven, whilst with cam motions it is difficult and expensive to construct a repeat of more than eight or ten picks. It is also easier to build dobbies for a large number of heald shafts. Dobbies were controlled by pattern chains containing rollers or pegs which accentuated the lifting mechanism of the heald shafts. Punched rolls of paper or plastic were used instead of the heavier wooden pegs or metal chains for long repeats. During the 1990s electronic dobbies have replaced mechanical ones enabling weaving machines to operate at much greater speeds, reducing the cost of preparing a pattern and the time required for changing to a new design. Following the development of electronic dobbies, cam machines are becoming less popular because cams for high speed machines are expensive. If large numbers are required, because of the weave structure or because of frequent pattern changes, it may be cheaper to buy machines fitted with dobbies.

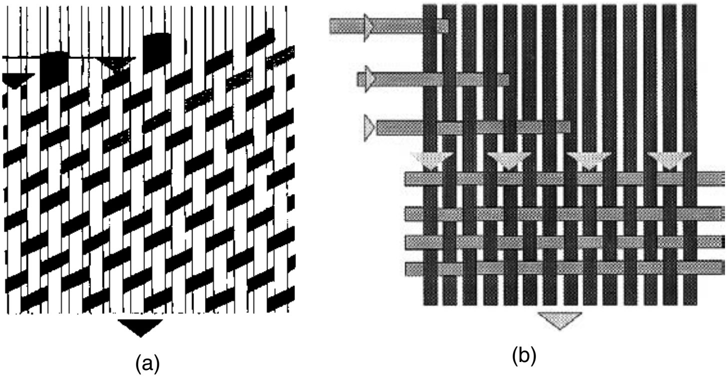
Shedding mechanisms are still undergoing intensive development and electronic control of individual shafts may soon reduce the difference in cost between crank, cam and dobby machines. Developments are likely to simplify the shedding units, reduce the cost of shedding mechanisms and their maintenance and make weaving machines more versatile.

When the patterning capacity of dobbies is insufficient to weave the required designs, Jacquards have to be used. Modern electronic Jacquards can operate at very high speeds and impose practically no limitation on the design. Every end across the full width of the weaving machine can be controlled individually and the weft repeat can be of any desired length. Jacquards are expensive and, if a very large number of ends have to be controlled individually, rather than in groups, the Jacquard may cost as much as the basic weaving machine above which it is mounted.

4.5.2.2 Shedding in multiphase weaving machines

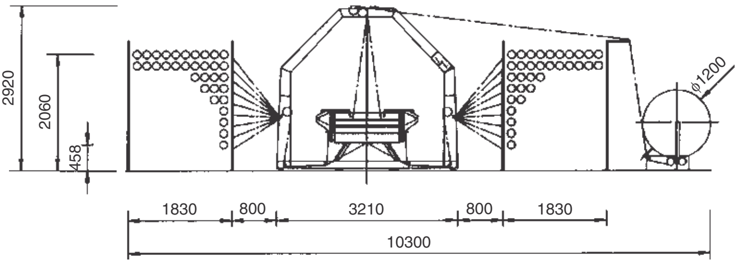
In all multiphase weaving machines[1] several phases of the working cycle take place at any instant so that several picks are being inserted simultaneously. In wave shed machines different parts of the of the warp sheet are in different parts of the weaving cycle at any one moment. This makes it possible for a series of shuttles or weft carriers to move along in successive sheds in the same plane. In parallel shed machines several sheds are formed simultaneously with each shed extending across the full width of the warp and with the shed moving in the warp direction. The difference between the methods of shed formation are shown schematically in Fig. 4.19.[15]

Weaving machines in which shuttles travel a circular path through the wave shed are generally referred to as 'circular weaving machines'. They have been widely used for producing circular woven polypropylene fabrics for large bags for heavy loads.

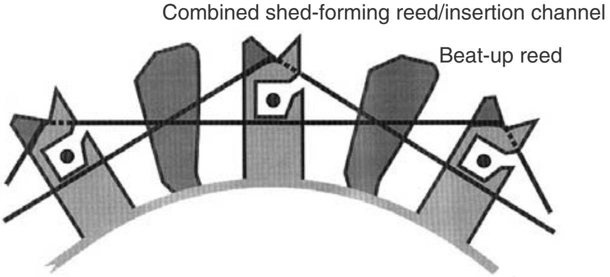


(a) (b)

4.19 Weft insertion on multiphase weaving machines (plain weave). (a) Wave shed principle, (b) multiphase parallel shed principle. Reproduced by kind permission of Sulzer Textil.



4.20 Schematic drawing of Starlinger circular loom SL4. Reproduced by kind permission of Starlinger & Co. G.m.b.H. (all dimensions in mm).



4.21 Shed formation of Sulzer Textil multiphase parallel shed M8300. Shed-forming reed with weft insertion channel and beat-up reed mounted on drum. Reproduced by kind permission of Sulzer Textil.

The layout of a Starlinger circular weaving machine[16] is shown in Fig. 4.20. The creels containing cheeses of polypropylene tape are located on either side of the weaving unit that is in the centre. The warp yarns are fed into the weaving elements from the bottom, interlaced with weft carried in either four or six shuttles through the wave shed in the weaving area, and the cloth is drawn off from the middle top and wound on to a large cloth roll by the batching motion located on the right.

No wave shed machine using weft carriers moving in a straight path has proved commercially successful because the shedding elements have no upper constraint, making it impossible to guarantee a correct cloth structure, and because maintaining a clean shed has proved very difficult. Their attraction was a weft insertion rate of up to 2200 m min^{-1} but they became obsolescent when simpler single phase air jet machines begun to exceed this speed.

The first parallel shed machine to win limited commercial acceptance was the Orbit 112,[13] which on a two head machine weaving used rigid rapiers for weft insertion and reached weft insertion rates of up to 3600 m min^{-1} when weaving bandage fabrics. Sulzer Textil released their new multiphase linear air jet machine, which is already operating at up to 5000 m min^{-1} and is only at the beginning of its operational development. This machine, which needs no healds, has a rotating drum on which the shed-forming reed and beat-up reed are mounted (Fig. 4.21).[17] On this machine shedding is gentle and individual picks are transported across the warp sheet at relatively low speeds. Weft yarns do not have to be accelerated and decelerated continuously thus reducing the stresses imposed on the yarns. This reduces demands on yarn and, for the first time, we have a machine with a high insertion rate which should be able to weave relatively weak yarns at low stop rate and high efficiency.

4.5.3 Weft insertion and beat-up (single phase machines)

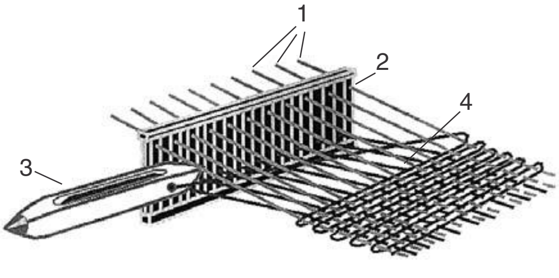
All single phase weaving machines are classified in accordance with their weft insertion system. The different types have been summarised in Table 4.3. The main methods of single phase weft insertion are by shuttle (Fig. 4.22), projectile (Fig. 4.23), rapier and air or water jet (Fig. 4.24).

4.5.3.1 Weft insertion by shuttle

Looms using shuttles for carrying the weft through the warp sheet dominated cloth production until the 1980s even in high wage countries like the USA. They are now obsolete, except for use in weaving a few highly specialised fabrics. In spite of this, large numbers of automatic bobbin changing looms are still in use but they are being rapidly replaced by shuttleless weaving machines. Shuttleless machines produce more regular fabrics with fewer faults and need less labour for weaving and maintenance. Millions of handlooms are still in operation in south east Asia being protected by legislation.

Figure 4.22 shows schematically the production of cloth on a shuttle loom. The shuttle carrying the pirn, on which the weft is wound, is reciprocated through the warp by a picking motion (not shown) on each side of the machine. For each pick the shuttle has to be accelerated very rapidly and propelled along the race board. Whilst crossing through the shed, one pick of weft is released and when the shuttle reaches the second shuttle box, the shuttle has to be stopped very rapidly. After each pick has been inserted it has to be beaten-up, that is moved to the fell of the cloth. The reed and the race board are mounted on the sley and during the weaving cycle are reciprocated backward and forward. Whilst the shuttle passes through the shed the sley is close to the healds to enable the shuttle to pass without damaging the warp yarns. The sley is then moved forward for beat-up. The need to have an open shed for weft insertion during a considerable part of the picking cycle, and the weight of the sley carrying the race board and the reed, impose restrictions on the picking speed, i.e. the number of revolutions at which the loom can operate.

The basic weakness of fly shuttle weaving machines is the unsatisfactory ratio existing between the large projected mass of the shuttle and the weft bobbin in relation to the small variable mass of the weft yarn carried in the shuttle.[13] Only about



4.22 Weft insertion by shuttle (schematic). 1, Warp yarns; 2, reed; 3, shuttle carrying pirn (entering shed); 4, fell of cloth. Picking motions and race board not shown. Reproduced by kind permission of Sulzer Textil.

3% of the energy imparted to the shuttle is used for the actual weft insertion. Further limitations on machine speed are imposed by the need to reciprocate the heavy sley. Whilst theoretically it is possible to attain weft insertion rates of up to 450 m min^{-1} for wide machines, few shuttle machines in commercial use exceed 250 m min^{-1}.

In a non-automatic power loom each time a pirn is nearly empty the weaver has to stop the loom and replace it. Pirns should be replaced when there is still a little weft left on them to prevent the weft running out in the middle of the shed and creating a broken pick which has to be repaired. In industrialized countries most power looms have been replaced by automatic pirn changing weaving machines that, in turn, are now being replaced by shuttleless weaving machines. In automatic weaving machines the pirns are changed without attention from the weaver and without the loom stopping. The replacement pirns are periodically placed into a magazine by an operative so that the machine can activate the pirn replacement whenever necessary. The magazine fillers can be replaced by a 'box loader' attachment when the pirns are brought to the loom in special boxes from where they are transferred automatically to the change mechanism. Shuttle change looms, where the shuttle rather than the pirn is changed whenever the pirn empties, are available for very weak yarns. All these methods require pirns to be wound prior to being supplied to the loom. Alternatively a Unifil attachment can be fitted to wind the pirns on the weaving machine and feed them into the change mechanism.

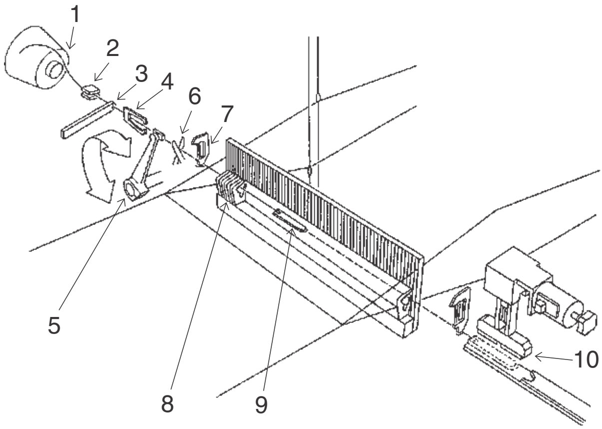
There are practically no restrictions on the widths or area density of fabrics which can be woven on shuttle machines. Automatic looms can be fitted with extra shuttle boxes and special magazines so that more than one weft yarn can be inserted in accordance with a prearranged pattern. Compared with similar equipment for shuttleless machines this equipment is clumsy and labour intensive.

4.5.3.2 Projectile machines

Projectile machines can use either a single projectile, which is fired from each side of the machine alternately and requires a bilateral weft supply, or use a unilateral weft supply and a number of projectiles which are always fired from the same side and are returned to the picking position on a conveyor belt. Since Sulzer commenced series production of their unilateral picking multiple projectile machines in the 1950s they have dominated the market and have sold more shuttleless machines than any other manufacturer. Sulzer Textil have continuously developed their machines, improved weft insertion rates and machine efficiency and extended the range of fabrics that can be woven on them. They are now used not only for weaving a vast range of standard fabrics but also for heavy industrial fabrics of up to 8 m wide, for sailcloth, conveyor belts, tyre cord fabrics, awnings, geotextiles, airbags and a wide range of filter fabrics of varying area density and porosity.

One of the major advantages of all shuttleless machines is that weft on cone does not have to be rewound before it is used. This eliminates one process and reduces the danger from mixed yarn and ensures that weft is used in the order in which it is spun. On shuttle looms weft is split into relatively short lengths, each one of which is reversed during weaving which can show up long periodic faults in a yarn.

The standard projectile is 90 mm long and weighs only 40 g, a fraction of the mass of a shuttle. For pick insertion on a Sulzer machine (see Fig. 4.23) weft is withdrawn from the package through a weft brake and a weft tensioner to the shuttle feeder,



4.23 Weft insertion by projectile (Sulzer system) (schematic). 1, Weft (on cone); 2, yarn brake (adjustable); 3, weft tensioner; 4, weft presenter; 5, torsion rod; 6, weft cutter (scissors); 7, gripper (to hold cut end); 8, guide teeth; 9, projectile; 10, projectile brake (receiving side). Reproduced with kind permission of Sulzer Textil.

which places it into the gripper of the projectile. A torsion bar system is used for picking which transfers the maximum possible strain-energy to the projectile before it separates from the picker shoe. The torsion bar can be adjusted to deliver the energy required to propel the projectile through the guide teeth to the shuttle brake. Sulzer redesigned the reed and the beat-up mechanism so as to obtain a stronger and more rapid beat-up thus making a higher proportion of the picking cycle available for weft insertion.

Narrow machines can operate at weft insertion rates of up to 1000 m min^{-1} whilst 3600 mm wide machines can insert weft at up to 1300 m min^{-1}. Models are available for weaving heavy fabrics, for weaving coarse and fancy yarns and for up to six weft colours. The machines can be fitted with a variety of shedding motions and are equipped with microprocessors to monitor and adjust machine performance. Because of the increase in weft insertion rates with increases in reed width and because of the decrease in capital cost per unit width for wider projectile machines, it is often attractive to weave a number of widths of fabric side by side in one projectile machine.

For even wider and heavier fabrics Jürgens[18] build a machine using the Sulzer Rüti system of pick insertion. They can propel a heavier projectile carrying a weft yarn of up to 0.7 mm diameter across a reed width of up to 12 m. Their machines take warp from one, two or three sets of warp beams and maintain weaving tensions of up to 30 000 N m^{-1}, accommodate up to 24 shafts controlled by an extra heavy dobby, and deliver the cloth on to a large batching motion. Jäger have developed a projectile weaving machine for fabrics of medium area density and up to 12 m wide using a hydraulically propelled projectile.

4.5.3.3 Rapier machines

At ITMA Paris 1999, out of 26 machinery manufacturers showing weaving machines no fewer than 17 offered rapier machines and some offered machines of more than one type. Rapier machines were the first shuttleless machines to become available but, at first, they were not commercially successful because of their slow speed. With the introduction of precision engineering and microprocessor controls, the separation of the weft insertion from the beat-up and improved rapier drives and heads, their weft insertion rates have increased rapidly. For machines of up to 2500 mm reed space they equal those of projectile machines with which they are now in direct competition.

Machines may operate with single or double rapiers. Single rapier machines generally use rigid rapiers and resemble refined versions of ancient stick looms. They have proved attractive for weaving fairly narrow cloths from coarse yarns. Wide single rapier machines are too slow for most applications. In single rapier machines the rapier traverses the full width of the shed and generally picks up the weft and draws it through the shed on its return. A variation of the single rigid rapier is the single rapier working bilaterally, sometimes referred to as a two-phase rapier. As it has not been used to any extent for industrial fabrics it is not considered here but details can be found in the book by Ormerod and Sondhelm.[13]

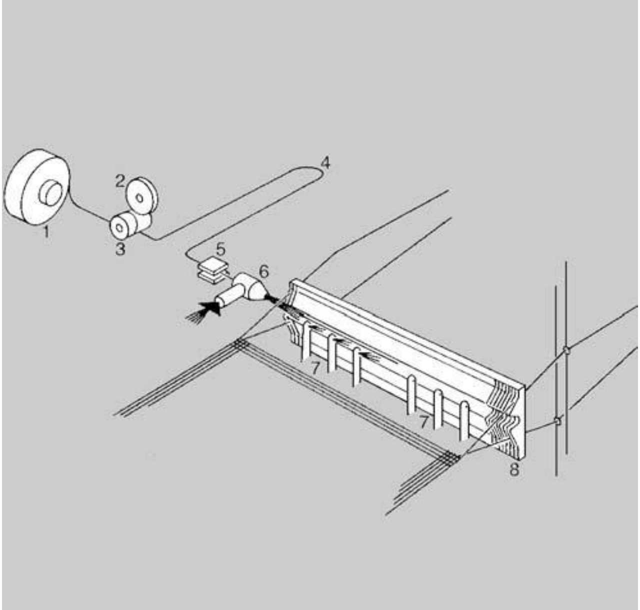
Most rapier machines use double rapiers, one rapier entering the shed from each side. They meet in the middle and transfer the yarn. With the Gabler system weft is inserted alternately from both sides of the machine and yarn is cut every second pick with hairpin selvedges being formed alternately on both selvedges. The Gabler system has now been largely superseded by the Dewas system where weft is inserted from one side only and is cut after every pick.

Double rapiers machines use either rigid or flexible rapiers. Rigid rapier machines need more space than machines fitted with any other weft insertion system. Rigid rapier machines, of which the Dornier HTV and P[19] series are prime examples, are capable of weaving most types of industrial fabrics with weft linear densities of up to 3000 tex, in widths of up to 4000 mm and at weft insertion rates of up to 1000 m min^{-1}. Typical fabrics being produced on them range from open-coated geotextile mesh to heavy conveyor belting. A variation of the rigid rapier is the telescopic rapier.

By far the largest number of rapier machines use double flexible rapiers which are available in widths up to 4600 mm with even wider machines being custom built for industrial applications. Standard machines have a relatively low capital cost and can be used to weave a wide range of low and medium area density fabrics. They are ideal for weaving short runs and for fabrics woven with more than one weft because their weft change mechanism for up to eight colours is simple and cheap. They are widely used for furnishing and fashion fabrics, often with Jacquards. They are also used for some industrial cloths.

4.5.3.4 Fluid jet weaving machines

Fluid jet machines use either air or water to propel the yarn through the shed. They do not need a weft carrier or a rapier for weft insertion and therefore have fewer moving parts and less mass to move. Water jets are only suitable for hydrophobic yarns whilst most yarns can be woven on air jets. Water jets generally use a single nozzle at the picking side to propel the yarn through the full width of the shed and this limits their width to about 2 m. As the flow of air is more difficult to control than the flow of water under pressure, air jets with single nozzles have only been commercially successful in widths of up to 1700 mm. For wider machines, booster or relay nozzles are placed along the reed to ensure the smooth movement of the weft across the full reed width. Although theoretically wide air jets can be built, com-



4.24 Weft insertion by airjet (Sulzer Rüti L5000). 1, Supply package; 2, measuring disc; 3, rollers; 4, storage tube; 5, clamp; 6, main nozzle; 7, relay nozzles; 8, reed with tunnel. Reproduced by kind permission of Sulzer Textil.

mercially single width machines are most attractive and machinery makers limit their ranges to 3600 or 4000 mm reed width.

Compressed air is expensive to produce and its flow is difficult to control. The air flow in the shed has, therefore, to be restricted either by special air guides or 'confusers' or by passing the weft through a channel in a special 'profile' reed. The former method was pioneered by Elitex and is used in most of their 'P' type weaving machines (Fig. 4.18) of which a large number are in use for weaving light and medium weight fabrics up to 150 cm wide. Sulzer Rüti developed the 'te strake' profile reeds with relay nozzles and this system is shown schematically in Fig. 4.24. There is one main nozzle per colour and one set of relay nozzles spaced at regular intervals along the reed. The weft is measured to length in the weft feeder and then carried by the air stream of the main nozzle into the weft duct, accelerated and transported further by air discharged from the relay nozzles. After insertion, a stretch nozzle at the receiving side holds the pick under tension until it is bound into the cloth.

Since air jets came into large scale commercial use in the 1970s they have been developed rapidly. They can now weave the majority of fabrics and are dominant for the mass production of fairly simple cloths. They have reached weft insertion rates of up to 3000 m min^{-1}, twice that of any other single phase weft insertion system and are still under intensive development. Their capital cost per metre of weft inserted is highly competitive. Their operating costs depend largely on the local cost of electricity and whether low grade waste heat from the compressors can be used for other operations in the plant.

Air jet machines fitted with an automatic weft fault repair system can correct the majority of weft faults, including part picks, which occur between the main nozzle and the selvedge on the receiving side. The unit removes the broken thread from the shed without disturbing the warp ends and then restarts the machine. Only if the machine cannot locate and repair the fault will it signal for attention. As weft stops represent the majority of stops on an air jet, the system greatly reduces the weaver's work load, frequently by more than 50%. It also reduces machine interference and improves the quality of many fabrics.

4.5.4 Other motions and accessories for single phase weaving machines

4.5.4.1 Warp supply and let-off motion

Warp yarns are generally supplied to the weaving machine on one or more weaver's beams. In special cases, as already mentioned above, cone creels can be used. The warp yarns assembled on the weaver's beam should be evenly spaced and under standard tension to ensure that all are of exactly the same length when they are unwound for weaving. The larger the diameter of the beams the longer the length of warp which can be wound on to it and the fewer the warp changes required but the greater the tension variations which have to be compensated. Different weaving machines accommodate beams of different maximum diameter but most modern machines can take beams of up to 1000 mm diameter. If even larger diameter beams are needed for very coarse warp yarns, for example for industrial fabrics or denims, the beams can be placed into a separate beam creel outside the loom frame. Such units cater for beams of up to 1600 mm diameter.

The width of yarn on the weaver's beam has to be at least as wide as the yarn in the reed. When the warp width required exceeds 2800 mm, more than one beam is frequently used to simplify sizing and warp transport. If yarns from more than one beam are used in one cloth it is essential that both beams are prepared under identical conditions to prevent variations which can cause cloth faults after finishing. The let-off tensions of different beams have to be carefully controlled and this has become simpler with the introduction of electronic sensors. When the cloth design requires the use of warp yarns of widely differing linear densities or results in different warp yarns weaving with widely differing crimps, two or more warp beams may have to be used in parallel. They can be placed either above each other or behind each other in the weaving machine. Comparison of Figs. 4.17 and 4.18 shows how the layout of machines can be modified without impairing their efficiency.

During weaving the let-off motion will release the required amount of yarn for each pick cycle. It must also hold the warp yarns under even tension so that they separate easily into two or more sheets during shedding prior to weft insertion and so that the required tension is maintained during beat-up when the newly inserted weft is moved by the reed to the fell of the cloth. Let-off motions used to be mechanically controlled with tension being measured by the deflection of the back rest but now electronic sensors are used for tension measurements and the let-off is frequently controlled by separate servo motors.

4.5.4.2 Take-up motion

Take-up motions are required to withdraw the cloth at a uniform rate from the fell. The speed of withdrawal controls the pick spacing, which has to be regular to prevent weft bars and other faults. In most weaving machines the take-up motion also controls the winding of the cloth on to the cloth roller. If large rolls of large diameter have to be made, as is common for heavy fabrics, a separate batching motion is placed outside the loom frame. Batching motions can be on a different level from the weaving machine, either below or above, to reduce the area required for the weaving shed. To prevent the weaving of long lengths of reject fabric, batching motions can incorporate cloth inspection facilities, sometimes with an intermediate cloth storage unit.

4.5.4.3 Automatic stop motions

The first group, warp protector motions, are only necessary on machines which use a free flying shuttle or projectile. They are designed to prevent the forward movement of the reed if the shuttle fails to reach the receiving side. This prevents damage to the machine and the breakage of large numbers of ends if the shuttle is trapped.

Warp stop motions stop the machine if an end breaks. They are activated when a drop wire, through which an end has been threaded, drops because a broken end will no longer support it. Drop wires can be connected to mechanical or electrical stop motions. Yarns have to be properly sized to prevent them being damaged by the drop wires. Electronic warp stop motions, which do not require physical contact with the warp, are now being introduced especially for fine filament yarns.

Weft stop motions are used to activate weft changes in automatic shuttle looms and to stop weaving machines if the weft breaks during weft insertion. Electronic motions are available that will stop the machine even if a broken end catches on again before it reaches the receiving side. In air jet machines fitted with automatic repair facilities the weft stop motion also starts the weft repair cycle.

4.5.4.4 Quick style change

QSC (quick style change) equipment, first shown by Picanol in 1991 and now available from most manufacturers, greatly reduces the time a weaving machine has to be stopped for a warp change. The warp beam, back rest, warp stop motion, heald frames and reed are located on a module which separates from the main frame of the weaving machine and which is transferred by a special transport unit to and from the entering and knotting department where the module becomes the preparation frame for a replacement warp.[14] Thus 90% of the work load, which is normally carried out on the stopped weaving machine, is eliminated from the warp replenishment cycle and the weaving machine efficiency is improved. It also results in cleaner reeds and healds resulting in better machine performance and improved cloth quality.

4.5.5 Machine width

The reed width of the machine must be equal to or greater than the width in reed of the fabric to be woven. Width in reed must allow for the width of selvedge and dummy ends. If the machine is narrower the cloth cannot be woven in the machine. Generally it is impossible to increase the available reed width of a machine.

Whilst the machine width cannot be exceeded, it is generally possible to weave narrower fabrics. In Sulzer projectile machines weaving down by up to 50% is possible. Different manufacturers and models have different arrangements for weaving down – some allow for only 200 mm which is often insufficient considering likely changes in materials and styles. It is most economic to use a high proportion of the reed width because weaving down is likely to reduce the weft insertion rate. Wider machines also tend to have higher capital and running costs. On some occasions it is economic to weave a number of fabrics side by side in one machine. Five, six or seven roller towels, each with its own tucked selvedges, can be produced in a wide Sulzer projectile machine.

4.6 The future

Because of rapid technological advances modern weaving machines have become highly automated with most functions electronically controlled. Machine settings can be adjusted and transferred and many faults can be repaired without requiring attention by an operative. The frequency of machine stops and their duration has been reduced. The cost of labour has been desensitized and the cost of production has been reduced whilst product quality has improved. Because of the cost of modern machines it becomes ever more important to use the right equipment for the job and operate machines at high efficiency.

At present projectile weaving machines are the most versatile of conventional machines and by bolting the right equipment to the machine there is hardly a fabric they cannot weave well. Most simple fabrics can be woven at much lower capital cost on air jets fitted with simple shedding systems. Their economic range is being extended continuously. In between there are fabrics which can be woven most cheaply on rapiers. Multiphase machines, like Sulzer Textil's linear air jet M8300, are likely to become cheap producers of simple fabrics in the not too distant future.

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