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Textile fabrication technologies for embedding electronic functions into fibres, yarns and fabrics

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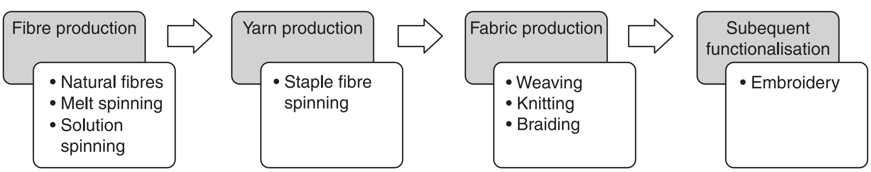
DOI: 10.1533/9780857093530.2.191

Abstract: In this chapter textile fabrication processes along the textile production chain will be presented. Starting from fibre and yarn production processes the general principles will be explained, also outlining how functionality can be brought into the fibre during the fibre and yarn production process. The chapter then outlines the basics of fabric production technologies. Here the integration of conductive materials, sensors and components will be discussed. Finally, technologies for subsequent functionalisation, such as embroidery and printing, will be presented.

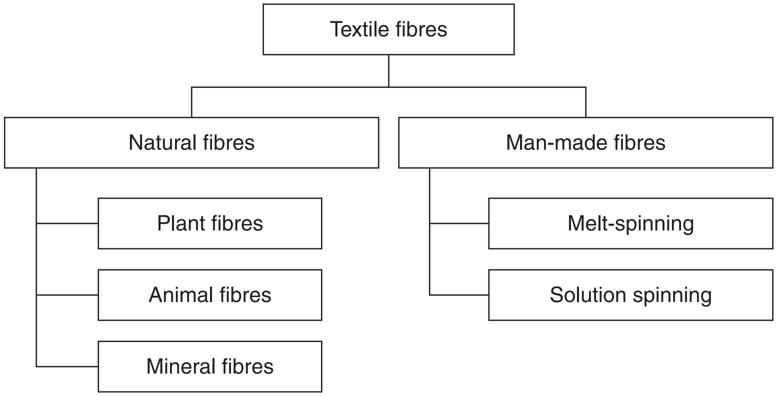
Key words: spinning, weaving, braiding, knitting, embroidery, functionalisation.

7.1 Introduction

In this chapter the basics of textile production technologies will be explained. The structure of this chapter is depicted in Fig. 7.1. Starting at the process of fibre production, the general principle of melt-spinning polymeric fibres will be explained. Natural fibre production using the example of cotton will be discussed. The next stage in the textile process chain is the production and functionalisation of yarns. Staple fibre spinning processes will be reviewed. Functionalisation technologies, such as electro-coating and winding, will be presented to illustrate the production of electrically conductive fibres and yarns. In the next part of this chapter, basic fabric production technologies are discussed. Weaving, knitting and braiding, as the most common fabric production principles, will be presented. Finally, processes for the subsequent functionalisation of textiles, such as sewing, embroidery or printing, will be outlined.



7.1 Textile fabrication processes.



7.2 Classification of fibre materials.

The first step in the textile process chain is the production of fibres. The world of fibre materials is divided into natural and man-made fibres (Fig. 7.2). The following sections deal with natural fibres and continuous (man-made) fibres, respectively.

7.2 Fibre and yarn production processes: natural fibres

In the area of natural fibre materials, a distinction can be made between fibres originating from plants (i.e. cotton) and fibres originating from animals (i.e. wool). There are also specialty fibres like mineral fibres (asbestos), but the most common natural fibre materials used are cotton and wool.

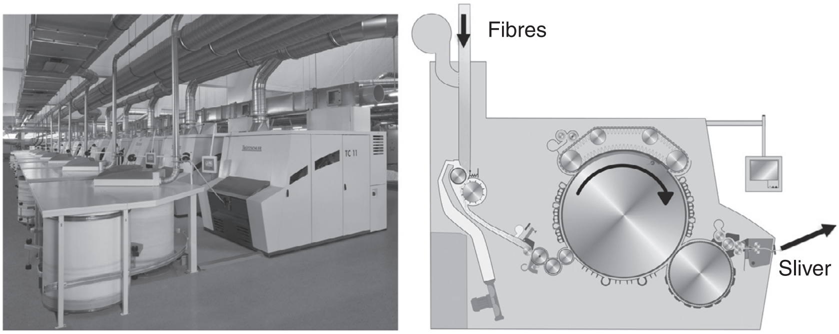
Cotton is an agricultural plant, which is mechanically harvested. The cotton plant is a small shrub and the cotton fibres grow in the capsules containing the cotton seed (Fig. 7.3). The fibres have a typical length of 25 to 30 mm. Such short fibres are called *staple fibres*. When the cotton capsules are ripe, they pop open, exposing the white cotton fibres (Fig. 7.3). During the harvesting process, the harvester grabs the cotton plant at the trunk and strips off all cotton capsules, leaves and smaller twigs. During this process the cotton plant is destroyed, so it has to be planted newly the next season.

In subsequent processes (Wulfhorst *et al.*, 2006) the fibres are separated from the seeds and other materials like capsule fragments, leaves, twigs and dirt. In a carding machine (Fig. 7.4) the fibres are combed by a series of rotating drums and moving carding bars equipped with metal combing teeth. As a result, a soft uniform fibre band is formed. In the fibre band, called sliver, the fibres lie parallel to each other. The sliver is held together by the friction between the parallel fibres, which provides just enough tenacity for subsequent production steps.

7.3 Cotton plant with ripe cotton capsules.

7.2.1 Staple fibre spinning

During the spinning process, the transition from a loose fibre bundle to an actual yarn takes place. The bundle of parallel fibres is twisted, which gives the yarn its tenacity. The tenacity of staple fibre yarns is based on inter-fibre friction. By



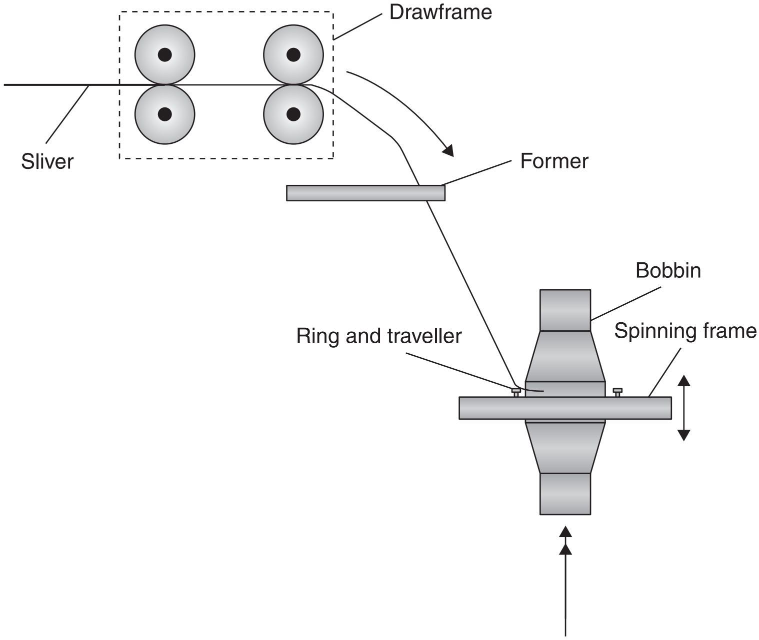
7.4 Left: Carding machine line in a factory. Right: Schematic drawing of a carding machine (images used with permission of Trützschler Spinning).

adding a twist to the fibre bundle, the axial load on the yarn is deflected into a radial force, which as a consequence induces a perpendicular (axial) reactive friction force. There are three predominant spinning technologies, which have been established in the industry: ring spinning, rotor spinning and airjet spinning. These three principles are presented in the following sections.

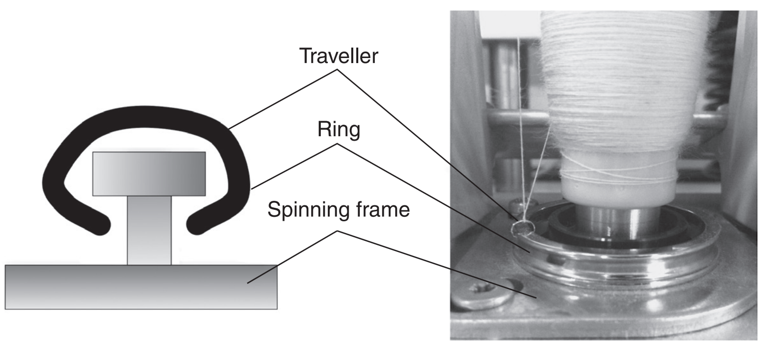
7.2.2 Ring spinning

Ring spinning is one of the oldest automated spinning principles. Figure 7.5 depicts a ring spinning position. The spinning machine is fed with a sliver of about 900 tex[1] (called 'flyer') to a drawframe. A drawframe consists of wheel pairs, which revolve at different speeds. The first pair is slower than the second pair, which draws the sliver apart, thus making it finer. The bobbin is actively rotated, while the spinning frame moves up and down. The flyer is guided through a stationary former and then through a traveller before being wound onto the bobbin. The traveller consists of a small metal clamp and slides on a ring with a T-shaped profile (for details, see Fig. 7.6).

During the spinning process the bobbin is actively rotated. The flyer is being wound onto the bobbin, dragging the traveller along the ring as the bobbin rotates. In this way, a twist is induced in the flyer, which continues back to the drawframe. Therefore the twist, which provides the yarn tenacity, is induced between drawframe and bobbin. The amount of twist induced depends on the difference between the bobbin rotation speed and the speed of the traveller. The spinning frame moves up and down during the process to wind the produced yarn in a way that allows rewinding in subsequent processes. Ring-spun yarns exhibit a high quality concerning evenness and tenacity. But the ring-spinning process is also slow, as only about 20 m/min are achievable.



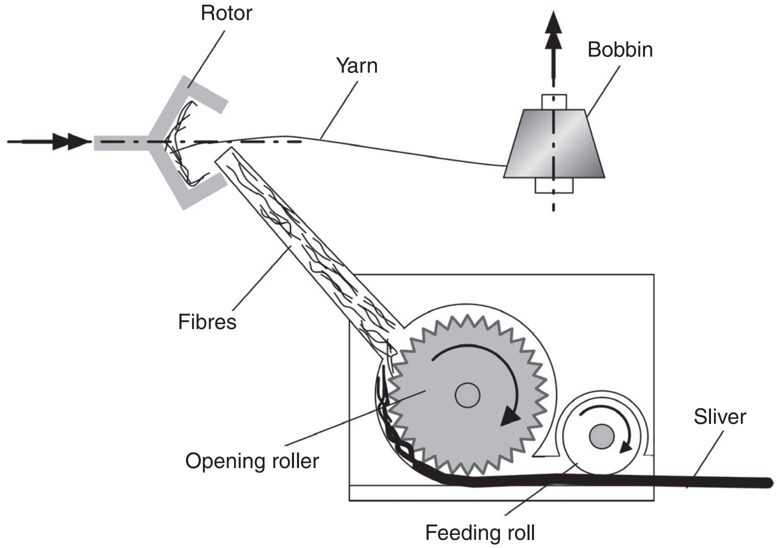
7.5 Schematic drawing of a ring-spinning position.



7.6 Ring and traveller.

7.2.3 Rotor spinning

To explain the rotor spinning principle, a simple analogy is applied. The rotor spinning principle works in a similar way to the production of candyfloss. Candyfloss is produced by melting sugar in a small drum rotating at high speed. Due to the centrifugal force, the molten sugar exits the small drum through the openings in the



7.7 Rotor spinning principle.

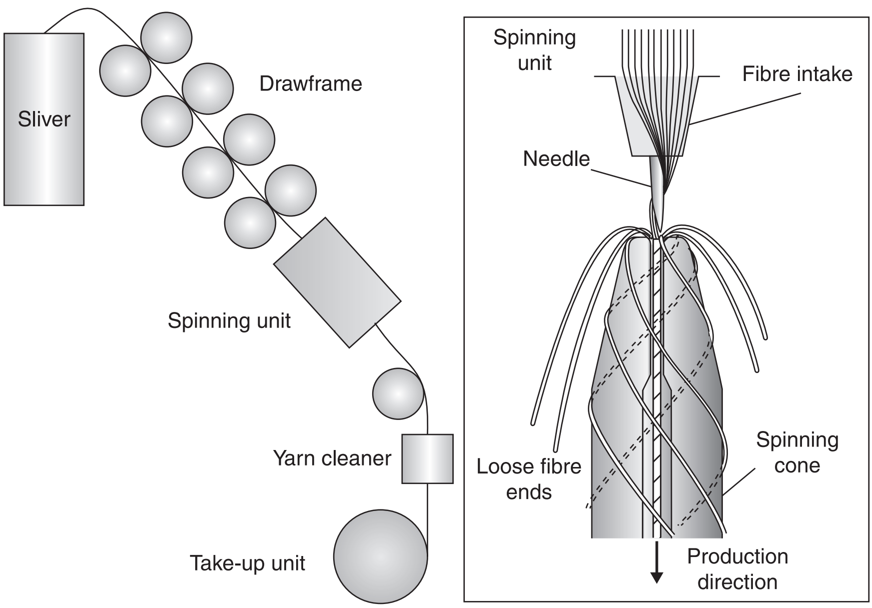
drum walls. In mid-air the sugar solidifies and forms fibres. The fibres are caught in a larger drum totally surrounding the smaller drum. A wooden stick is used to catch the sugar fibres and start the 'spinning' process of the candyfloss.

Rotor spinning works in a similar fashion (Fig. 7.7). A sliver of staple fibres is fed to an opening roller, which mainly consists of a drum equipped with a dense net of sewing teeth. The opening roller rips the fibre bundle apart and blows the single fibres into a rotor, which revolves at a very high speed (up to 150,000 min^{-1}). The yarn formation is started by inserting a short piece of yarn into the rotor. The end of the yarn rotates and is twisted together with the loose fibres, which are located in the rotor. By transporting the freshly spun yarn out of the rotor, a continuous yarn formation process can be established.

The rotor spinning process eliminates the need for a drawframe, since the fibre bundle is directly split into single fibres. The production speed of the rotor spinning process is around 100 to 200 m/min, which makes this process more productive than ring spinning. On the downside, the mechanical properties of rotor-spun yarns are lower than those of ring-spun yarns.

7.2.4 Airjet spinning

The airjet spinning technology is a more recent development. Here a jet of air is used to produce the yarn (Fig. 7.8). The drawing frame delivers the fibre band, which is sucked into a conical opening and moved over the needle. An air vortex



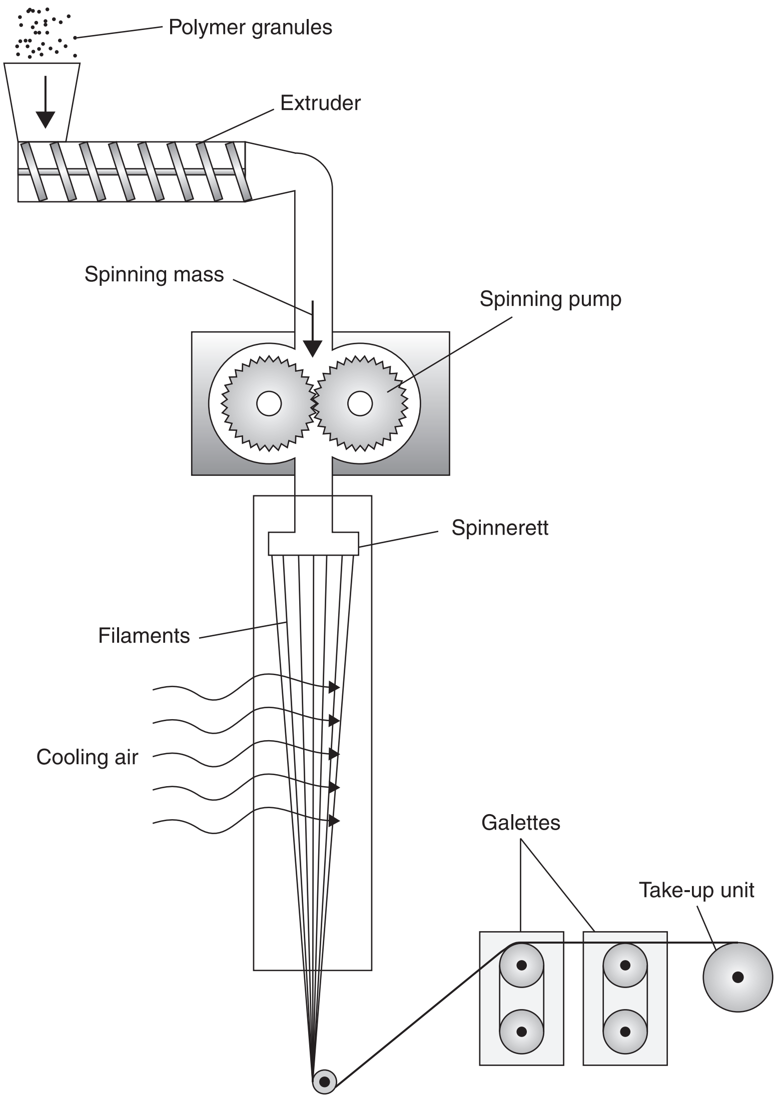
7.8 Airjet spinning process.

separates some fibre ends and bends them over the spinning cone. These bent back fibres wrap themselves around the core of parallel fibres, which gives the airspun yarn its tenacity. The airjet spinning technology is very productive, since production speeds are around 380 to 450 m/min (ring spinning: 20 m/min). On the downside, only the fibres wrapped around the parallel core contribute to the strength of the yarn. Therefore the strength of airspun yarns is lower compared to ring and rotor spun yarns.

7.3 Fibre and yarn production processes: continuous (man-made) fibres

7.3.1 Melt-spinning

Man-made fibres represent all fibre materials that have been artificially produced. There are diverse established spinning processes for producing fibres. Melt-spinning hereby accounts for the largest part of man-made fibre materials. Virtually any thermoplastic polymeric material can be melt-spun. Figure 7.9 shows the principle components of a melt-spinning plant. Polymeric granules are fed into an extruder, which melts and mixes the polymer. At the end of the extruder a homogenous, molten polymeric spinning mass is pressed into the spinneret by a spinning pump. The polymer is forced through the narrow openings of the



7.9 Principle components of a melt-spinning plant.

spinneret, resulting in a fine thin stream of molten polymer, called filaments. A spinneret can contain several hundred openings, resulting in several hundred filaments. In the subsequent cooling chamber, the filaments are treated with cooling air. During the cooling process, a certain amount of elongation is induced into the yarn by gravity. When the polymer solidifies, the filament bundle (yarn) is guided over several pairs of heated rotating drums, called galettes. The yarn is heated to glass temperature to soften the filaments and therefore make them more susceptible to mechanical strain. The strain, which is induced by the difference in rotation speed of the galettes, stretches the yarn. During the stretching process, the yarn becomes finer and the molecule chains of the polymer are oriented along the yarn axis, which heightens the mechanical tenacity of the yarn. Multiple galette pairs can be used to achieve the desired yarn fineness. Common materials, which can be melt-spun, are polyester (PES), polyethylen (PE), polypropylen (PP), polyamide (PA) and polyvinylidenfluoride (PVDF). Finally, the yarn is wound onto a bobbin. Filament yarns are also called 'endless fibres', due to the fact that on a bobbin each filament is one continuous piece of the yarn.

7.3.2 Solution spinning

Solution spinning follows another approach (Fig. 7.10). The polymeric material is dissolved and the spinning mass is pumped through the spinneret. Two principles of solution spinning can be applied, wet-spinning and dry-spinning.

In the *wet-spinning* process, the spinneret is located in a basin with a chemical liquid. By chemical precipitation, the polymer is spun out and the filament bundle can be drawn from the basin. Typical materials that are spun with the solution spinning method are viscose and ultra-high density polyethylene (UHDPE).

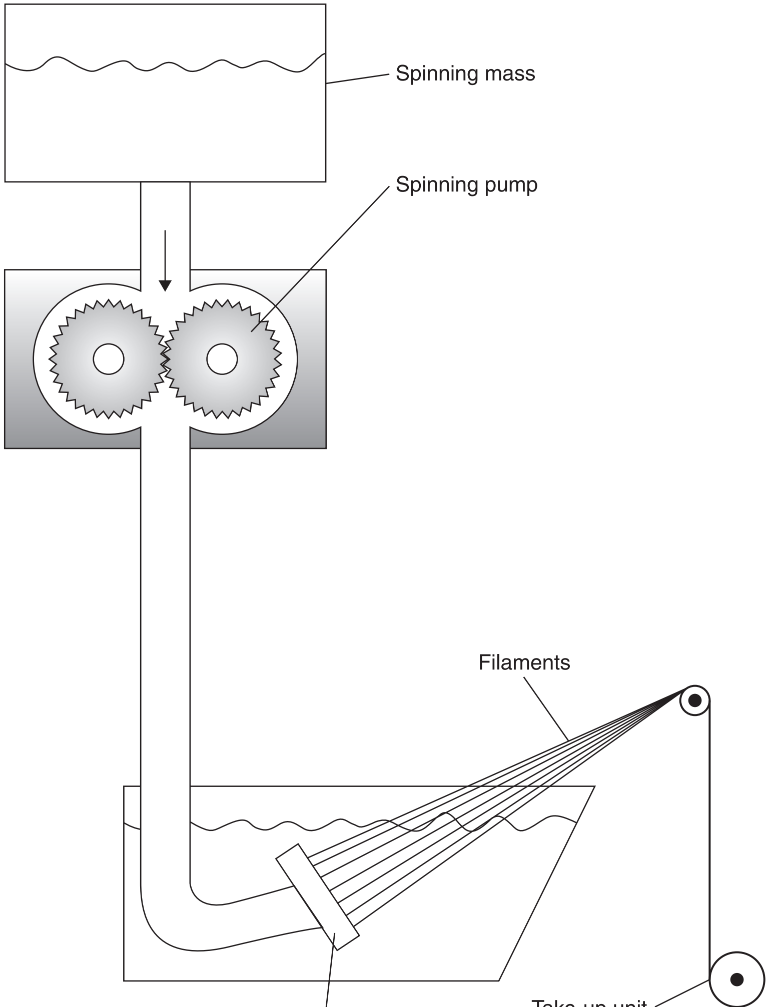
The process depicted in Fig. 7.10 is called 'wet-spinning', since the formation of the fibres takes place in the presence of a liquid chemical medium.

The *dry-spinning* process has a similar process diagram to the melt-spinning process. The polymer is dissolved and the spinning mass pumped through the spinneret. Hot air is injected, the solvent evaporates and is sucked out of the chamber. With the solvent evaporated, the polymer solidifies, forming the filaments.

7.4 Functionalisation of fibres and yarns

In the foregoing sections, the production of fibres and yarns has been discussed. The production processes represent standard textile production methods. For smart textiles, electrically conductive materials are necessary to distribute data and energy. The materials and processes affiliated with electrically conductive yarns are presented in Chapter 2 of this book. However, a very short summary of the possibilities to functionalise yarns in the yarn formation process are given.

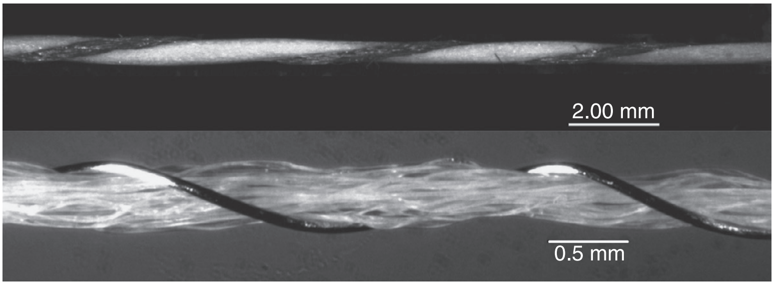
A staple fibre spinning is a mixture of staple fibre materials, which are employed in the clothing industry to modify yarn characteristics. Yarns for knitted woollen sweaters for example, contain a certain amount of acrylic fibres to increase the wear and rubbing resistance of the yarn. In terms of smart textiles, a certain amount of electrically conductive staple fibres can be mixed into the yarn to achieve a certain level of electrical conductivity. Since adding only a percentage of electrically conductive fibres will not result in high conductivities, such yarns are often employed in protective clothing to achieve an anti-static effect. The



7.10 Solution spinning process.

yarns for the inner lining of fire fighter jackets for example, contain a mixture of mainly aramide fibres (heat resistance) and a low percentage of carbon fibres (which are electrically conductive). Usually about 2% of the fibre material is carbon.[2] This eliminates the risk of static sparks, which might ignite a combustible gas that the fire fighter is exposed to.

Another method to functionalise staple fibre yarns is **winding and twisting**. By twisting a fine metal wire around a staple or multifilament fibre core yarn, an electrical conductivity can be achieved (Fig. 7.11). While the metal wire acts as an



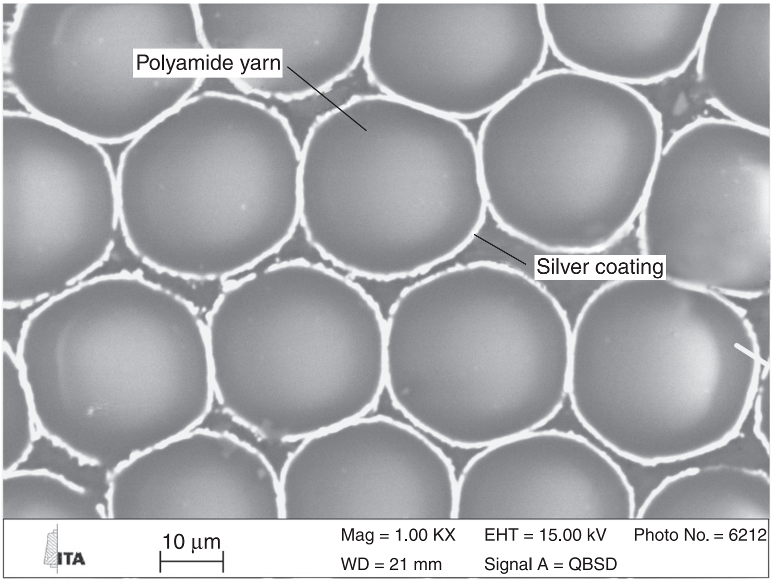
7.11 Electrically conductive material wound around a core yarn. Top: silver-coated Polyamide yarn. Bottom: silver wire.

electrical conductor, the staple fibre yarn is the load carrier. Flexibility of the complete yarn is given by the spiral-shaped path of the wire. When the core yarn is stretched, the angle of the wire helix becomes flatter, providing structural elongation without stressing the wire material.

In man-made fibres, electrical conductivity can either be achieved by spinning **intrinsically conductive polymers** or using **additives** such as **carbon nanotubes** or **carbon black particles**. An example of a polymer that can be produced in an electrically conductive form is PVDF. Walter *et al.* (2011) produced a piezoelectric sensor fibre made of PVDF, which was embedded in a fibre-reinforced sample part. To exploit the piezoelectric effect in a fibre (= generation of an electrical potential as a reaction to mechanical deformation), the PVDF fibres were melt-spun, drawn, implemented into a fibre-reinforced sample and then polarised between two electrodes under the influence of heat. The sample part was then subjected to an alternating mechanical load and the potential of the piezo fibres electrically measured. It was shown that the piezoelectric effect in fibres allows the measurement of mechanical deformation, thus enabling the monitoring of a technical sample part.

By adding particles to the spinning mass, polymers can be made electrically conductive, but a dilemma arises with the inclusion of particles. The more particles that are added, the better the electrical conductivity will be. However, the mechanical properties of the yarn will decrease as more particles are mixed into the molten polymer. The maximum conductivity, which can be achieved by these processes, is 1.000 S/cm (Siemens [S]: $1\,S = \Omega^{-1}$).

A common method for achieving electrical conductivity is **coating the yarns with a fine metal layer** (Schwarz *et al.*, 2009). By employing an electrochemical process, a fine layer of silver, copper or gold can be deposited on the surface of the fibres, giving the material a good surface conductivity (Fig. 7.12). The advantage of this process is that very good electrical resistance is achievable (up to 50 Ω/m for plied yarns[3]). However, often the metallic layer on such yarns is very susceptible to mechanical friction and rubbing. The metallic coating is damaged



7.12 Silver-coated polyamide fibres.

during the textile production process (weaving, knitting etc.). Subsequent washing of the product induces even more rubbing, creating cracks in the metal surface and rubbing the metallic material off partially. Also, the price for such yarns is comparatively high and therefore not fit for the mass market (100–1.000 €/kg).

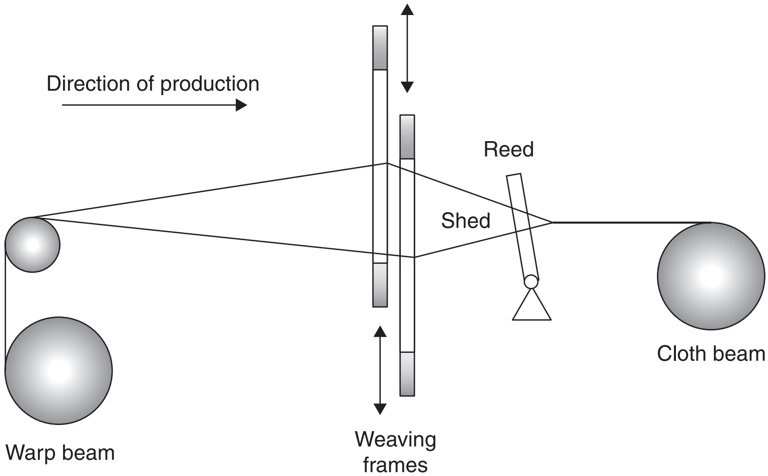
The 'holy grail' of electrically conductive fibres would be a material with:

- a high electrical conductivity;
- a high mechanical tenacity;
- wash resistance;
- is comparatively cheap and available in large quantities.

In current research projects, electrically conductive materials are being researched and good progress has been made, broadening the range of possibilities for smart-textiles developers. Future research will intensify this trend.

7.5 Fabric production: weaving

In the fabric production process, the step from linear textile systems (yarns) to two-dimensional (2-D) textiles (fabric) is made. The three most common production methods for fabrics are weaving, knitting and braiding. This section discusses weaving. Weaving is one of the oldest fabric production technologies, dating back thousands of years. In the weaving process, two yarn systems are used, warp and weft thread (Fig. 7.13).

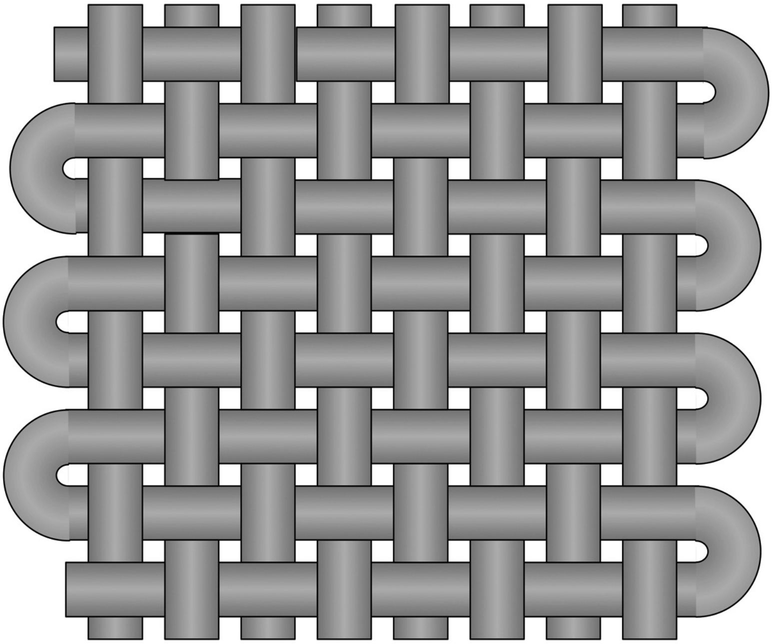


7.13 The basic principle of weaving.

The warp threads are oriented in the direction of production, and the weft threads are oriented perpendicular to the direction of production. The warp threads are stored on a warp beam. Depending on the width of the fabric, several hundred to thousands of warp threads are spooled onto a warp beam. From the warp beam the warp threads are guided through several weaving frames. The weaving frames can be moved up and down, pulling a part of the warp threads with them. In the space between the warp threads (called the shed), the weft thread can be inserted. After the weft thread has been inserted into the shed, the reed dashes the weft thread against the fabric border. After that, the weaving frames move in opposite directions, binding the weft thread into the fabric and another weft thread insertion cycle can begin. The produced fabric is rolled up on the cloth beam.

There are several methods for inserting the weft thread into the fabric, the most common being *shuttle*, *rapier* and *airjet* technology. The **shuttle** weaving process is the oldest weft insertion technology. A shuttle consists of a small frame, which holds a bobbin with the weft material. During the weft insertion phase, the complete amount of thread is transported through the shed. This produces a closed rim on the side of the fabric (Fig. 7.14).

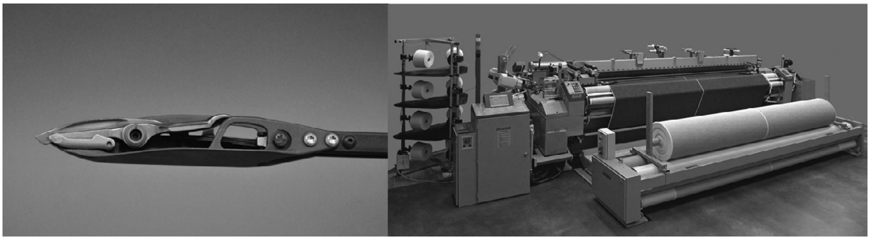
With the **rapier technology**, the weft thread is inserted into the shed using two grippers (Fig. 7.15). The rapier/gripper on the left side of the machine clamps the weft thread and pulls the thread from an external bobbin into the shed. In the middle of the fabric, the two rapiers meet. The thread passes from one gripper to the other and the rapiers retract. The reed dashes the weft thread against the fabric border and the weft thread is cut. The weaving frames change position and the gripper takes hold of the bobbin-side weft thread end, which has been cut off.



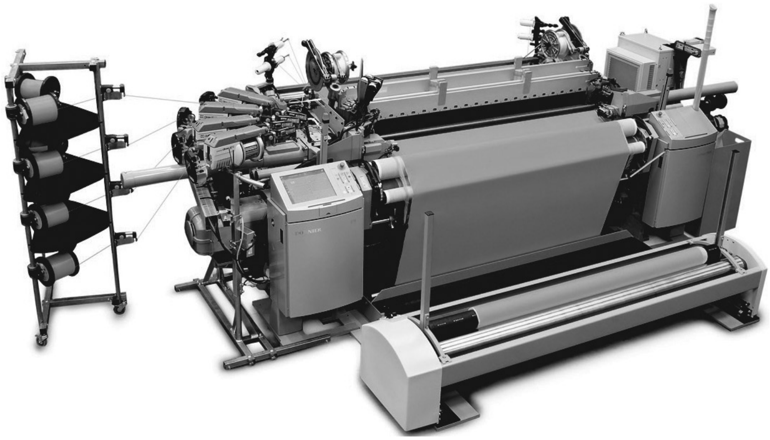
7.14 Closed fabric rim.

Since the weft thread is cut after each insertion cycle, the border of the fabric exhibits loose thread ends – the weft is not one continuous thread.

Another possibility for inserting the weft thread is **airjet technology** (Fig. 7.16). Compressed air is used to shoot the weft thread through the shed. A series of air nozzles are placed along the weft path, which provide an air cushion on which the weft thread travels towards the other end of the fabric. With airjet technology, the weft thread is also cut, producing the same fabric edge type as the rapier technology. Since no mechanical parts have to be moved to insert the weft thread, airjet weaving machines have a high productivity. Up to 900 weft insertions per minute are feasible.



7.15 Left: Rapier head with gripper. Right: Rapier loom weft insertion (image used with permission of Lindauer Dornier).



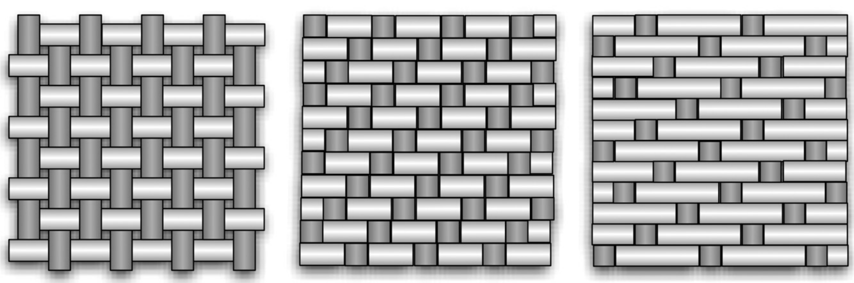
7.16 Airjet weaving loom (image used with permission of Lindauer Dornier).

7.5.1 Weave patterns

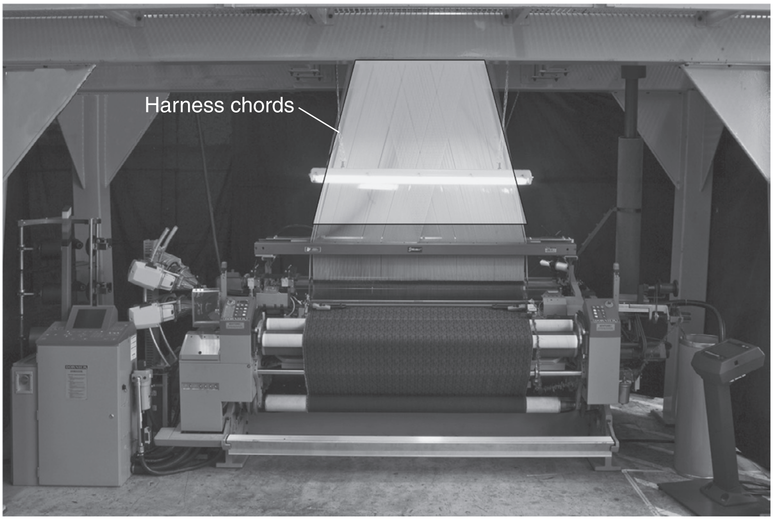
The weave pattern is determined by the configuration of the weaving frames. The most common standard weave patterns are plain weave (Fig. 7.17, left), twill weave (Fig. 7.17, middle) and atlas weave (Fig. 7.17, right).

At the plain weave, the warp thread passes alternately over and under a weft thread. With the twill weave, the warp thread passes over two and under one weft thread alternately. Also the twill weave exhibits an offset of one weft thread (Fig. 7.17, middle). At the atlas weave, the warp threads pass over three weft threads and then below one weft thread. This creates a unique pattern for each weave. More sophisticated weave patterns are possible by using more weaving frames.

When weaving frames are employed, a certain set of warp threads is tied to a weaving frame. Only the complete set of warp threads can be moved up or down,



7.17 Typical weave patterns. Left: Plain weave. Middle: Twill weave. Right: Atlas weave.



7.18 Jacquard weaving loom (image used with permission of Lindauer Dornier).

thus limiting the weavable patterns. To achieve complex patterns, **Jacquard technology** can be used. With Jacquard technology, each warp thread can be controlled individually by a set of harness cords. Figure 7.18 depicts a weaving loom with a Jacquard attachment. A frame resides over the weaving machine. Above the warp threads, a Jacquard attachment is installed. Each warp can be individually pulled up or let down. This enables weaving of complex designs.

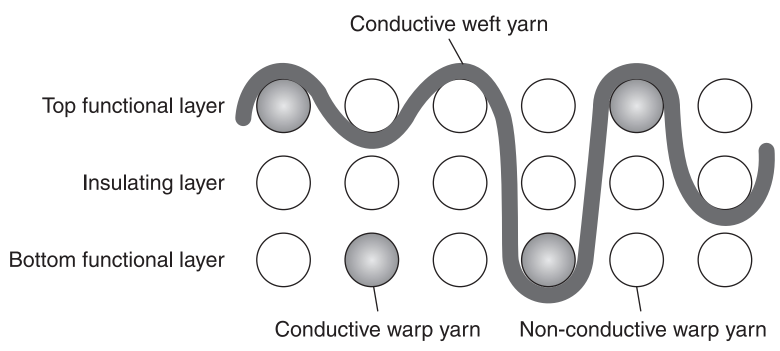
7.5.2 Functionalising woven fabrics

The individual characteristics of each weaving pattern and weft insertion principle offer a variety of possibilities towards the development of smart textiles. In most applications, conductive yarns are used in the weft, since weft yarns can be exchanged easily when another product is to be manufactured on the machine. In general, functional yarns can also be used in the warp. But this is more complicated and cost-intensive, since a special warp beam must be produced with an exact spacing of the warp threads. Also the warp yarns are exposed to more process steps, machine elements and therefore friction and tension. The warp yarns must be spooled onto the warp beam, then guided through the weaving frames and bent up and down during the shed action. This exposes the warp yarns to an increased amount of stress, possibly damaging the electrically conductive coating or breaking conductive filaments, which can cause short circuits in the woven product.

This implies also that there are challenges when weaving electrically conductive yarn material. In order to achieve high productivity, it is desirable to weave at high speeds. The weaving process must be controlled in such a way that mechanical stress on the yarns and abrasion are kept to a minimum. It has to be kept in mind that weaving is inseparably connected to the production of dust. Hundreds of yarns are in motion, rubbing against each other and producing fine fibre fragments, which float in the air; this is mainly the case when staple fibres are used for weaving, since the loose fibre ends sticking out of a yarn body can break or be pulled out of the yarn. Electrically conductive loose fibres, which float in the air, are a danger to the electronics in the machinery, since the fine fibres can pass through tiny gaps and short circuit the control boards of the weaving machine. The electrical parts of the weaving machines can, of course, be encapsulated against these fibres. The problem of short circuiting caused by conductive fibres is severe when, for example, carbon fibre fabrics for fibre-reinforced parts are produced. Machinery processing carbon fibres must be specially encapsulated, which is cost-intensive. Therefore it is desirable to use as few conductive fibre elements as possible, which can be achieved by employing functional fibres only in the weft.

Using *shuttle weaving* technology and an electrically conductive yarn in the weft, it is possible to weave a fabric in which the conductive weft thread is going through the complete textile (Fig. 7.14). Such a textile could be used, for example, as a large area heater. Only the ends of the yarns would have to be in contact to an electrical current, which makes the contacting process easy. Fabrics woven with shuttle technology could also be employed as a sensor textile in applications where the detection of an event on a large area is required (e.g. deformation or damage of the fabric).

In fabrics woven with **rapier** or **airjet technology**, each weft thread is cut. The highest degree of design flexibility is achieved by using a combination of Jacquard technology and a three-layered woven fabric. A three-layered fabric is created by employing multiple weaving frames, which create two sheds. Using this set-up and electrically conductive warp and weft threads, it is possible to establish an electrical contact at defined positions in the fabric (Fig. 7.19). The top and bottom



7.19 Textile circuit board realised by employing a three-layered Jacquard woven fabric.

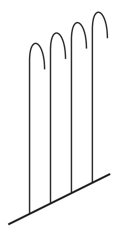
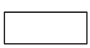
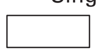
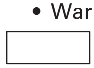
warp thread layer contain electrically conductive yarns. The middle layer electrically separates the two outer layers. By employing Jacquard weaving technology, each warp thread can be controlled individually. Complex patterns can be woven into the fabric, which control the contact points between the conductive yarns. This method allows the production of textile circuit boards with exactly defined electrical paths and interconnections.

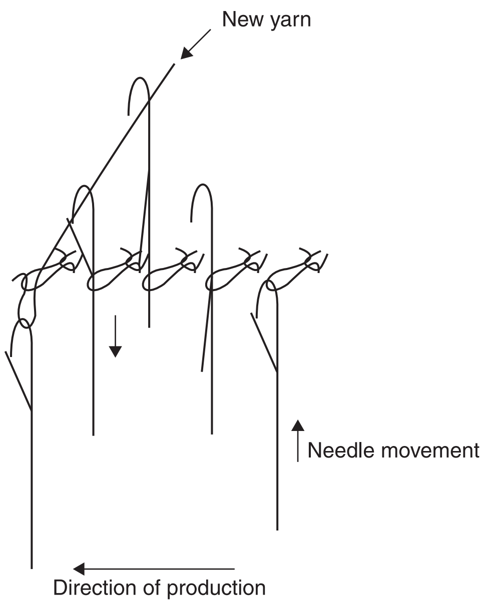
7.6 Fabric production: knitting

The term knitwear includes two main textile techniques, weft and warp knitting (Spencer, 2001; Weber and Weber, 2008) (Table 7.1). After weaving, it is the most common method of manufacturing textile fabrics. Because of the interlooped structure of the knitted fabric, the properties are completely different to woven fabrics. The difference in weft and warp knitting originates in the way the needles move during the production and in the way the yarn is supplied. Weft knitting is a one fibre technique, which means that only one fibre is needed to build the stitches. The needles are moved separately, whereas the warp knitting needles are moved simultaneously. Therefore, all needles need the fibre material at the same time. For this reason, the yarn is supplied with the help of warp beams. The most important knitwear fabrics are circular knitted, warp knitted, flat-knitted fabrics and fully-fashioned fabrics.

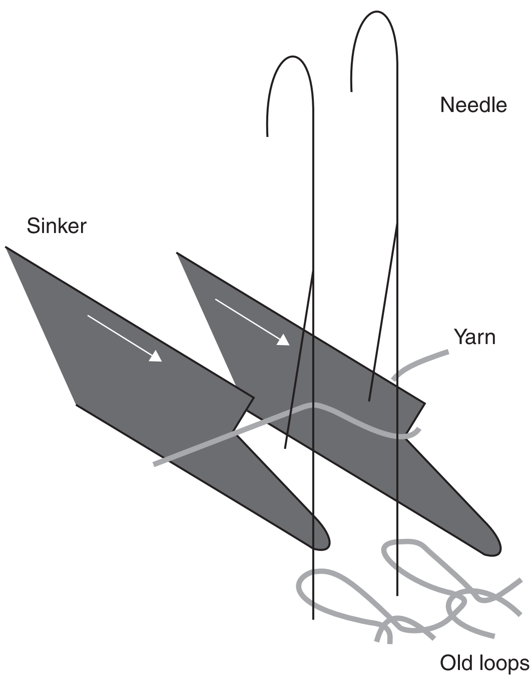
The knitted textile structure evolves from loops that are intermeshed row after row. The needle hook is responsible for the formation of a new loop with the supplied yarn. During the upward movement of the needle in order to catch the

Table 7.1 Classification of weft and warp knitting

	Weft knitting	Warp knitting
Needle arrangement		
Needle movement	Separately	Simultaneously
Yarn supply	Single yarn	Depending on machine
Techniques	Flat knitting 	Fully-fashioned knitting machine • Single yarn supply 
	Circular knitting 	Flat warp knitting machine • Warp beam supply 



7.20 Needle movement during loop formation.



7.21 Sinker.

yarn to build a new loop, the old loop slides down the needle (Fig. 7.20). This causes the opening of the needle. The needle hook is now open to catch the yarn. The newly built loop is drawn through the old loop from the previous knitting circle. During this movement, the needle is closed. Now the old loop can be released as the new loop remains in the needle hook.

The sinker is also important for the production of knitwear (Fig. 7.21). It is a thin metal plate, which can have different shapes. Each sinker is positioned between two needles and its main purpose is to help build the loop. Furthermore, it holds the loops that were formed in the previous circle down when the needle moves upwards and downwards to build the new loops.

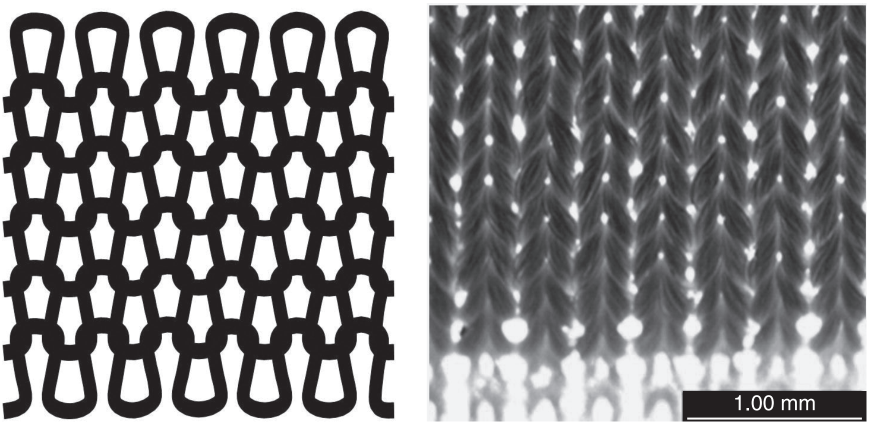
7.6.1 Circular knitting

Circular knitting machines always produce a tube-shaped fabric. They exist in different sizes or diameters, depending on the field of application. The needles and sinkers in these machines are arranged in a circle. The machines can be divided into two different types, depending on the number of sets of needles:

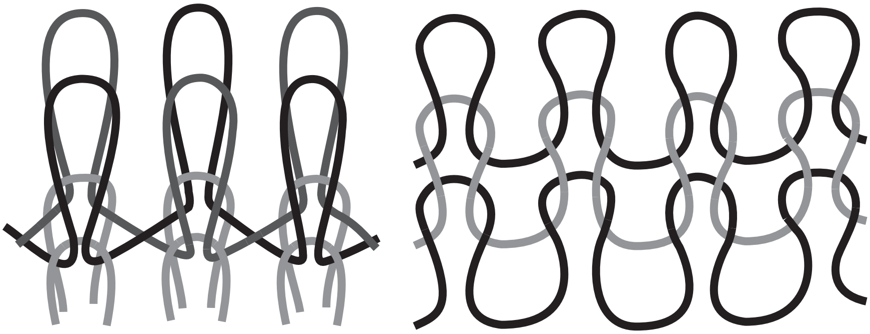
- *single set*: plain;
- *two sets*: rib, interlock, spacer fabric.

Both single set und double set machines also exist as Jacquard machines, which are needed for special designs. In these machines, the movement of each needle can be controlled from each cam. Common products that are produced with circular knitted fabric are T-shirts. For production, nearly every material can be used. The form varies from filament to staple fibre yarn. For special purposes, also monofilaments and wires are used.

Machines that possess just one set of needles are only able to produce plain-knitted structures (Fig. 7.22). In these structures, one side of the fabric shows right



7.22 Plain-knitted structure.



7.23 Left: Interlock structure. Right: rib structure.

loops and the other side rib loops. The following picture shows the loop structure of a plain knitted fabric.

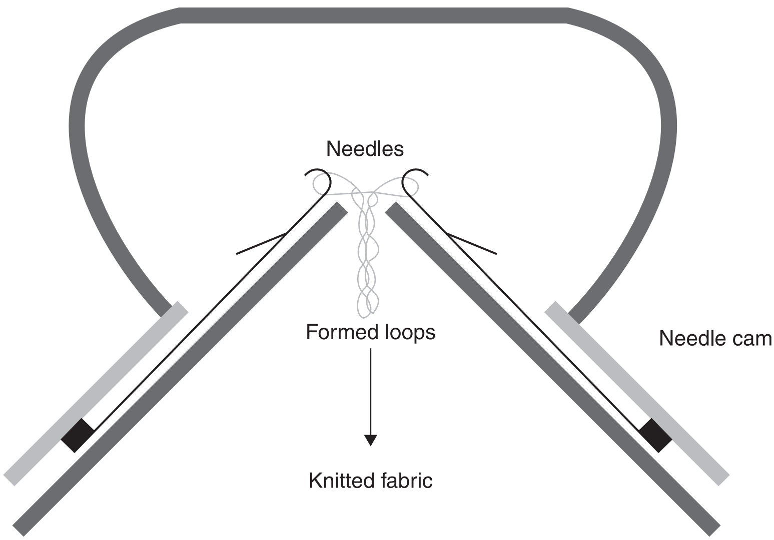
The interlock structure was derived from the rib structure (Fig. 7.23). For the production of this kind of fabric, two needle sets are necessary and the needles need to be arranged in a different way. The loops are formed in two different directions (Fig. 7.24). The result is a fabric with smooth surfaces on both sides. This is due to the right loop structure on each side. The rib structure shows rib loops on both sides of the fabric. These fabrics can be produced using loop- or needle transfer.

7.6.2 Flat knitting

Machines for the production of flat-knitted fabrics are the most versatile of the weft-knitting machines. Flat-knitting machines can be divided into two groups:

1. hand-propelled and hand-manipulated models;
2. automated, electronically-controlled, power driven machines.

Normally, the machine for flat knitting has two stationary beds that are arranged in an inverted V formation. These beds possess tracks in which the needles can be moved. The fabrics produced by a flat-knitting machine are mainly coarse and intensely patterned. An advantage of flat-knitted products is that vertical and horizontal stationary threads can be integrated into the fabric. In this case, the fabric serves to fix these threads. Fabrics produced this way can be used for technical textiles. Common products produced on conventional flat knitting machines are outer-wear, such as jumpers that consist of staple fibre yarns.



7.24 Loop formation.

7.6.3 Warp knitting

Dependent on the angle of take-off of the fabric from the needle and dependent on the pattern possibilities, it is possible to divide warp-knitting machines into two different types:

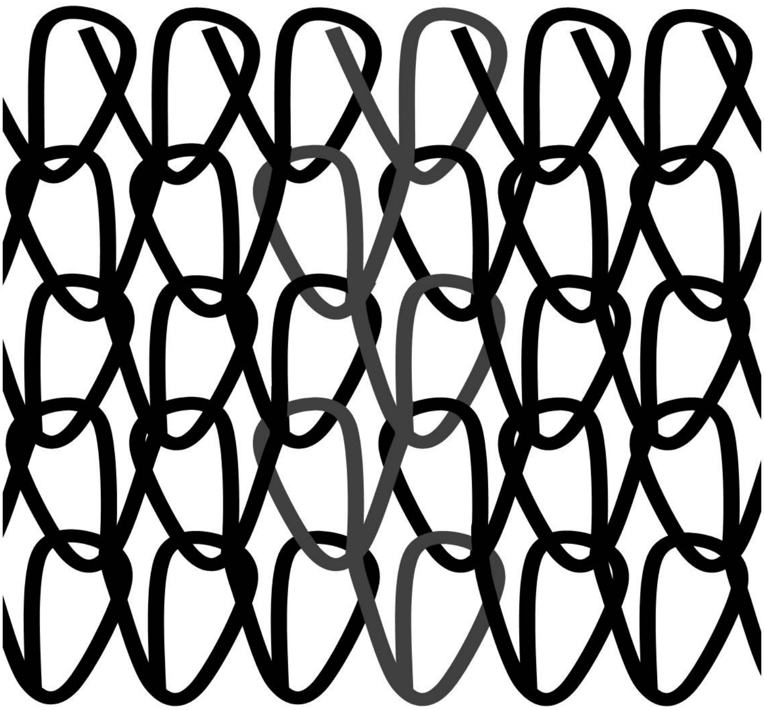
1. warp-knitting machines;
2. Raschel warp-knitting machines.

Raschel knitting machines often possess more guide bars. A common warp-knitted structure is shown in Fig. 7.25. As mentioned before, the needles in warp knitting machines are moved simultaneously. The structure that one single thread forms is shown in grey.

Mainly filament yarn is used for these fabrics, due to the high yarn tension during production. The yarn breaks more often if staple fibres are used, which is also possible. In comparison with filament yarns, the machine efficiency is therefore lower, because broken fibres need to be repaired.

7.7 Fabric production: braiding

Note: The information in this section can be found in Eichhoff (2012). Braiding is a fabric production method, which requires at least three yarns. By intertwining the yarns alternately following a certain algorithm, the braid is formed. According



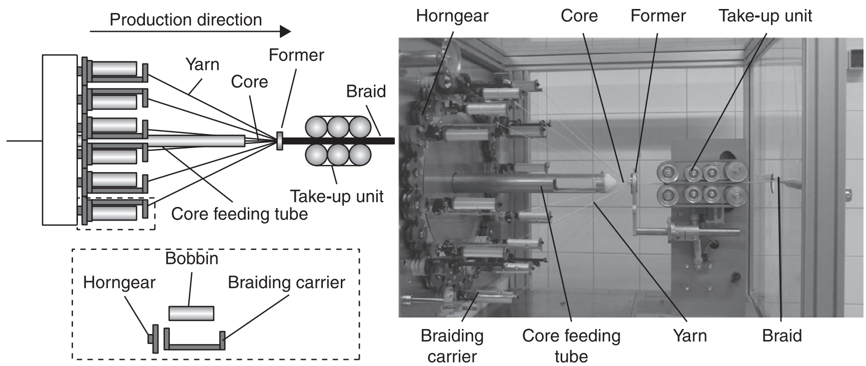
7.25 Warp-knitting structure.

to DIN 60.000, braids can be defined as 'areal- or voluminous bodies with a regular thread density and a closed product surface, whose braid- (bobbin-) yarns are intertwined diagonally towards the product edge.' In contrast, the threads in a woven fabric are intertwined in a perpendicular fashion towards the product edge. Industrial braids are produced on braiding machines. The main elements of a braiding machine are depicted in Fig. 7.26.

The yarn is stored on bobbins, which reside on braiding carriers. The braiding carriers store the yarn material, control the yarn tension, release yarn material in a controlled manner during the braiding process and move the bobbins as dictated by the braiding machine mechanism.

Horngears hold the braiding carriers and transport them from one horngear to the next. The braiding carriers are grouped in two sets, with opposite movement directions (clockwise and counter-clockwise). The layout of the horngears dictates the form of the braid. Two different horngear layouts are depicted in Fig. 7.27.

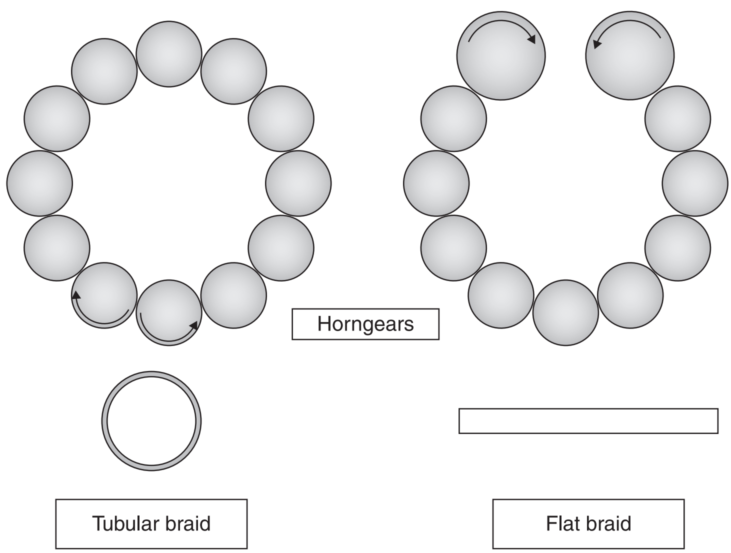
> [A tubular] braid consists of two systems of yarns, alternately passing over and under each other, causing a zig-zag pattern on the surface of the fabric. One



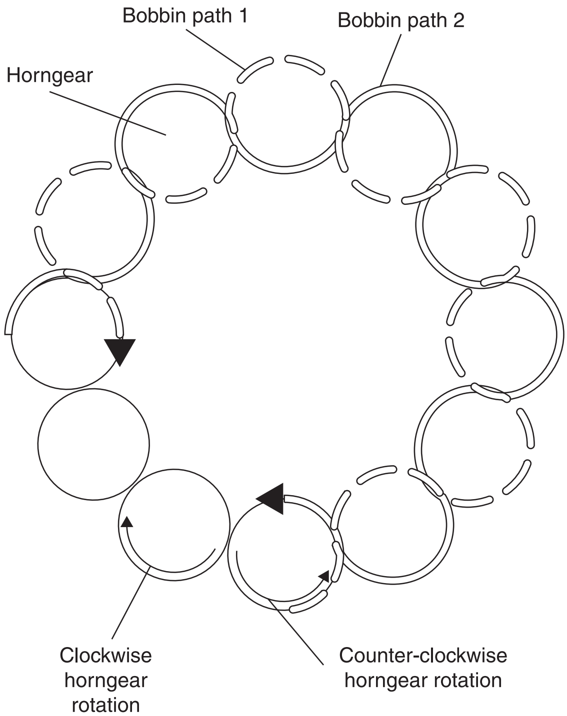
7.26 Main elements of a braiding machine.

system of yarns moves helically clockwise with respect to the fabric axis while the other moves helically counter-clockwise (Ko *et al.*, 1989).

For tubular braids (Fig. 7.27, left) the horngears are arranged in a concentric fashion. The horngears have alternating directions of rotation, turning subsequently clockwise and counter-clockwise. This way a braiding carrier takes an (approximated) sinusoidal path around the centre of the braid (Fig. 7.28).



7.27 Two layouts of horngears on a braiding machine. Left: circular (tubular) braid. Right: flat braid.

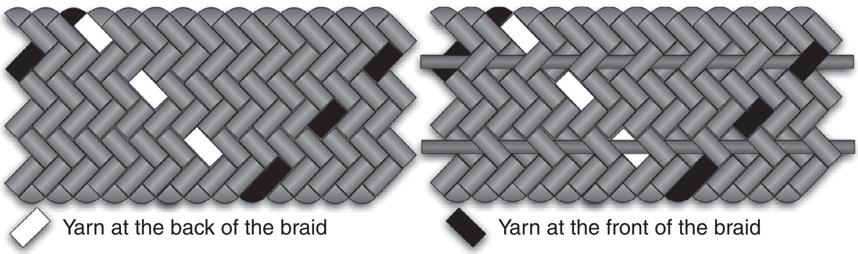


7.28 Path of braiding carriers.

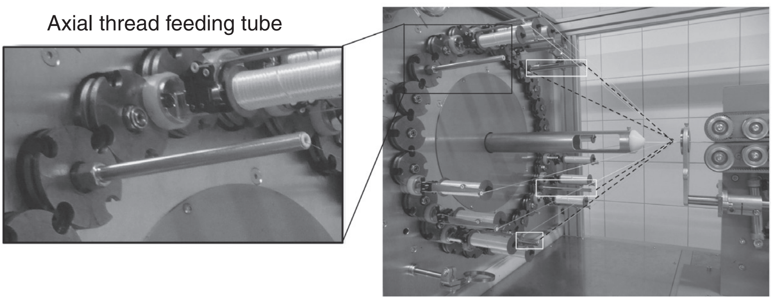
The two sets of braiding carriers constantly change inward and outward position, intertwining the yarns and forming the braid.

Flat braids can be produced by arranging the horngears in an open pattern (Fig. 7.27, right). The bobbins travel along the horngears until they reach one of the final horngears. There they complete a full turn on the horngear and travel back. The resulting textile fabric is a non-tubular, flat braid. The braid is guided through a former. At the point of braiding (also called the fell) the yarns intertwine, forming the braid. A take-up unit controls the movement of the braid and transports the finished product away from the former to provide space for the new fabric.

Braids can have a biaxial or a triaxial structure (Fig. 7.29). Biaxial braids have two sets of yarns, their structure as described above. Triaxial braids have one additional, (axial) thread system. In addition to the two helical yarn systems in the textile, a third yarn system is introduced. This technology is used, for example, in fibre-reinforced composites. Reinforcement yarns can take up the load only along the axis of the yarn. The axial yarns are introduced into the braid using stationary feeding tubes.



7.29 Left: Biaxial braid. Right: Triaxial braid.



7.30 Introduction of a third yarn system on a braiding machine. raiding with 12 textile yarns in helical direction and 4 metal wires in axial direction.

In Fig. 7.30, the machine set-up for introducing axial threads into a braided structure is depicted. In the example shown, 12 braiding carriers are used to form the braid. On four horngears, an axial yarn feeding tube is installed. The feeding tube is screwed onto the axis of the horngear and does not rotate. Through this tube, an additional thread can be fed into the braiding process. The bobbins for the axial threads are placed outside the machine. In the example depicted in Fig. 7.30, four copper wires are fed into the braided structure (dotted black lines).

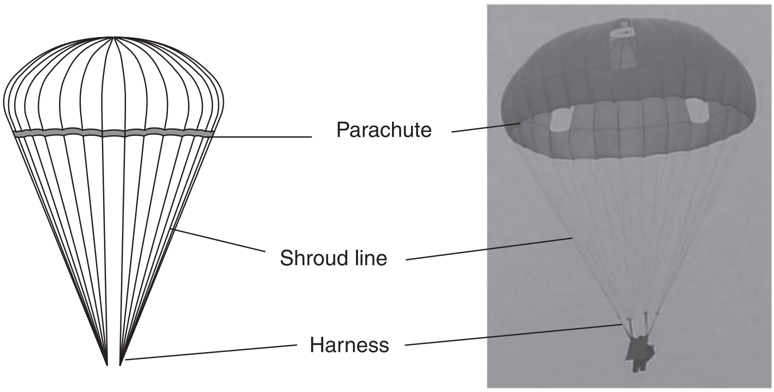
7.7.1 Functionalising braids

By using electrically conductive yarns in braided structures, sensors and data leads can be realised. Two examples will be given in this section. In the **Smart Rope** project, which was conducted at the Institut für Textiltechnik of RWTH Aachen University, a yarn-based monitoring system for braided ropes has been developed. An electrically conductive yarn was braided into a textile fibre rope.

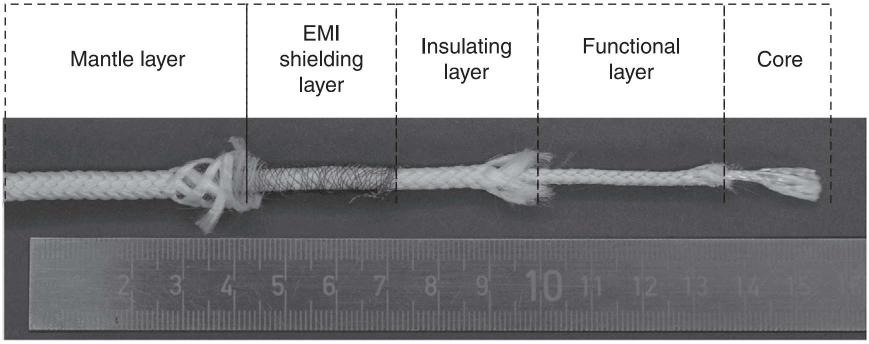
When the rope is exposed to mechanical stress, the sensor fibre is also elongated and changes its electrical resistance. This change can be measured and provide information on the status of the rope. The Smart Rope system has been constructed in different application scenarios. The sensor system has been integrated into the shroud lines of a parachute (Fig. 7.31). When the chute opens and the jumper is slowed down, a high impulse is forced upon the shroud lines to stop the jumper from free fall. After each jump, the shroud lines have to be inspected for damage. With smart-textile sensors, the inspection time could be reduced from two hours to ten minutes.

The sensor threads have also been integrated into personal safety lines, elevator ropes and mooring lines for ships and oil rigs, to assess the condition of the rope in order to provide additional security.

In the **Profitex** project (www.project-profitex.eu), a data-transmitting security rope for fire fighters has been developed. The security rope has been braided with integrated data leads. The electrical leads were used as braiding yarn in a biaxial braid. By using four copper wires as braiding yarns in the functional layer, individual data leads could be realized. Since the copper wires run in the same set of bobbins, they never interlace. The copper wires run in four parallel helixes. Figure 7.32 shows an example of such a braided data cable. Four layers are braided over a core rope. The functional layer includes the electrical copper wire leads. The insulating layer separates the functional layer from the electromagnetic interference (EMI) shielding layer. The EMI shielding layer protects the signal-carrying lines from being influenced by external electromagnetic waves and is a necessary element in any high-frequency signal cable. The braided data cable is covered by a mantle layer, which protects it from mechanical wear.



7.31 Sensorised shroud lines in a parachute.



7.32 Braided data cable with four electrical leads in the functional layer.

7.8 Embroidery

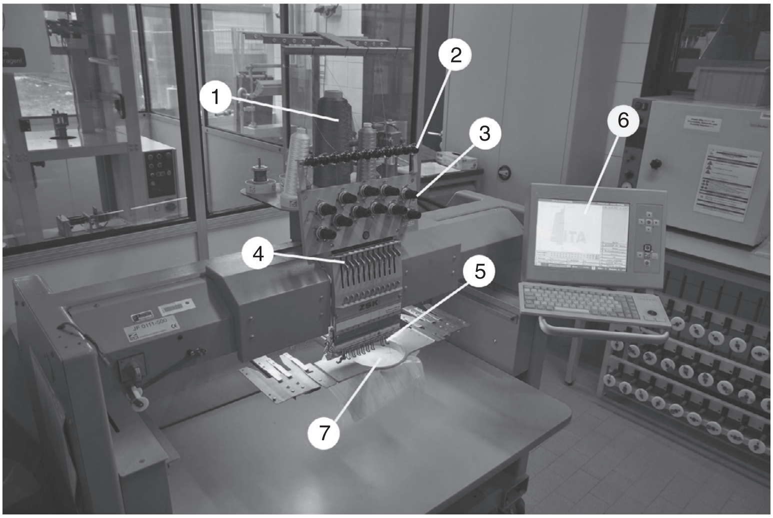
Embroidery is a method that can be used to apply yarn materials to a textile substrate in a defined pattern (Gries and Klopp, 2007). In this section, two embroidery methods are presented. At first the ‘classic’ embroidery method will be discussed, which employs a two-thread system. After that, a variant of the embroidery process will be presented – the tailored fibre placement (TFP) method. This method introduces a third yarn system, which enables the exact placement of sensor yarns, tubes or stiff materials like metal wire, etc.

7.8.1 Standard embroidery (two-thread system)

Figure 7.33 depicts an embroidery machine. The upper thread (1) is stored on a conical bobbin. It is guided through two yarn brakes (2,3) and through the yarn tensioning lever (4). The lever moves up and down to compensate for the movement of the needle (5) during the embroidery operation. The basic fabric (7) is held under tension in the embroidery frame. A computer unit (6) controls the braiding operation.

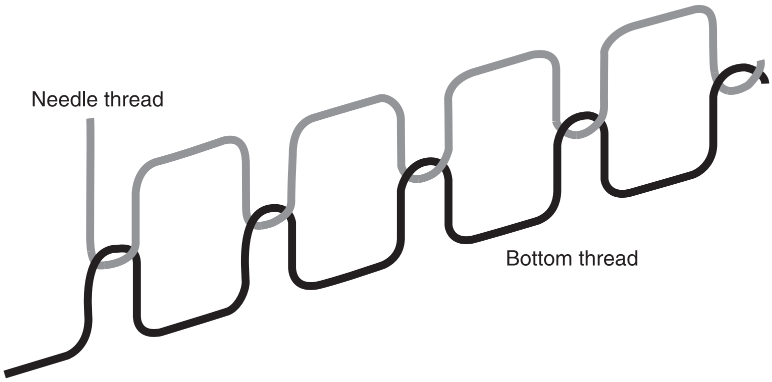
During the embroidery process, the frame with the basic fabric is moved in X- and Y-direction to create the pattern. The needle punches through the fabric, interlacing the upper thread with the bottom thread by means of a rotating gripper, which is located below the basic fabric. The bottom thread capsule is depicted in Fig. 7.34.

The resulting stitch can be observed in Fig. 7.35. A symmetrical stitch is created, which has the same appearance on the upper side as on the bottom side of the fabric. With the embroidery process, complex patterns can be realised. Conductive yarns can be used to realise circuits and sensors (Tao, 2001, 2005;



7.33 Embroidery machine elements: 1-bobbin; 2,3-yarn brakes; 4-yarn tensioning level; 5-needles; 6-computer unit; 7-asic fabric.

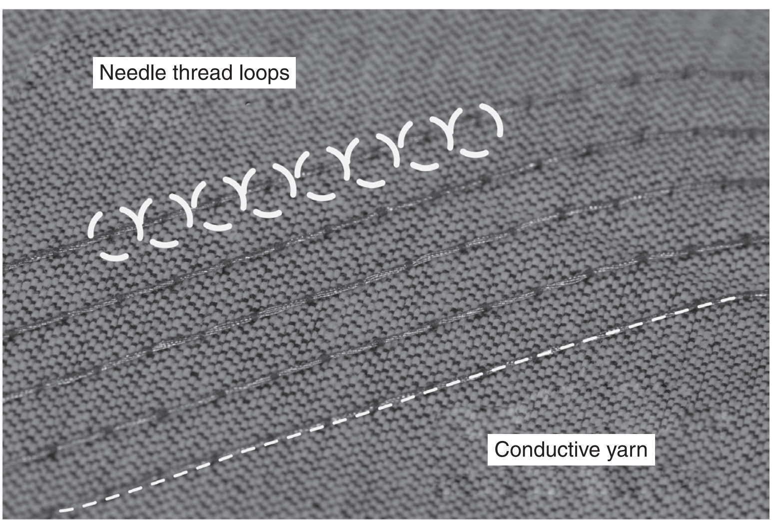
7.34 Capsule containing the bottom thread spool.



7.35 Double lock stitch.

Linz, 2005, 2006, 2007). Since the process is computer-controlled, it is very accurate and reproducible.

Figure 7.36 shows an example of embroidered circuits. A thin electrical cable has been used as bottom thread. The needle thread is PES. By adjusting the yarn tension in such a way that the bottom thread receives a higher tension than the needle thread, the bottom thread is placed straight onto the textile substrate. The needle thread does not exert enough force to pull the (stiff) bottom thread into a loop, therefore only small needle thread loops fixing the electrical cable are visible.



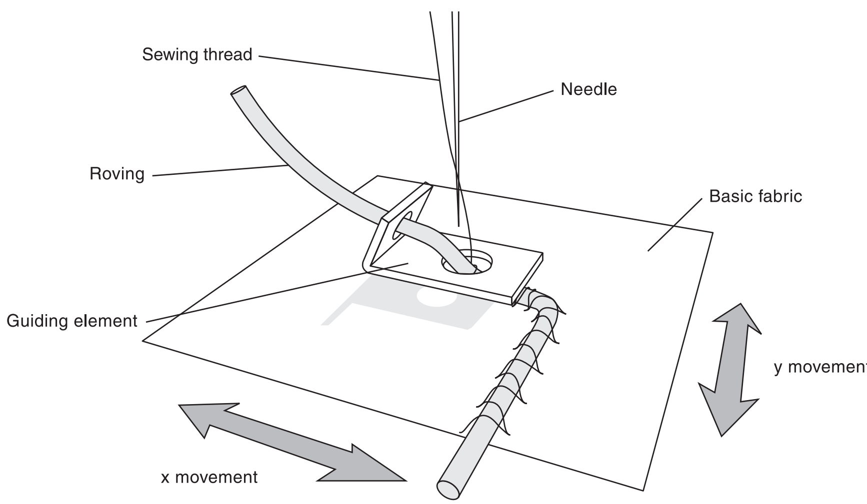
7.36 Embroidered conductive lines.

7.8.2 Tailored fibre placement (three-thread system)

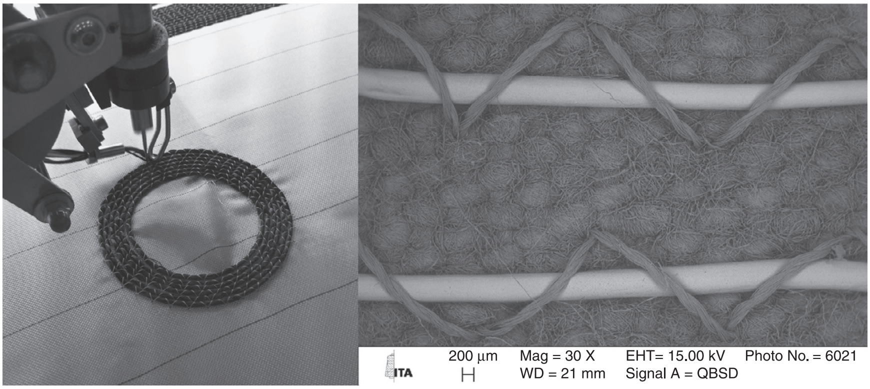
TFP was originally invented to apply high tenacity rovings like glass or carbon fibre material onto a textile substrate to create 'preforms' for fibre-reinforced polymers. Preforms are dry textiles, which have the contour and dimensions of the technical part that will be produced. By infusing the preform with a polymeric resin, the fibre-reinforced part is created. The TFP method employs a three-yarn-system. In addition to the top yarn and the bottom yarn, a functional yarn is introduced. Figure 7.37 depicts the principle components of the TFP process.

The roving is placed on the textile substrate (basic fabric). The needle punches left and right of the roving into the basic fabric, creating a zigzag stitch across the roving. The top and bottom sewing threads act only to fix the roving. As the roving is never penetrated by the needle, no damage is induced in the yarn. The accuracy of the computer-controlled embroidery process allows a very close spacing of the roving material, therefore a closed surfaced can be created using this process.

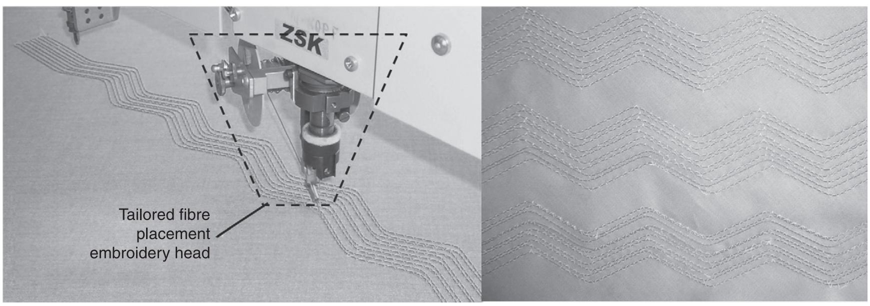
Two examples of applications using the TFP method can be observed in Fig. 7.38. In the left image, the production process using the TFP method is depicted. In this image, the embroidery head places carbon fibres on a textile substrate. The pattern could be used as a preform for fibre-reinforced parts or as a smart textile, representing a resistor heating. The right image shows a scanning electron microscopy (SEM) image of an electrical cable, which has been applied using the TFP method (Fig. 7.39). The zigzag stitch of the bottom thread is clearly visible in this image.



7.37 The tailored fibre placement (TFP) Method.



7.38 Left: TFP embroidery with carbon fibres. Right: electrical wire applied to a textile substrate using the TFP method.



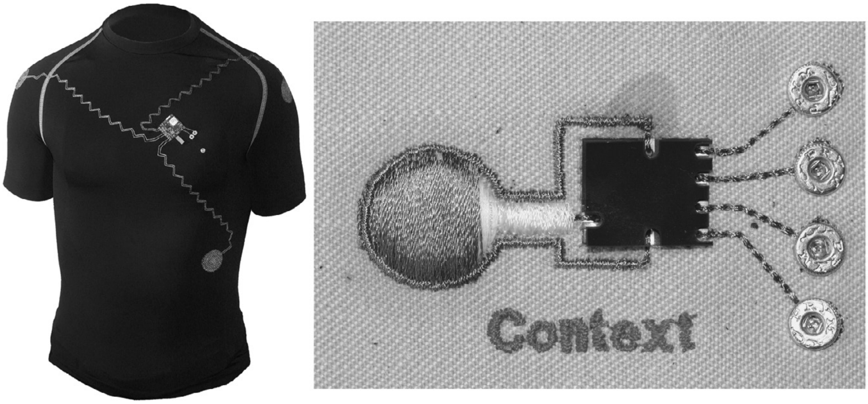
7.39 Application of electrical wire using the TFP method. Left: TFP embroidery process. Right: embroidered data lines.

7.8.3 Functionalising textiles using embroidery

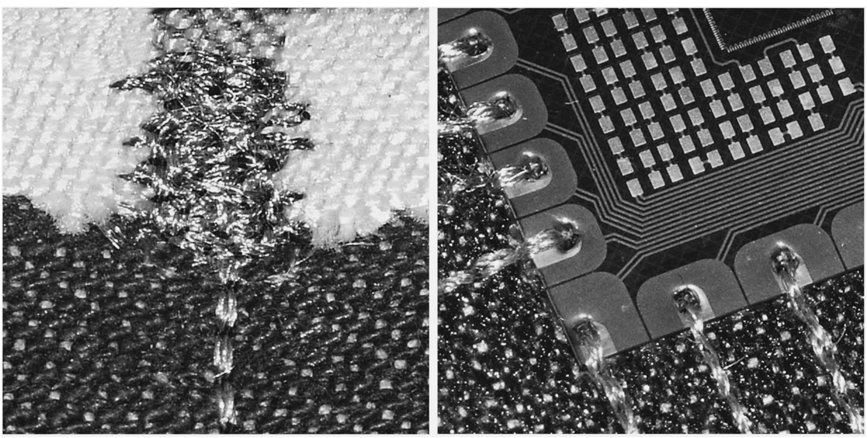
'Regular' embroidery (two-thread system) can be used to apply yarns and fine metal wire onto a textile. The TFP method was initially employed to place high tenacity fibres on a basic fabric to create preforms. TFP allows the exact placement of fibre and fibre-like materials onto a textile substrate. Electrically conductive yarns and metal wire can be embroidered onto the fabric. Also, the use of tubes is possible. With this method, liquid-powered heating or cooling applications can be realised (Fig. 7.40).

Applying electrically conductive yarns offers a variety of braiding possibilities (Fig. 7.41):

- textile electrodes for body function measurement (Tao, 2001, 2005; Linz, 2006, 2007);



7.40 Applications making use of embroidered contacts. Left: an ECG shirt with embroidered electrodes for measuring an electrocardiogram (Linz *et al.*, 2006). Right: sensor for measuring an electro-myogram (EMG) (Linz *et al.*, 2007).



7.41 Machine embroidered electrical contacts to woven keypad (left) and to electronics substrate (right) (Linz *et al.*, 2005).

- circuits (by laying the fibres in the pattern of the electrical circuits) (Linz, 2005, 2006);
- heating applications[4] (Kochman and Gurevich, 2001);
- strain and deformation sensors (resistive or capacitive sensors);
- moisture sensors (either capacitive or short-circuit based);
- capacitive sensors (embroidering conductive pads into a three-dimensional (3-D) fabric).

7.9 Challenges in smart-textile production

Textiles and electronic devices are two very different partners and marrying them to a smart textile is a complex task (Schwarz *et al.*, 2010). In the world of electronics, an accuracy of production in the nanometer-scale is possible. Chips and circuits can be placed with an incredibly repeatable accuracy on the substrate. The most complex circuits can be realised in a small space. The substrates on which electronics are built are mostly stiff-printed circuit boards (PCB). Complex electronic devices can be manufactured at very low cost (cell phones with colour displays, built-in radios and a multitude of other functions are available for around 25 €).

However, textiles are flexible and the precision of manufacturing ranges in some tenths of a millimetre. Textiles produce dust and during their use some fibres will break and be set free. Marrying these two very different partners is a delicate task. When approaching smart-textile development, we should not target substituting a certain application built on regular PCB electronic circuitry with textiles. Referring to the above example, transferring cell phone circuitry onto a fabric is most probably not the way we should take. Regular PCB electronics are too advanced for smart textiles to be substituted.

Smart textiles must be regarded as a new medium, a new substrate for alternative applications. The strength of smart textiles lies in the flexibility and versatility of fabrics. Using the fabrics as conductors, sensors and actors can provide applications and products, which are not feasible with regular PCB electronics. Example products, to which these criteria match, are illuminated curtains (Philips: Luminous Textiles;[5] SensingTex: Illuminating Textile[6]), sensorised floor mats to detect movement in a building (Future Shape: SensFloor[7]) or monitoring fibre-reinforced parts with textile sensing systems.[8]

PCB electronics will not vanish. The 'real intelligence' will still be located in the evaluation and control units attached to smart textiles. Smart textiles offer a wide variety of applications and open exciting new markets in the future. A symbiotic co-existence of PCB electronics and textile-based electronics has been demonstrated in various research projects. The main challenges which impede the breakthrough of smart textiles are, as outlined earlier:

- robust, cheap and highly conductive yarn materials;
- automated production systems (placing electronics, contacting, encapsulating);
- robust interfaces (stiff PCB electronics ⇔ flexible fabrics).

By designing Smart-Textile solutions, which take into account the behaviour of textiles and the methods of textile production processes, integral products can be developed that are durable, effective and producible at low cost.

7.10 Notes

1 tex is the unit of measure for the fineness of a yarn. 1 tex = 1 g / 1.000 m; 1 dtex = 1 g / 10.000 m

[2] Source: Texport Fire fighting Jacket 'Fire Breaker Action Tough'. Outer shell: Nomex tough fibres with 75% m-Aramide (Nomex), 23%p-Aramide (Kevlar) and 2% P140 (Carbon), www.texport.at

[3] '*plying*' means that two or more yarns of the same type are twisted together to achieve a thicker yarn with a higher tenacity

[4] Heizteufel, Berlin (Germany), www.heizteufel.de

[5] http://www.lighting.philips.com/main/application_areas/luminous-textile/index.wpd

[6] http://www.sensingtex.com/index.php/en/products/illuminating-textile

[7] http://www.future-shape.com/de/technologies/11/sensfloor

[8] Walter *et al.* (2011) (monitoring FRP parts), (Messervey, 2010; Measures, 2001 (reinforced concrete)

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