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Technical fabric structures – 2. Knitted fabrics

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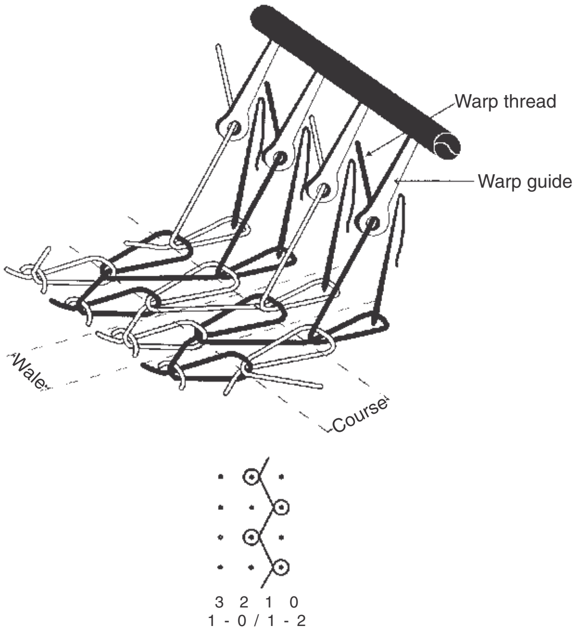
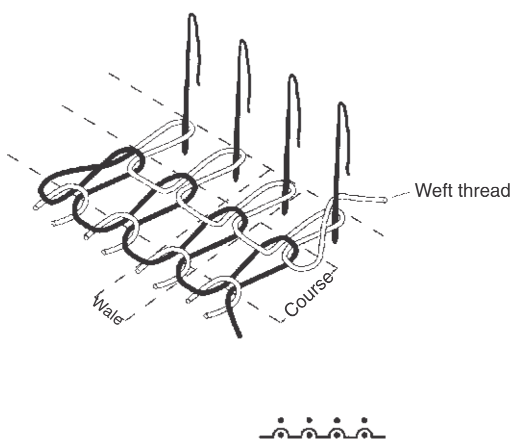
5.1 Terms and definitions

- *Warp knitting* is a method of making a fabric by normal knitting means, in which the loops made from each warp are formed substantially along the length of the fabric. It is characterised by the fact that each warp thread is fed more or less in line with the direction in which the fabric is produced. Each needle within the knitting width must be fed with at least one separate and individual thread at each course. It is the fastest method of converting yarn into fabric, when compared with weaving and weft knitting (Fig. 5.1).
- *Weft knitting* is a method of making a fabric by normal knitting means, in which the loops made by each weft thread are formed substantially across the width of the fabric. It is characterised by the fact that each weft thread is fed more or less at right angles to the direction in which the fabric is produced. It is possible to knit with one thread only, but up to 144 threads can be used on one machine. This method is the more versatile of the two in terms of the range of products produced as well as the type of yarns utilised (Fig. 5.2).
- *Single-jersey fabric* is a weft-knitted fabric made on one set of needles.
- *Double-jersey fabric* is a weft-knitted fabric made on two sets of needles, usually based on rib or interlock gaiting, in a manner that reduces the natural extensibility of the knitted structure. These fabrics can be non-Jacquard or Jacquard.
- *Course* is a row of loops across the width of the fabric. Courses determine the length of the fabric, and are measured as courses per centimetre.
- *Wale* is a column of loops along the length of the fabric. Wales determine the width of the fabric, and are measured as wales per centimetre.
- *Stitch density* is the number of stitches per unit area of a knitted fabric (loops cm^{-2}). It determines the area of the fabric.
- *Stitch length* is the length of yarn in a knitted loop. It is the dominating factor for all knitted structures. In weft knitting, it is usually determined as the average length of yarn per needle, while in warp knitting, it is normally determined as the average length of yarn per course.

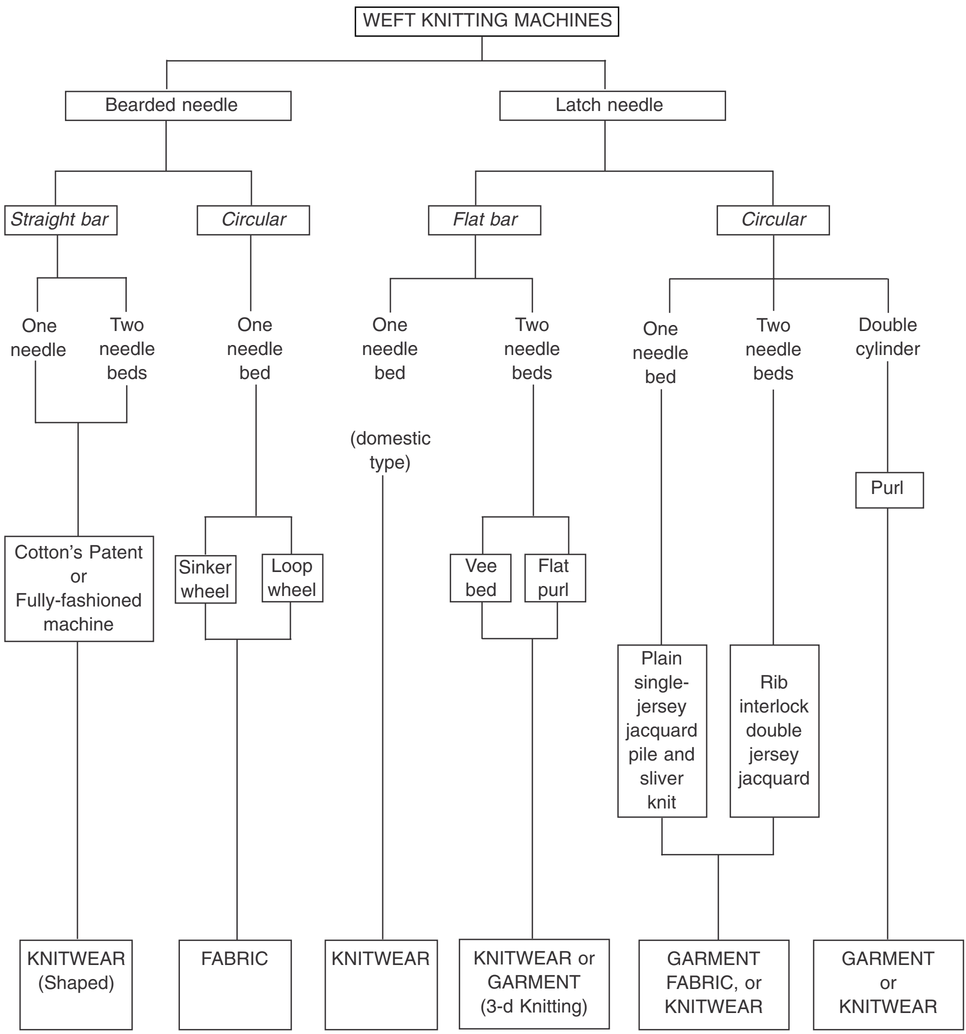


5.1 Warp knitting.



5.2 Weft knitting.

- *Yarn linear density* indicates the thickness of the yarn and is normally determined in tex, which is defined as the mass in grams of 1 km of the material. The higher the tex number, the thicker is the yarn and vice-versa.
- *Overlap* is the lateral movement of the guide bars on the beard or hook side of the needle. This movement is normally restricted to one needle space. In the fabric a loop or stitch is also termed the overlap.
- *Underlap* is the lateral movement of the guide bars on the side of the needle remote from the hook or beard. This movement is limited only by the mechani-



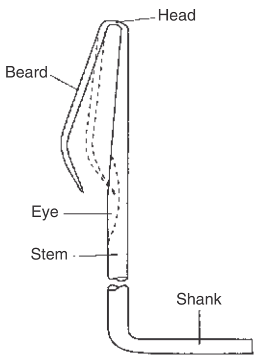
5.3 Simplified classification of knitting machinery.

cal considerations. It is the connection between stitches in consecutive courses in a warp knitted fabric.

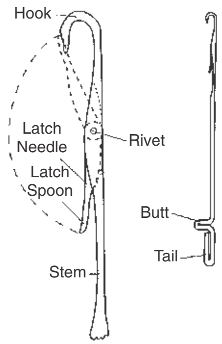
- *Tightness factor K* is a number that indicates the extent to which the area of a knitted fabric is covered by the yarn. It is also an indication of the relative looseness or tightness of the knitting. ($K = \text{tex}^{1/2} l^{-1}$), where l is the stitch length.
- *Area density* is a measure of the mass per unit area of the fabric ($\text{g}\,\text{m}^{-2}$).

5.2 Weft knitting machines

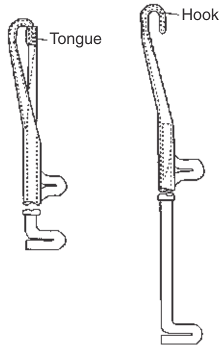
Figure 5.3 shows a simplified classification of weft knitting equipment. It will be noticed from Fig. 5.3 that the latch needle is the most widely used needle in weft knitting, because it is self-acting or loop controlled. It is also regarded as more ver-



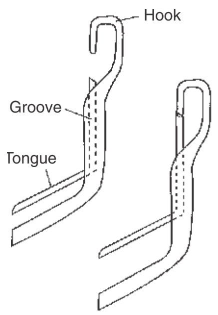
5.4 Bearded needle.



5.5 Latch needle.



5.6 Compound needle (fly needle frame).



5.7 Compound needle (Kokett needle).

satile in terms of the range of materials that can be processed on latch needle machines. Bearded needles are less expensive to manufacture, can be produced in finer gauges and supposedly knit tighter and more uniform stitches compared with latch needles, but have limitations with regard to the types of material that can be processed as well as the range of structures that can be knitted on them. Bearded needle machines are faster than the equivalent latch needle machines. The compound needle has a short, smooth and simple action, and because it requires a very small displacement to form a stitch in both warp and weft knitting, its production rate is the highest of the three main types of needle. Compound needles are now the most widely used needles in warp knitting and a number of manufacturers also offer circular machines equipped with compound needles. The operation speeds of these machines are up to twice those of the equivalent latch needle machines.

The main parts of the bearded, latch, compound needle (fly needle frame) and compound needle (Kokett) are shown in Figs. 5.4, 5.5, 5.6 and 5.7, respectively. Variations of latch needles include rib loop transfer needles and double-ended purl needles, which can slide through the old loop in order to knit from an opposing bed and thus draw a loop from the opposite direction.

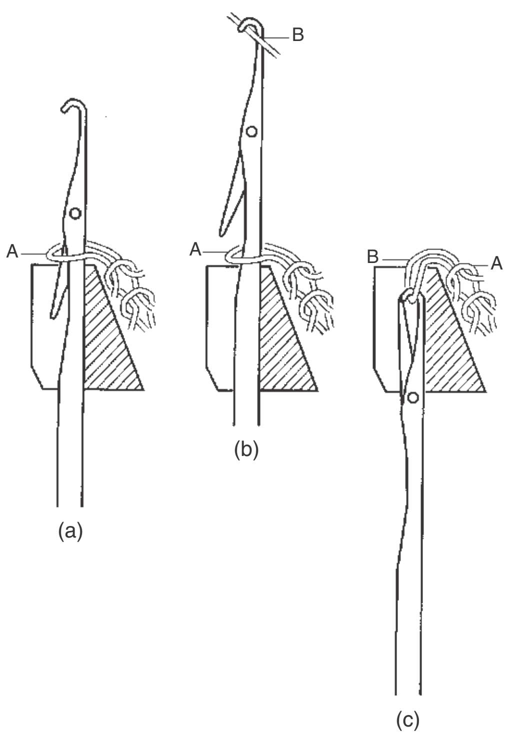
5.2.1 Loop formation with latch needles

Figure 5.8(a) illustrates the needle at tuck height, that is high enough to receive a new yarn, but not high enough to clear the old loop below the latch. The needle is kept at this position because the loop formed at the previous course (A) lies on the open latch and stops the latch from closing. Note that once a latch is closed, it can only be opened by hand, after stopping the machine.

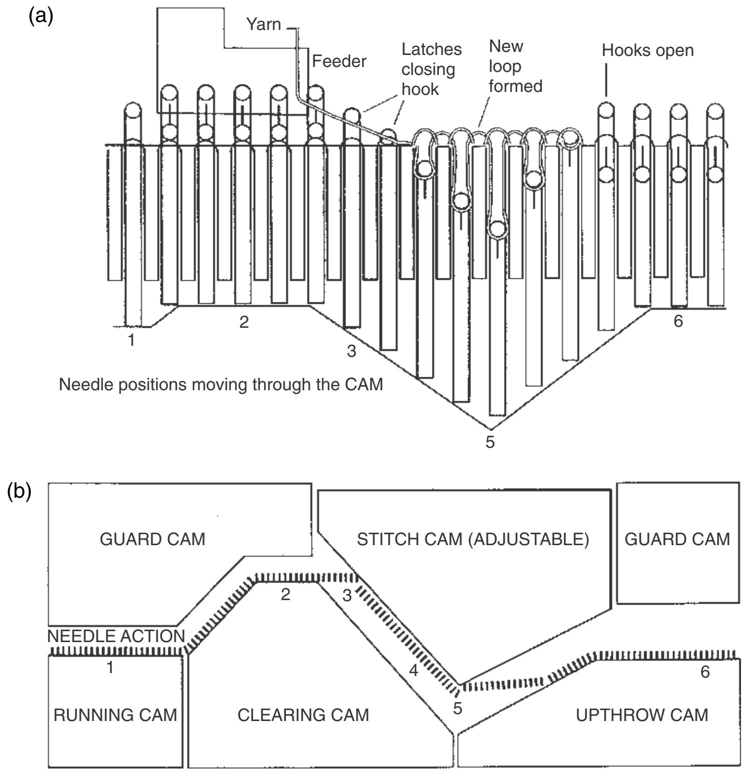
In Fig. 5.8(b), the needle has been lifted to the clearing position and the new yarn (B) is presented. The old loops (A) are below the latch and the new yarn (B) is fed into the needle hook. A latch guard normally prevents the latch from closing at this point.

In Fig. 5.8(c), the needle has now moved to its lowest position or knitting point and has drawn the new loop (B) through the old loop (A) which is now cast-off or knocked over. The needle now rises and the sequence of movements is repeated for the next course.

The loop formation on a latch needle machine is also illustrated in Fig. 5.9(a) and a typical cam system on such a machine is shown in Fig. 5.9(b).



5.8 Loop formation with latch needles.



5.9 (a) Loop formation and (b) typical cam system on a latch needle machine.

5.2.2 Single-jersey latch needle machines

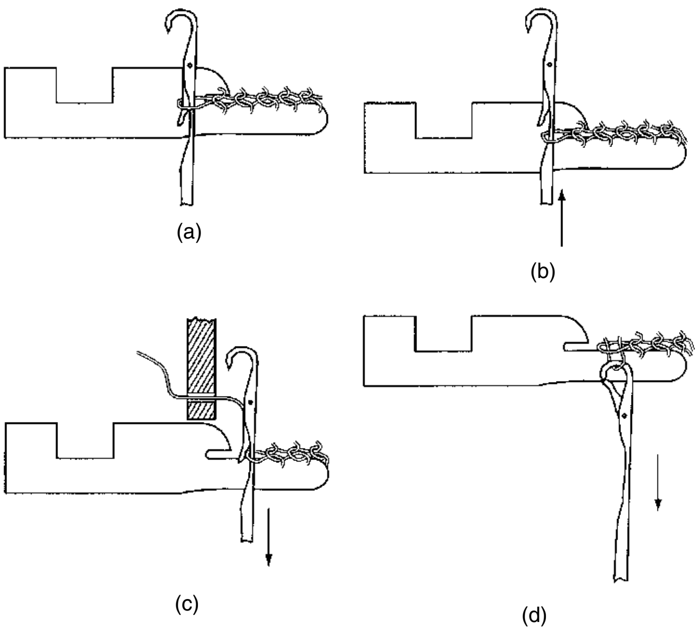
This type of machinery is employed throughout the world, either as a basic machine or with certain refinements and modifications, to produce fabric ranging from stockings to single-jersey fabric for dresses and outerwear, as well as a wide range of fabrics and products for technical applications. The machine sizes vary from 1 feeder 1 inch diameter to 144 feeds 30 inches diameter. Most single-jersey machines are rotating cylinder type, although a few rotating cam box machines are still used for specialised fabrics. These machines are referred to as sinker top machines and use web holding sinkers. Comprehensive reviews of single- and double-jersey knitting machinery and accessories exhibited at ITMA'95 and ITMA'99 were published that illustrate the versatility and scope of modern weft knitting equipment.[1,7]

5.2.2.1 Knitting action of a sinker top machine

Figures 5.10(a) to (d) show the knitting action of a sinker top machine during the production of a course of plain fabric.

Figure 5.10(a) illustrates the rest position. This shows the relative position of the knitting elements in-between the feeders with the needle at tuck height and the fabric loop held on the needle latch by the forward movement of the sinker towards the centre of the machine.

Figure 5.10(b) illustrates the clearing position. The needle has been raised to its



5.10 Knitting action of a sinker top machine.

highest position by the clearing cam acting on the needle butt; the old loop slides down from the open latch on to the needle stem.

Figure 5.10(c) illustrates the yarn feeding position. The sinker is partially withdrawn allowing the feeder to present its yarn to the descending needle hook, at the same time freeing the old loop so that it can slide up the needle stem and under the open latch spoon.

Figure 5.10(d) illustrates the knock-over position. The needle has now reached its lowest position and has drawn the new loop through the old loop which is now knocked over the sinker belly.

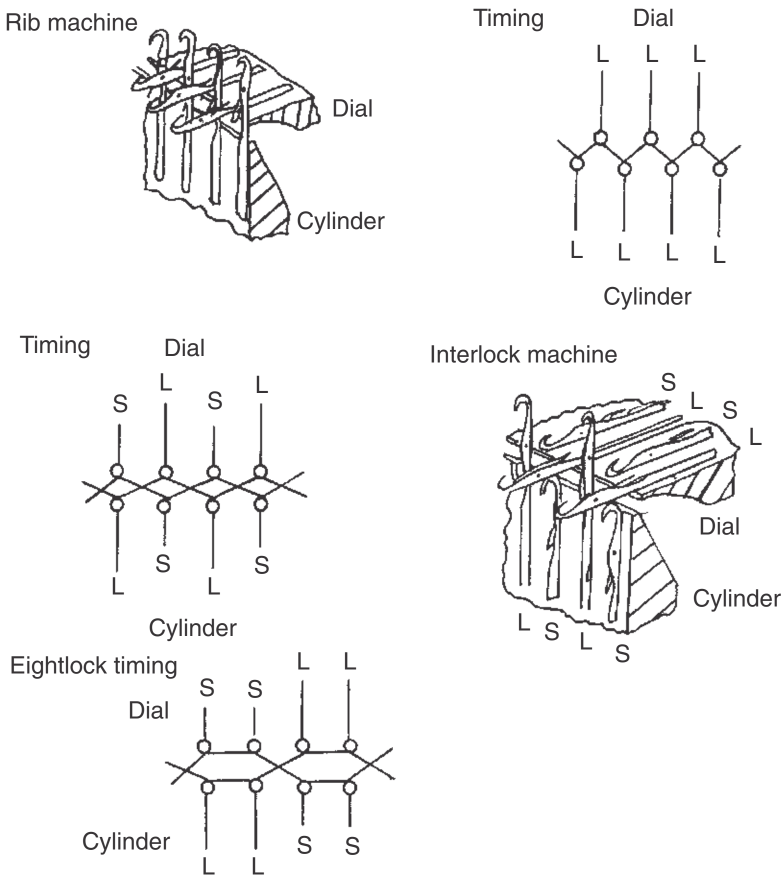
Stitch length may be controlled in a number of ways. On machines without positive feed mechanism, it is controlled mainly by the distance the needle descends below the sinker belly. Other factors such as input tension (T_i), yarn to metal coefficient of friction (μ) and take-down tension also influence the final stitch length in the fabric. When a positive feed device is used, the length of yarn fed to the needles at a particular feed is the factor that decides the stitch length. Other factors such as input tension T_i, μ, stitch cam setting and take-down tension influence the yarn or fabric tension during knitting, and hence determine the quality of the fabric. Stitch length is fixed by the positive feed device setting.

The sinker has two main functions and these are:

- to hold the fabric loop in a given position whenever the needles rise and
- to provide a surface over which the needles draw the loops.

Other advantages of using sinkers include:

- The control exerted by the sinker allows minimum tension on the fabric thus producing a good quality fabric with even loops.



5.11 Double-jersey machine needle layouts.

- Fine adjustments in quality and those required in the knitting of certain difficult yarns and structures are possible.
- The sinker facilitates the setting-up of the machine after a partial or full press-off (after the latches have been opened manually).

5.2.3 Double-jersey machines

Figure 5.11 shows the needle layout of rib and interlock machines. Both types of machine are available as circular or flat machines, whereas straight bar or fully fashioned machines are available in rib-type only.

Rib and interlock double-jersey machines are used either as garment length machines or for producing rolls of fabric. They can be either plain or equipped with a wide range of mechanical patterning mechanisms at each feed in the cylinder. Both types can also be equipped with electronic needle mechanisms to produce large area Jacquard patterns at high speeds.

5.2.3.1 Rib machines

Rib machines use two sets of needles and can be flat, circular or fully fashioned. The needles in the two beds are staggered or have spaces between them (rib gaiting). Most machines have revolving needle cylinders but in some cases the cams rotate past stationary needles. Patterning is obtained by altering cam and needle set-out or by using various needle selection mechanisms including individual needle electronic selection with computer aided design system. Machine diameters range from $7\frac{1}{2}$–20 inches for garment length and from 30–33 inches for fabric machines. An example of a modern double-jersey machine is the Monarch V-7E20, a 30 inch diameter, E20, 72 feeders 8-lock machine with RDS on dial and ACT II motorised automatic friction take-down system. The machine has 2 × 2 cam tracks and can be converted from rib to interlock or 8-lock timing in minutes. All basic non-jacquard double-jersey structures can be knitted at a speed factor of 900 (machine diameter (inches) × machine rpm).

5.2.3.2 Interlock machines

These are latch needle circular machines of the rib type, provided with a cylinder and dial. Unlike rib machines where the tricks of the dial alternate with the tricks of the cylinder (rib gaiting) the needle tricks of the cylinder are arranged exactly opposite those of the dial (interlock gaiting). Long-and short-stemmed needles are used that are arranged alternately, one long, one short in both cylinder and dial as shown in Fig. 5.11. An example of a modern high-speed interlock machine is Sulzer Morat Type 1L 144, which is a 30 inches diameter, 144 feeds, 28 or 32 gauge (npi, needles per inch), 28 rpm, producing at 100% efficiency $86.4\,m\,h^{-1}$ ($15.55\,kg\,h^{-1}$) of 76 dtex polyester with 14 cpc (courses per centimetre) and with an area density of $180\,g\,m^{-1}$ (60 inches wide) finished fabric.

To accommodate the long- and short-stemmed needles, the cam system is provided with a double cam track. The long dial needles knit with the long cylinder needles at feeder 1 and the short cylinder needles knit with the short dial needles at feeder 2. Thus two feeders are required to make one complete course of loop.

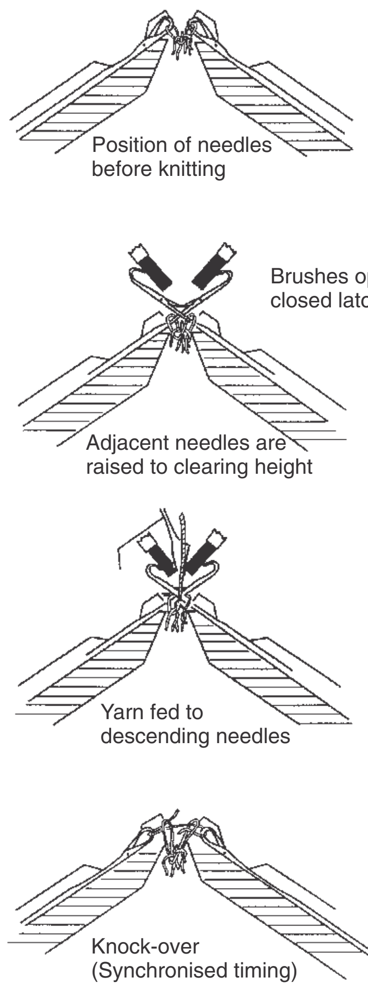
5.2.3.3 Needle timing

Two different timings can be employed on 1 × 1 rib and 1 × 1 interlock machines.

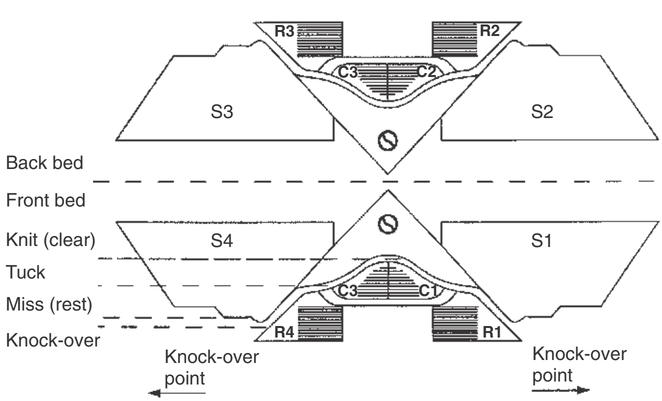
- *Synchronised timing* is the timing of a machine that has two sets of needles where the point of knock-over of one set is aligned with the point of knock-over of the other set.
- *Delayed timing* is the setting of the point of knock-over of one set of needles on a two-bed knitting machine out of alignment with that of the other set so as to permit the formation of a tighter stitch. Broad ribs (i.e. 2 × 2, 3 × 3 etc.), and rib Jacquard fabrics cannot be produced in delayed timing because there will not always be cylinder needles knitting either side of the dial needles from which to draw yarn. Up to nine needles delay is possible, but 4–5 needles delay is normal.

5.2.3.4 Knitting action of V-bed flat machine

Figure 5.12 illustrates the different stages of loop formation on a V-bed flat knitting machine, and Fig. 5.13 shows the cam system used on a simple single system flat



5.12 Loop formation on a V-bed flat knitting machine.



5.13 V-bed single-system cams. S are stitch cams, R are raising cams and C are clearing cams.

machine. Power V-bed flat machines are used mainly for the production of knitwear for children, women and men. They range from simple machines through mechanical jacquard machines to fully electronic and computerised flat machines, even equipped with presser foot. The developments in the automation of fabric designing, pattern preparation, and electronic needle selection, as well as in the range of structures and effects which can be produced, have been tremendous and flat machines and their products are now regarded as extremely sophisticated. High quality garments can now be produced at competitive prices owing to revolutionary garment production systems feasible with presser foot. Two- and three-dimensional structures as well as complete garments without any seams or joins can be produced on the latest electronic flat knitting machines and the associated design systems.

5.3 Weft-knitted structures

The basic weft-knitted structures and stitches are illustrated in Fig. 5.14 (A to G), and the appearance, properties and end-use applications of plain, 1×1 rib, 1×1 purl and interlock structures are summarised in Table 5.1. These basic stitches are often combined together in one fabric to produce an enormous range of single- and double-jersey fabrics or garments. Weft-knitted fabrics are produced commercially for apparel, household and technical products and they are used for an extremely large array of products, ranging from stockings and tights to imitation furs and rugs.

The importance and diversity of warp- and weft-knitted fabrics used for various technical applications has been discussed by Anand,[2] who highlighted the fact that knitted fabrics are being increasingly designed and developed for technical products ranging from scouring pads (metallic) to fully fashioned nose cones for supersonic aircrafts. Warp- and weft-knitted products are becoming popular for a wide spectrum of medical and surgical products.[3]

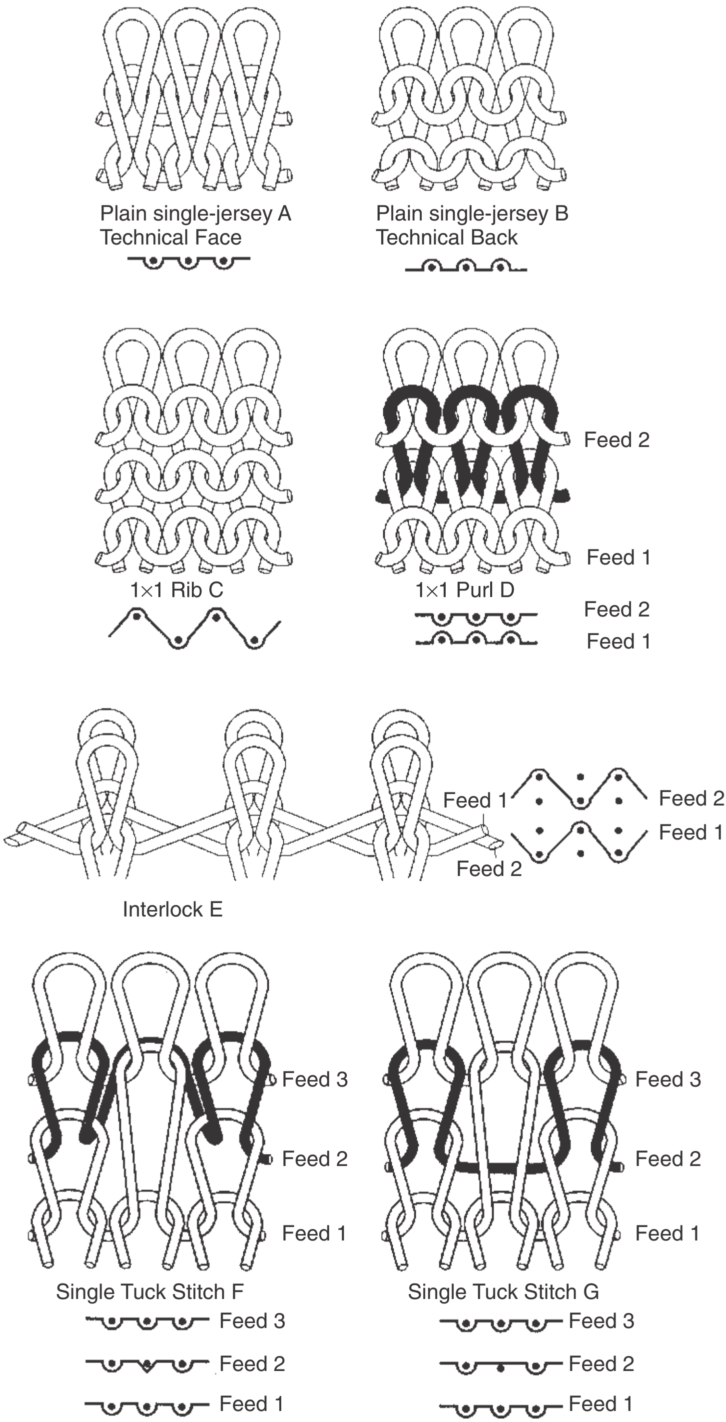
5.4 Process control in weft knitting

5.4.1 Main factors affecting the dimensional properties of knitted fabrics or garments

- *Fabric structure:* different structures relax differently.
- *Fibre(s) type:* fabrics or garments made from different fibre(s) relax differently.
- *Stitch length:* the length of yarn in a knitted loop is the dominating factor for all structures.
- *Relaxation/finishing route:* the fabric dimensions vary according to relaxation/finishing sequence.
- *Yarn linear density:* affects the dimensions slightly, but affects fabric tightness, area density ($g\,m^{-2}$) and other physical properties.

5.4.2 Laboratory stages of relaxation

- *On machine – Strained state:* this is predominantly length strain.
- *Off machine – Dry relaxed state:* the fabric moves to this state with time. The dry



5.14 Weft-knitted structures (A–G).

ıble 5.1 Comparison of appearance and properties

roperty	Plain	1 × 1 Rib	1 × 1 Purl	Interlock
ppearance	Different on face and back; V-shapes on face, arcs on back	Same on both sides, like face of plain	Same on both sides, like back of plain	Same on both sides, like face of plain
xtensibility				
Lengthwise	Moderate (10–20%)	Moderate	Very high	Moderate
Widthwise	High (30–50%)	Very high (50–100%)	High	Moderate
Area	Moderate–high	High	Very high	Moderate
hickness and warmth	Thicker and warmer than plain woven made from same yarn	Much thicker and warmer than plain woven	Very much thicker and warmer than plain woven	Very much thicker and warmer than plain woven
nroving	Either end	Only from end knitted last	Either end	Only from end knitted last
urling	Tendency to curl	No tendency to curl	No tendency to curl	No tendency to curl
nd-uses	Ladies' stockings Fine cardigans Men's and ladies' shirts Dresses Base fabric for coating	Socks Cuffs Waist bands Collars Men's outerwear Knitwear Underwear	Children's clothing Knitwear Thick and heavy Outerwear	Underwear Shirts Suits Trouser suits Sportswear Dresses

relaxed state is restricted by fabric structure and fibre type. Only *wool* can attain this state.

- *Static soak in water and dry flat – Wet relaxed state:* tight structures do not always reach a 'true' relaxed state. Only *wool* and *silk* can attain this state.
- *Soak in water with agitation, or Agitation in steam, or Static soak at selected temperatures (>90°C) plus, dry flat – Finished relaxed state:* the agitation and/or temperature induces a further degree of relaxation, producing a denser fabric. *Wool, silk, textured yarn fabrics, acrylics.*
- *Soak in water and Tumble dry at 70°C for 1 hour – Fully relaxed state:* three-dimensional agitation during drying. *All* fibres and structures.

5.4.3 Fabric geometry of plain single-jersey structures

1. Courses per cm (cpc) $\alpha\, 1/l = \dfrac{k_c}{l}$
2. Wales per cm (wpc) $\alpha\, 1/l = \dfrac{k_w}{l}$
3. $s = (\text{cpc} \times \text{wpc})\ \alpha\, 1/l^2 = \dfrac{k_s}{l^2}$
4. $\dfrac{\text{cpc}}{\text{wpc}}\ \alpha\, c = \dfrac{k_c}{k_w}$ (shape factor)

k_C, k_W, k_S are dimensionless constants, l is the stitch length and s is the stitch density.

5.4.4 Practical implications of fabric geometry studies

- Relationship between yarn tex and machine gauge is given by Equation (5.1):

$$\text{Optimum tex} = \frac{\text{constant}}{(\text{gauge})^2} \tag{5.1}$$

For single-jersey machines, the optimum tex = $1650/G^2$, and for double-jersey machines, the optimum tex = $1400/G^2$, where G is measured in needles per centimetre (npc).

- Tightness factor is given by Equation (5.2):

$$K = \sqrt{\frac{\text{tex}}{l}} \tag{5.2}$$

where l is the stitch length, measured in millimetres. For single-jersey fabrics: $1.29 \le K \le 1.64$. Mean $K = 1.47$. For most weft-knitted structures (including single- and double-jersey structures and a wide range of yarns): $1 \le K \le 2$. Mean $K = 1.5$. The tightness factor is very useful in setting up knitting machines. At mean tightness factor, the strain on yarn, machine, and fabric is constant for a wide range of conditions.

- Fabric area density is given by Equation (5.3):

$$\text{Area density} = \frac{s \times l \times T}{100}\,\text{g m}^{-2} \tag{5.3}$$

Table 5.2 *k*-Constant values for wool plain single jersey[a]

	k_c	k_w	k_s	k_c/k_w
Dry relaxed	50	38	1900	1.31
Wet relaxed	53	41	2160	1.29
Finished relaxed	56	42.2	2360	1.32
Fully relaxed	55 ± 2	42 ± 1	2310 ± 10	1.3 ± 0.05

[a] Courses and wales are measured per centimetre and l is measured in millimetres.
For a relaxed fabric cpc/wpc = 1.3. cpc/wpc > 1.3 indicates widthwise stretching. cpc/wpc < 1.3 indicates lengthwise stretching. $k_s > 2500$ indicates felting or washing shrinkage. Relaxation shrinkage is the change in loop shape. Felting/washing shrinkage is the change in loop length.

where s is the stitch density/cm^2; l is the stitch length (mm) and T is the yarn tex, or, Equation (5.4):

$$\frac{k_s}{l} \times \frac{T}{100} \text{ g m}^{-2} \tag{5.4}$$

where k_s is a constant and its value depends upon the state of relaxation, that is, dry, wet, finished or fully relaxed. The area density can also be given by Equations (5.5) and (5.6)

$$\text{Area density} = \frac{n \times l \times \text{cpc} \times T}{10\,000} \text{ g m}^{-1} \tag{5.5}$$

where n is the total number of needles, l is the stitch length (mm) and T is the yarn tex, or

$$\frac{n \times k_c \times T}{10\,000} \text{ g m}^{-1} \tag{5.6}$$

where k_c is a constant and its value depends upon the state of relaxation, that is dry, wet, finished or fully relaxed.

- Fabric width is given by Equation (5.7)

$$\text{Fabric width} = \frac{n \times l}{k_w} \text{ cm} \tag{5.7}$$

where k_w is a constant, and its value depends upon the state of relaxation, that is, dry, wet, finished or fully relaxed. It can also be given by Equation (5.8)

$$n \times l = L \text{ (course length)} \quad \therefore \text{Fabric width} = \frac{L}{k_w} cm \tag{5.8}$$

Fabric width depends upon course length and not upon the number of needles knitting.

- Fabric thickness. In the dry and wet relaxed states, fabric thickness (t) is dependent upon fabric tightness, but in the fully relaxed state, it is more or less independent of the fabric tightness factor. In the fully relaxed state $t \approx 4d$ where d is the yarn diameter.

5.4.5 Quality control in weft knitting

The dimensions of a weft-knitted fabric are determined by the number of stitches and their size, which in turn is determined by stitch length. Most knitting quality control therefore reduces to the control of stitch length; differences in mean stitch length give pieces of different size; variation of stitch length within the piece gives appearance defects, by far the most common one being the occurrence of widthwise bars or streaks owing to variation in stitch length between adjacent courses.

5.4.5.1 Measurement of stitch length, l

- *Off machine (in the fabric):*
  - HATRA course length tester
  - Shirley crimp tester.
- *On machine (during knitting):*
  - Yarn speed meter (revolving cylinder only)
  - Yarn length counter (both revolving cylinder and cambox machines).

5.4.5.2 Control of stitch length, l

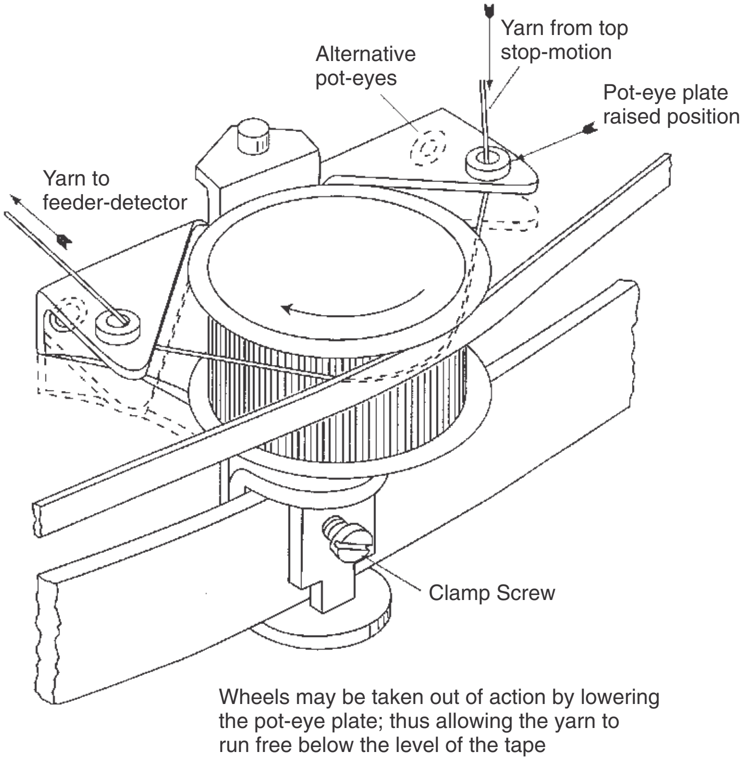
- *Positive feed devices:*
  - Capstan feed: cylindrical or tapered
  - Nip feed: garment length machines
  - Tape feed: (Rosen feed) circular machines producing plain structures
  - Ultrapositive feed: IPF or MPF
- *Constant tension device:* Storage feed device: flat, half-hose, hose and circular machines producing either plain or jacquard structures.
- *Specialised positive feed devices:*
  - Positive Jacquard Feeder MPF 20 KIF
  - Striper Feeder ITF
  - IROSOX Unit (half-hose machines)
  - Elastane Feed MER2
  - Air controlled feeds for flat and fully fashioned machines. Figure 5.15 shows a tape feed. A modern ultrapositive feed and a yarn storage feed device are illustrated in Figs. 5.16 and 5.17, respectively.

5.5 End-use applications of weft-knitted fabrics

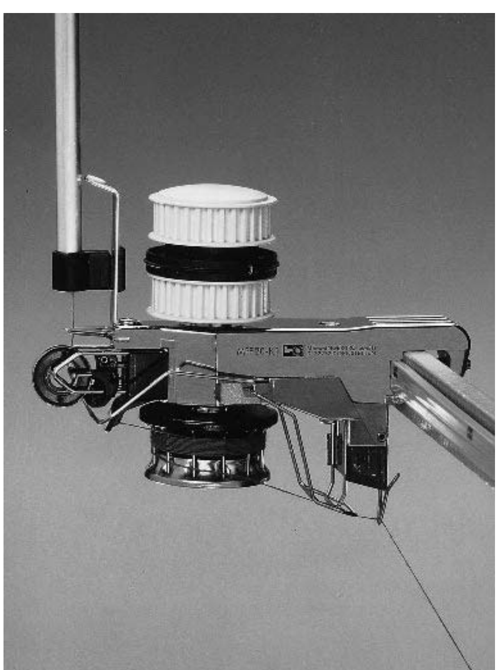
Weft-knitted fabrics are used for apparel, household and technical products. The main outlets for the different types of weft-knitted fabrics are as shown below. The knitting equipment used to produce these fabrics is also given.

5.5.1 Flat bar machines

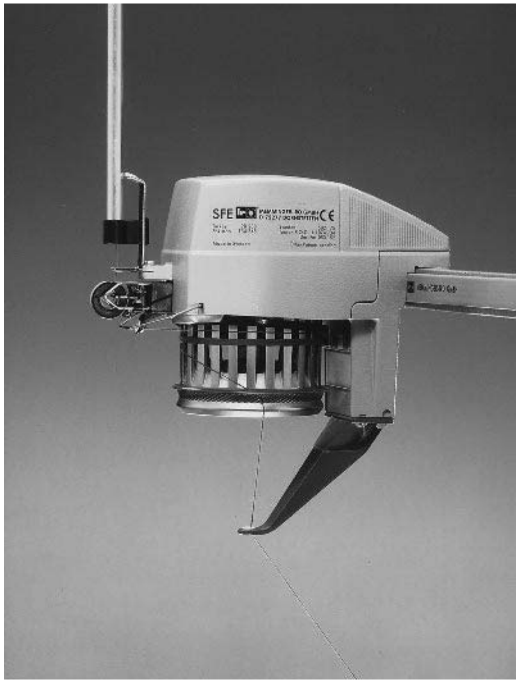
- Machine gauge: normally needles per inch, 3–18 npi
- Machine width: up to 78.7 inches
- Needle type: latch (compound needle machines are being developed)
- Needle bed type: single (hand machines), but mainly rib type



5.15 Tape positive feed device.



5.16 Ultrapositive feed device.



5.17 Yarn storage feed device.

- Products: jumpers, pullovers, cardigans, dresses, suits, trouser suits, trimmings, hats, scarves, accessories, ribs for straight-bar machines (fully fashioned machines). Cleaning clothes, three-dimensional and fashioned products for technical applications, multiaxial machines are under development.

5.5.2 Circular machines

- Machine gauge: normally needles per inch, 5–40 npi
- Machine diameter: up to 30 inches. Up to 60 inch diameter machines are now available
- Needle type: latch, (bearded on sinker wheel and loop wheel, some compound needle machines)
- Needle bed type: single, rib, interlock, double cylinder
- Products
  - Hose machines: seamfree hose, tights, industrial use dye bags, knit-de-knit yarns, industrial fabrics
  - Half-hose machines: men's and boy's half-hose, ladies' stockings, children's tights, sports socks
  - Garment blank machines: underwear, T-shirts, jumpers, pullovers, cardigans, dresses, suits, trouser suits, vests, briefs, thermal wear, cleaning cloths, technical fabrics
  - Fabric machines: rolls of fabric with the following end-uses: jackets, ladies'

tops, sports and T-shirts, casual wear, suits, dresses, swimwear, bath robes, dressing gowns, track suits, jogging suits, furnishing, upholstery, automotive and technical fabrics, household fabrics.

5.5.3 Straight-bar machines (fully fashioned machines)

- Machine gauge: normally needles per $1^1/_2$ inch, 9–33 (up to 60 gauge machines have been produced)
- Machine width: from 2–16 section machines – each section up to 36 inches wide (up to 40 section machines have been produced)
- Needle type: bearded or bearded and latch
- Needle bed type: single and rib
- Products: jumpers, pullovers, cardigans, dresses, suits, trouser suits, fully fashioned hose, sports shirts, underwear, thermal wear.

5.6 Warp-knitting machines

5.6.1 Introduction

The first weft-knitting machine was built by William Lee in 1589. In 1775, just under 200 years later, the first warp-knitting machine was invented by Crane, an Englishman. It was a single guide bar machine to make blue and white zig-zag striped silk hosiery and these fabrics were named after Van Dyck, the painter. With the advent of acetate continuous-filament yarns after World Ward I, the first bulk production of tricot fabrics was commenced by British Celanese on German Saupe 2-guide bar, 28 gauge machines. Locknits replaced the single guide bar atlas fabrics for lingerie, the latter being difficult to finish and laddered easily.

From 1950 to 1970, the growth of the warp-knitting industries in the UK and other western countries was phenomenal. The main reasons for this colossal expansion are summarised below (although developments in the various fields mentioned here were taking place concurrently). The state of the art and current developments in tricot and raschel machinery have been summarised below.

Anand also published a review of warp-knitting equipment exhibited by Karl Mayer at ITMA in 1995[4] and ITMA'99.[8]

5.6.1.1 Yarn developments

- The discovery of thermoplastic yarns and their suitability, even in very low linear densities (deniers) and in flat or low-twist form, to be knitted with very low yarn breakage rates on modern high speed tricot and raschel machines
- The extra design scope offered by differential dye yarns
- Improved cover-comfort attained through textured and producer-bulked yarns
- Elastomeric yarns, which have given a tremendous fillip to the raschel power-net industry.

5.6.1.2 Machinery developments

- Higher machine speeds, (up to 3500 cpm)
- Finer gauges (up to 40 needles per inch)

- Wider machines (up to 260 inches)
- Increased number of guide bars (up to 78 guide bars)
- Special attachments such as cut presser, fallplate, swanwarp, etc.
- Some speciality raschel machines such as Co-we-nit and Jacquard machines and, more recently, redesigned full-width weft insertion raschel and tricot machines
- High speed direct-warping machines and electronic yarn inspection equipment during warping
- Electronic stop motions for the knitting machines
- Larger knitting beams and cloth batches
- Modern heat-setting and beam-dyeing machinery
- Electronic warp let-off, electronic patterning, electronic jacquard and electronic fabric take-up mechanisms
- Loop-raised fabrics
- Stable constructions, such as sharkskins, queenscord, etc.
- Various net constructions utilising synthetic yarns
- Mono-, bi-, tri- and multiaxial structures for technical applications
- Three-dimensional and shaped (fashioned) structures for medical and other high technology products.

It is well known that the warp-knitting sector, particularly tricot knitting has grown in step with the expansion of manufactured fibres. In 1956, 17.8 million lbs of regenerated cellulosic and synthetic fibre yarns were warp knitted; the figure reached a staggering 70.6 million lbs in 1968.

In the mid-1970s, the tricot industry suffered a major setback, mainly because of a significant drop in the sale of nylon shirts and sheets, which had been the major products of this sector. It is also true that the boom period of textured polyester double-jersey was also a contributing factor in the sudden and major decline in the sales of tricot products. A change in fashion and the growth in the demand for polyester/cotton woven fabrics for shirting and sheeting was another cause of this decline. The two major manufacturers of warp-knitting equipment, Karl Mayer and Liba, both in West Germany, have been actively engaged in redesigning their machinery in order to recapture some of the lost trade. The compound needle is the major needle used on both tricot and raschel machines, and many specialised versions of warp-knitting machines are now available for producing household and technical products. One of the major developments in warp knitting has been the commercial feasibility of using staple-fibre yarns for a wide range of products. It is also significant to note that the warp-knitting sector has broadened its market base and has expanded into household and technical fabric markets, such as lace, geotextiles, automotive, sportswear and a wide spectrum of surgical and healthcare products. The current and future potential of warp-knitted structures in engineering composite materials has been discussed by Anand.[5]

5.6.2 Tricot and raschel machines

The principal differences between tricot and raschel machines are listed here:

1. Latch needles are generally used in raschel machines, while bearded or compound needle machines are referred to as tricot machines. Compound needle

raschel machines are also now fairly common. The compound needle is the most commonly used needle on warp knitting equipment.
2. Raschel machines are normally provided with a trick plate, whereas tricot machines use a sinker bar.
3. In raschel machines the fabric is taken up parallel to the needle stems; in the tricot machines, however, it is taken up at approximately right angles to the needles.
4. Raschel machines are normally in a coarser gauge; they are also slower compared with tricot machines, because more guide bars are frequently used and they also require a longer and slower needle movement.
5. Raschel machines are much more versatile in terms of their ability to knit most types of yarns such as staple yarns, and split films, etc. Only continuous-filament yarns can be successfully knitted on most tricot machines.
6. Generally, warp beams are on the top of the machine on raschel machines; on tricot machines, they are generally at the back of the machine.

A simplified classification of warp-knitting equipment is given in Fig. 5.18; it will be noticed that apparel, household and technical fabrics are produced on modern warp-knitting machinery. It is in fact in the technical applications that the full potential of warp knitting is being exploited. It is virtually possible to produce any product on warp-knitting equipment, but not always most economical.

The simplest warp-knitted structures are illustrated in Fig. 5.19. It can be seen that both closed- and open-loop structures can be produced and there is normally very little difference in the appearance and properties between the two types of loops.

5.6.3 Knitting action of compound needle warp-knitting machine

In Fig. 5.20(a) the sinkers move forward holding the fabric down at the correct level in their throats. The needles and tongues rise with the needle rising faster until the hook of the needle is at its highest position and is open. In Fig. 5.20(b) the guides then swing through to the back of the machine and Fig. 5.20(c) shows the guides shog for the overlap and swing back to the front of the machine.

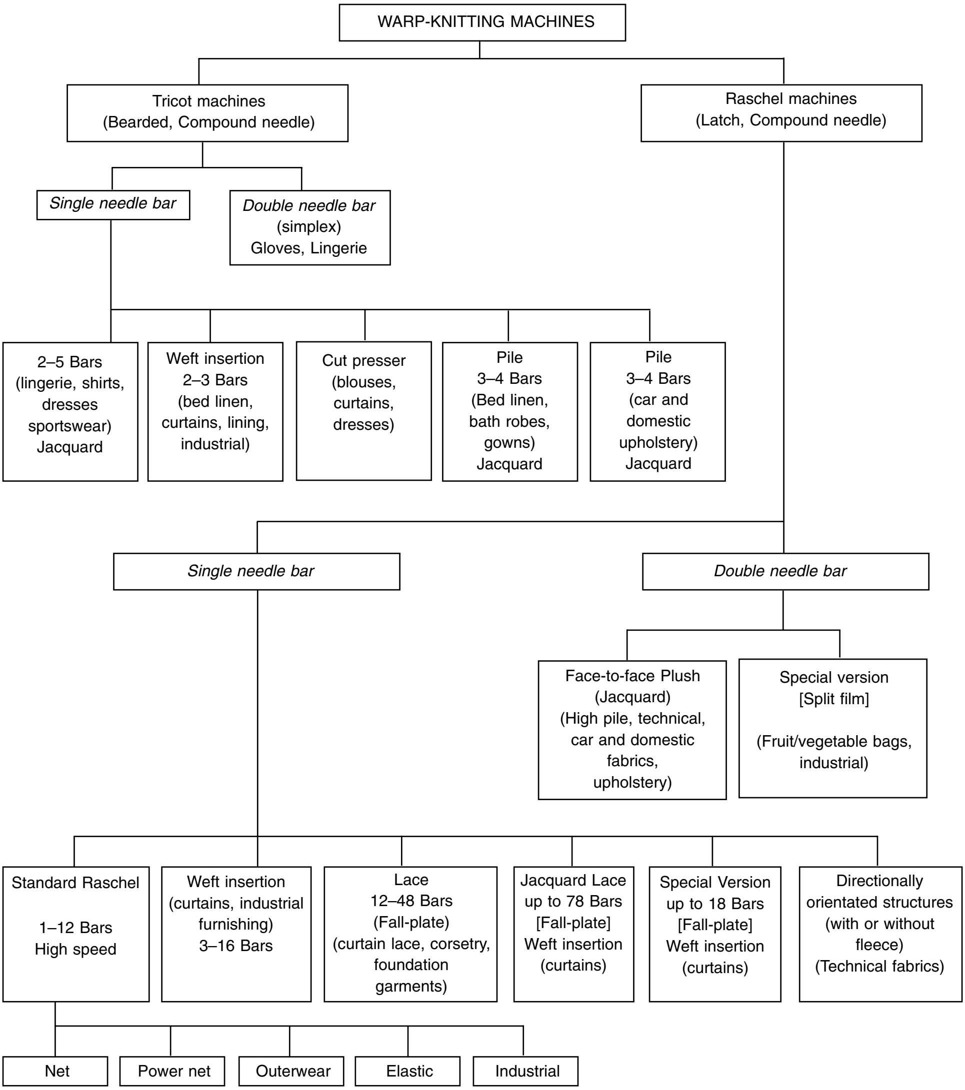
Figure 5.20(d) shows the needles and the tongues starting to descend, with the tongues descending more slowly thus closing the hooks. The sinkers start to withdraw as the needles descend so that the old loop is landed onto the closed hook and the new loops are secured inside the closed hook.

In Fig. 5.20(e) the needle descends below the sinker belly and the old loop is knocked-over. At this point, the underlap occurs and in Fig. 5.20(f) the sinkers move forward to hold down the fabric before the needles commence their upward rise to form a fresh course.

5.6.4 Knitting action of standard raschel machine

In Fig. 5.21(a) the guide bars are at the front of the machine completing their underlap shog. The web holders move forward to hold the fabric down at the correct level, whilst the needle bar starts to rise from knock-over to form a fresh course.

Figure 5.21(b) shows that the needle bar has risen to its full height and the old

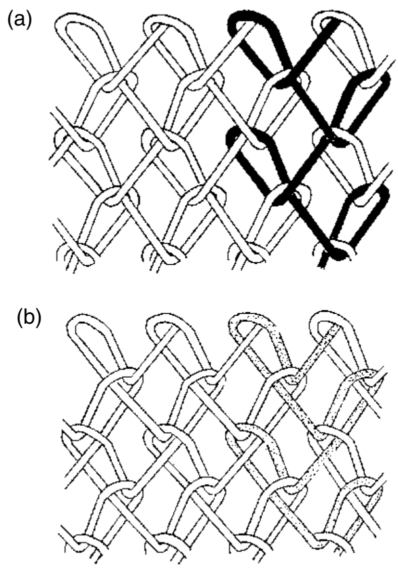


5.18 Simplified classification of knitting machinery.

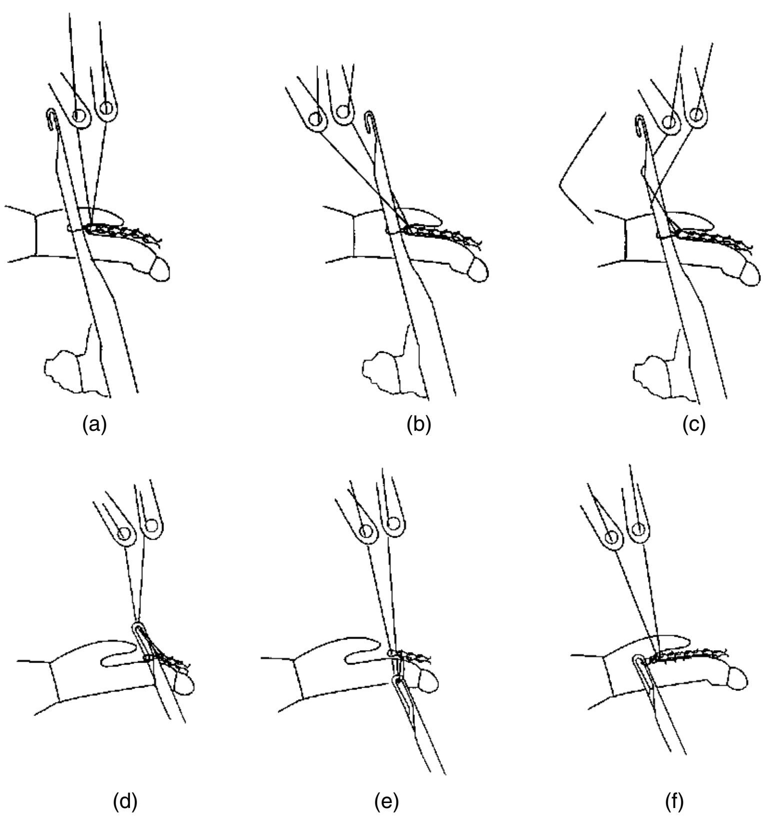
loops slip down from the latches onto the stems after opening the latches. The latches are prevented from closing by the latch guard. The web holders then start to withdraw to allow the guide bars to form the overlap movement.

In Fig. 5.21(c) the guide bars swing to the back of the machine and then shog for the overlap and in Fig. 5.21(d) the guide bars swing back to the front and the warp threads are laid into the needle hooks. Note: only the front guide bar threads have formed the overlap movement, the middle and back guide bar threads return through the same pair of needles as when they swung towards the back of the machine. This type of movement is called laying-in motion.

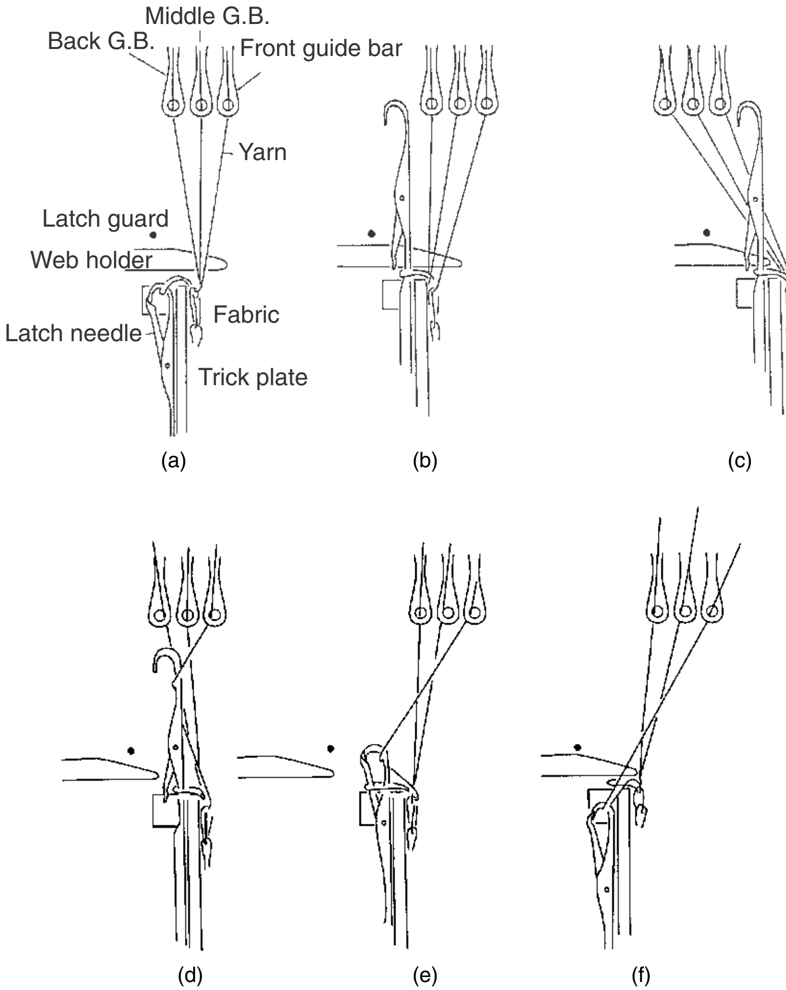
In Fig. 5.21(e) the needle bar descends so that the old loops contact and



5.19 Single-guide bar warp-knitted fabrics. (a) Closed lap fabric, (b) open lap fabric.



5.20 Knitting action of compound needle warp-knitting machine.

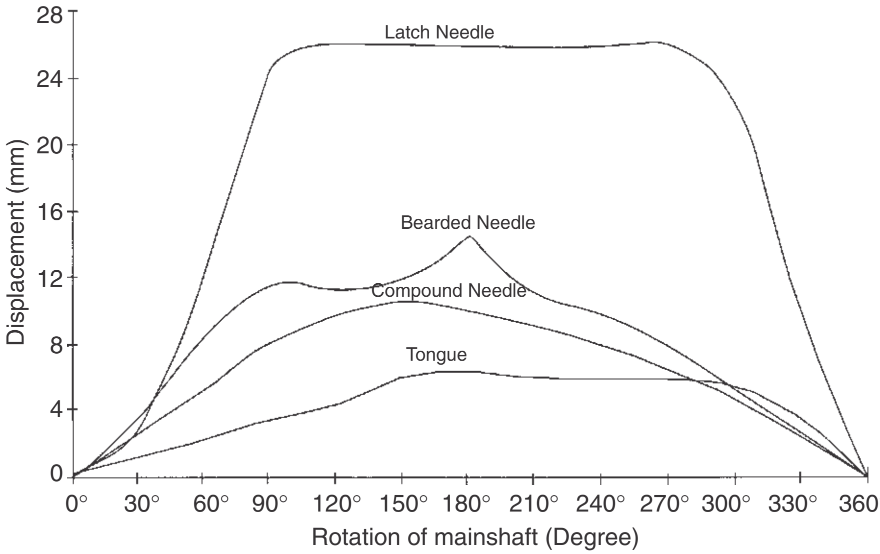


5.21 Knitting action of a standard raschel machine. (a) Start of new course, (b) start of overlap, (c) guide bar swinging motion, (d) return swing after overlap, (e) old loop closing latch, (f) knock-over and underlap movements.

close the latches, trapping the new loops inside. The web holders now start to move forward.

Figure 5.21(f) shows the needle bar continuing to descend, its head passing below the surface of the trick-plate, drawing the new loops through the old loops, which are cast-off, and as the web holders advance over the trick-plate, the underlap shog of the guide bar is commenced.

The knitting action of bearded needle warp-knitting machines has not been given here because in the main the machines likely to be used for technical textile products would use either latch or compound needles. Also the proportion of new bearded needle machines sold has decreased steadily over the years. This is mainly due to the lack of versatility of these machines in terms of the variety of yarns that can be processed and the range of structures that can be normally knitted on them. The displacement curves for the three main types of needle are shown in Fig. 5.22.



5.22 Displacement curves of various needles.

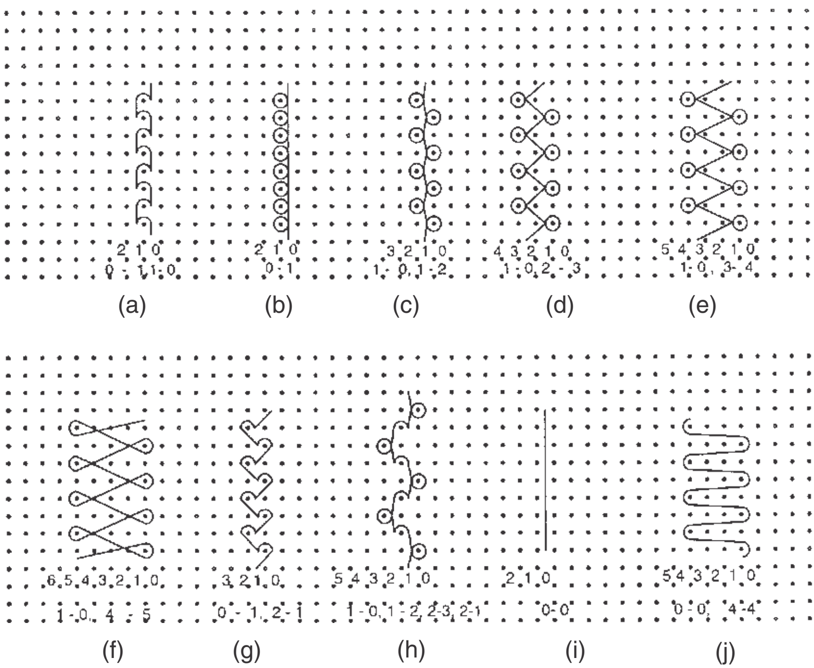
It is obvious that compound needle machines would operate at faster rates, provided all other factors are similar.

5.7 Warp-knitted structures

5.7.1 Stitch notation

Some of the more popular stitches used in the production of warp-knitted fabrics are given in Fig. 5.23. These stitches, together with the number of guide bars used, a comprehensive range of types and linear densities of yarns available, fancy threading, controlling individual run-ins and run-in ratios, and various finishing techniques are combined and modified to construct an endless variety of fabrics. The lapping movements of the individual guide bars throughout one repeat of the pattern are normally indicated on special paper, called point paper. Each horizontal row of equally spaced dots represents the same needles at successive courses. The spaces between the dots, or needles, are numbered 0, 1, 2, 3, 4, and so on, and show the number of needles transversed by each guide bar. Although three links per course are normally employed, only two are actually required; the third (last link) is only used to effect a smoother movement of the guide bar during the underlap. The first link determines the position of the guide bars at the start of the new course. The second link determines the direction in which the overlap is made. The links, therefore, are grouped together in pairs and the lapping movements at each course are separated by a comma. For instance, the lapping movements shown in Fig. 5.23(c) are interpreted as follows:

- (1-0) is the overlap at the first course
- (0,1) is the underlap at the same course, but made in the opposite direction to the overlap
- (1-2) is the overlap at the second course, and



5.23 Stitch notation in tricot knitting. (a) Open pillar, (b) closed pillar, (c) tricot stitch, (d) 2 × 1 closed lap, (e) 3 × 1 closed lap, (f) 4 × 1 closed lap, (g) open tricot stitch, (h) two-course atlas, (i) misslapping, (j) laying-in.

- (2,1) is the underlap at the second course, but made in the opposite direction to the previous underlap.

It will also be observed from Fig. 5.23 that when the underlap is made in the opposite direction to the immediately preceding overlap, a closed loop is formed, but when the underlap is made in the same direction as the immediately preceding overlap, or no underlap is made, then an open loop will result.

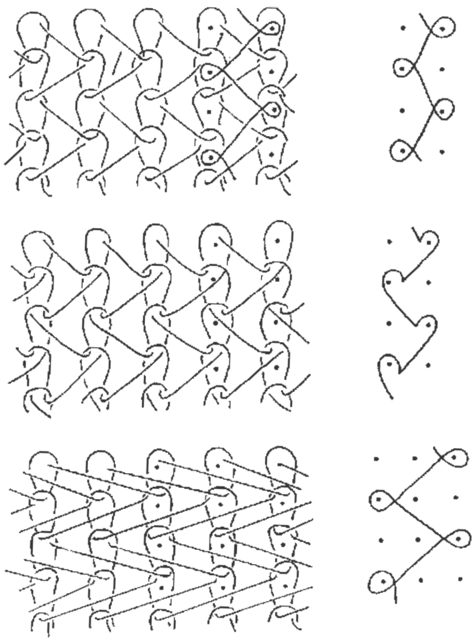
It is vital to ensure when placing a pattern chain around the drum that the correct link is placed in contact with the guide bar connecting rod, otherwise the underlap will occur on the wrong side of the needles, or open loops may be formed instead of the intended closed loops.

5.7.2 Single-guide bar structures

Although it is possible to knit fabrics using a single fully threaded guide bar, such fabrics are now almost extinct owing to their poor strength, low cover, lack of stability and pronounced loop inclination on the face of the fabric. Three examples of single guide bar structures are shown in Fig. 5.24.

5.7.3 Two-guide bar full-set structures

The use of two guide bars gives a much wider pattern scope than is possible when using only one, and a large proportion of the fabrics produced in industry

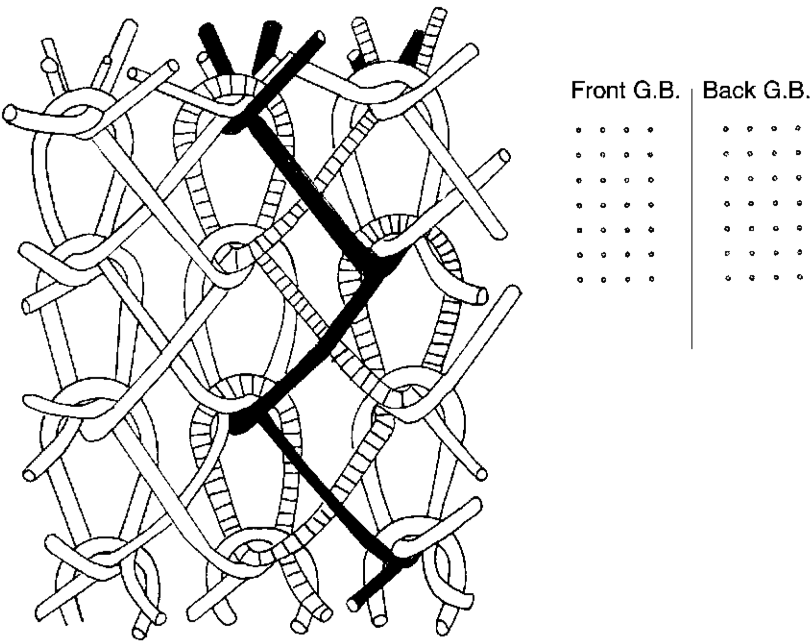


5.24 Single-guide bar structures.

are made with two guide bars. The first group of fabrics to consider are those made with fully threaded guide bars, as many different effects may be obtained by altering the lapping movements and these effects may be increased still further by the use of colour, mixing different yarn, linear densities or using different yarn types, such as yarns with different dyeing characteristics, textured yarns, and so on.

5.7.3.1 Loop plating

With two fully threaded guide bars, each loop in the fabric will contain two threads, one supplied by each bar. The underlaps made by the front guide bar are plated on the back of the fabric and the loops from this bar are plated on the face of the fabric, whereas the loops and the underlaps formed by the back guide bar are sandwiched between those from the front guide bar (see Fig. 5.25). It will be observed from Fig. 5.20(c) that when the guide bars swing through the needles to form the overlap, the ends will be crossed on the needle hook (normally the two bars form overlaps in opposite directions). As the guide bars return to the front of the machine, the threads of the front guide bar are first to strike the needles and are wrapped around the needle hook first, whereas the back guide bar threads are placed later and above those from the front guide bar. If the tensions of the two warp sheets are similar and the heights of the guide bars are correctly adjusted, the front bar loops will always be plated on the face of the fabric. Any coloured thread in the front guide bar will thus appear prominent on both fabric surfaces, an important factor to be remembered in warp-knit fabric designing (see Fig. 5.25 for loop plaiting).



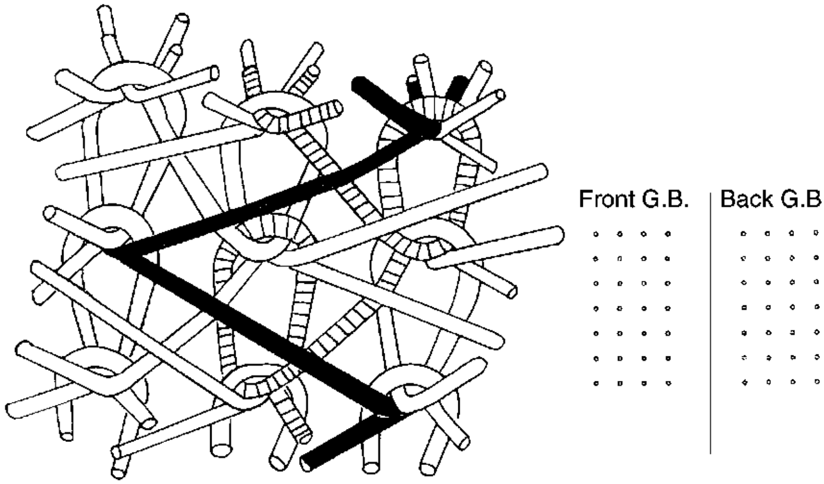
5.25 Full tricot.

5.7.3.2 Different structures

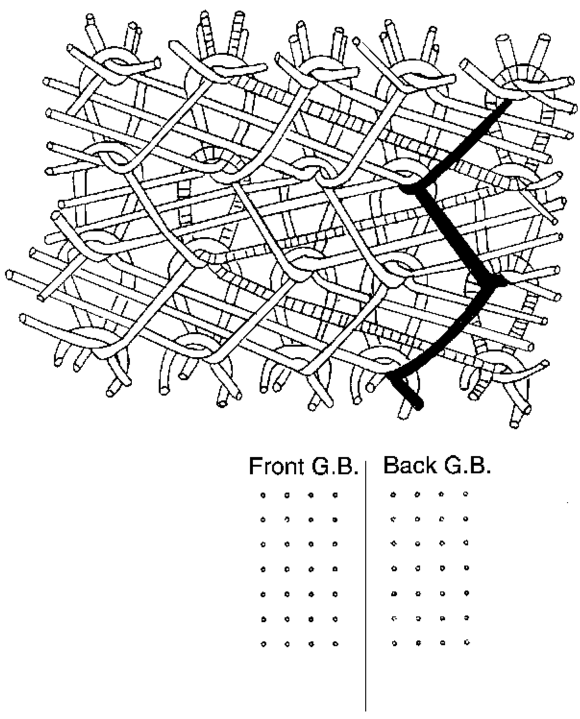
The two guide bars may make their underlaps in the same or opposite directions. If made in the same direction, the fabric will show distortion similar to the single bar fabric (see Fig. 5.29(a)) as the loops will be inclined. If, however, the underlaps are made in opposite directions, an equal tension will be imposed in both directions, and loops will be upright.

The structure of the simplest fabric made with two guide bars is shown in Fig. 5.25 and is known as full tricot. The appearance of full tricot may be varied by threading the guide bars with different coloured threads to give vertical stripes of colour.

The most common fabric of all is locknit and its structure and the lapping movements are shown in Fig. 5.26. When correctly knitted, the fabric shows even rows of upright loops on the face of the fabric, and the two needle underlaps on the back of the fabric give a smooth sheen. It has a soft handle and is very suitable for lingerie. If the lapping movements for the bars are reversed to give reverse locknit, the fabric properties are completely changed (Fig. 5.29(e)). The short underlaps will now appear on the back of the fabric and will trap in the longer ones to give a more stable and stiff structure, with far less width shrinkage from the needles than ordinary locknit. The underlaps of the back guide bar may be increased to give even greater stability and opacity with practically no width shrinkage from the needles. An example of this is sharkskin, whose structure and lapping movements are shown in Fig. 5.27. Another stable structure is shown in Fig. 5.28, and is know as queens cord. The long back guide bar underlaps are locked firmly in the body of the fabric by the chain stitches of the front guide bar. Both sharkskin and queenscord structures can be made more stable, heavier and stronger by increasing the back guide underlaps to four or five needle spaces. The vertical chains of loops from the front



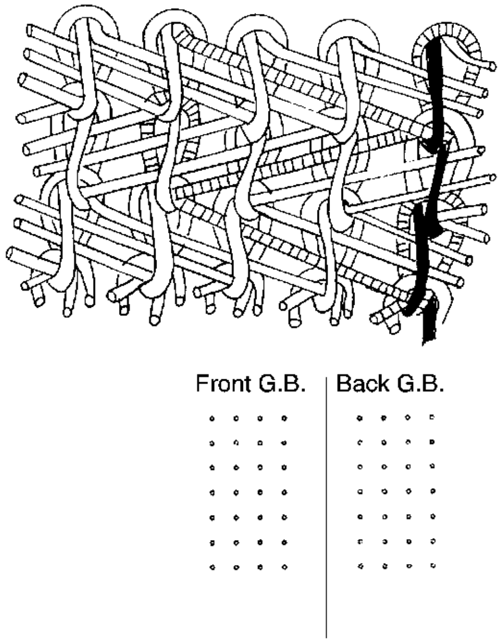
5.26 Locknit.



5.27 Three-needle sharkskin.

guide bar may be used to give single wale vertical stripes of colour, such as pin stripes in men's suiting.

If the guide bars making a sharkskin are reversed, that is, if the front bar makes the longer underlaps, the resultant fabric is known as satin which is a lustrous soft fabric similar to the woven satin. Because of the long floats on the back of the fabric,



5.28 Three-needle queenscord.

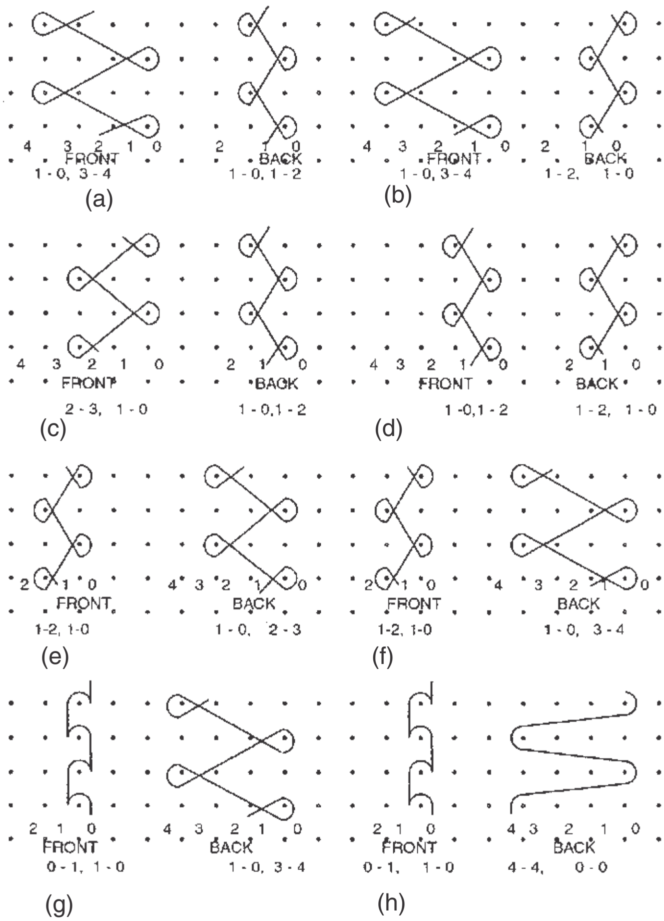
satin laps are used to make loop-raised fabrics. The raising machine is set so that the underlaps are raised into loops without actually breaking any filaments. In order to achieve the maximum raising effect, the two guide bars in a loop-raised fabric are normally made to traverse in the same direction, and open loops may also be used. The lapping movements of three-needle satin are shown in Fig. 5.29(b) and those for a three-needle loop-raised fabric are shown in Fig. 5.29(a). The density and height of pile can be increased by increasing the front guide bar underlaps to four, five or six needle spaces.

Yarns may be introduced into the fabric without actually knitting. Figure 5.30 shows the structure lapping movements and pattern chains of a laid-in fabric. The laid-in thread is trapped between the loop and the subsequent underlap of the guide bar which must be situated in front of the laying-in bar. In order to lay-in a yarn, therefore, that yarn must be threaded in a guide bar to the rear of the guide bar (knitting bar), and it must make no overlaps. Laying-in is a useful device because a laid-in thread never goes round the needle, and therefore very thick or fancy yarns may be introduced into the fabric, such as heavy worsted yarn or metallic threads. Figure 5.31 shows the laid-in thread being trapped in the fabric by the front guide bar threads knitting an open tricot stitch (0-1, 2-1).

5.7.4 Grey specification of a warp-knitted fabric

A complete grey specification of a warp-knitted fabric should include the following details:

1. gauge of machine in needles per inch
2. number of guide bars in use

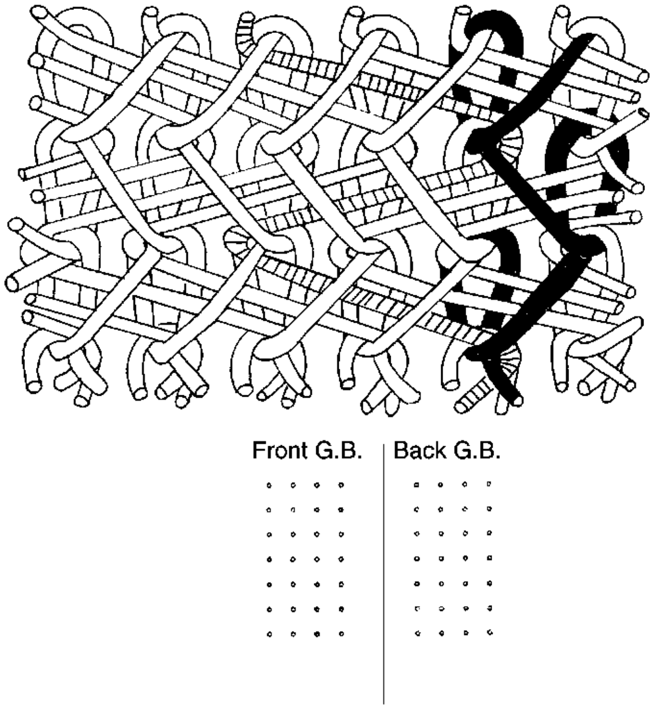


5.29 Some two-guide bar full set structures. (a) Loop raised, (b) satin, (c) locknit, (d) full tricot, (e) reverse locknit, (f) sharkskin, (g) queenscord, (h) laid-in fabric.

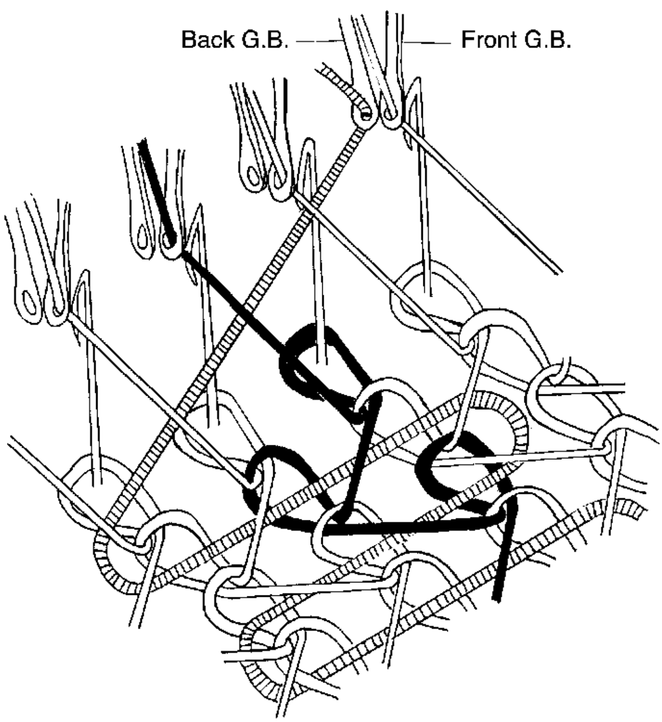
3. number of ends in each warp
4. types and linear densities of yarns used
5. run-in per rack for each warp
6. knitted quality of the fabric in courses per centimetre
7. order of threading in each guide bar
8. lapping movements of each guide bar during one repeat of the pattern or details of the pattern wheels or pattern chains
9. relative lateral positions of the guide bars at a given point in the lapping movements
10. any special knitting instructions.

5.7.5 Fabric quality

The main parameter controlling the quality and properties of a given structure is the run-in per rack, or the amount of yarn fed into the loop. Run-in per rack is



5.30 Laid-in structure.



5.31 Principle of laying-in.

defined as the length of warp fed into the fabric over 480 courses (1 rack = 480 courses). In two-guide bar fabrics, the run-in per rack for each guide bar may be the same or different, depending upon the fabric structure. For example, in full tricot structures (front: 1-2, 1-0 and back: 1-0, 1-2), it is normal to use the same run-in per rack from both beams or 1:1, whereas in three-needle sharkskin fabrics (front: 1-2, 1-0 and back: 1-0, 3-4), the run-in per rack required from the back beam would be more than the front beam say 1:1.66.

The run-in may be altered in two different ways, first by altering the total run-in of the bars, and second by altering the ratio or difference between the bars. Altering the total run-in will affect the finished number of courses per centimetre and hence the area density of the fabric, the stability and the cover, but not the general shape of the loop. Altering the difference between the guide bars will change the balance of the fabric, affect the inclination of the loops and, because it puts more or less strain on the individual yarns, change the strength.

Fabric take-up on the machine is adjusted to attain trouble-free knitting and also to effect ease of finishing.

5.7.6 Tightness factor

The tightness factor K of a knitted fabric is defined as the ratio of the fabric area covered by the yarn to the total fabric area. It is regarded as a measure of looseness or tightness of the structure, and influences dimensions such as the length, width, and thickness and many other fabric characteristics such as area density, opacity, abrasion resistance, modulus, strength and shrinkage.

If the tightness factor of a single-guide bar fabric is defined as in Equation 5.2

$$K = \sqrt{\frac{\text{tex}}{l}} \tag{5.9}$$

where l is the stitch length, measured in millimetres, and tex is the yarn linear density, then the tightness factor of a two-guide bar, full-set fabric is given by Equation (5.10)

$$K = \frac{\sqrt{\text{tex}_\text{f}}}{l_\text{f}} + \frac{\sqrt{\text{tex}_\text{b}}}{l_\text{b}} \tag{5.10}$$

where suffixes f and b refer to front and back guide bars, and l is the stitch length equal to (run-in/rack)/480 and is measured in millimetres. If the same tex is employed in both bars, then

$$K = \sqrt{\text{tex}}\left(\frac{1}{l_\text{f}} + \frac{1}{l_\text{b}}\right) \tag{5.11}$$

For most commercial two-guide bar full-set fabrics $1 \leq K \leq 2$ with a mean tightness factor value of 1.5.[6]

5.7.7 Area density

The area density of a single-guide bar fabric can be determined from Equation (5.12)

$$\begin{aligned} \text{Mass of the fabric} &= \text{cpc} \times \text{wpc} \times l \times T \times 10^{-2}\,\text{g}\,\text{m}^{-2} \\ &= s \times l \times T \times 10^{-2}\,\text{g}\,\text{m}^{-2} \end{aligned} \tag{5.12}$$

where s is the stitch density (cm^{-2}) or (cpc × wpc), l is the stitch length (mm) and T is the yarn tex.

Similarly, the area density of a two-guide bar full-set fabric would be Equation (5.13):

$$\text{Mass of the fabric} = s[(l_f \times T_f) + (l_b \times T_b)] \times 10^{-2}\,\text{gm}^{-2} \tag{5.13}$$

where suffixes f and b refer to the front and back guide bars. If the same tex is used in both guide bars, then the above equation can be written as Equation (5.14):

$$\text{Mass of the fabric} = s \times T \times 10^{-2}(l_f + l_b)\,\text{gm}^{-2}$$

or

$$= s \times T \times 10^{-2}\left(\frac{\text{Total run-in}}{480}\right)\text{gm}^{-2} \tag{5.14}$$

If the stitch density, that is, the number of loops cm^{-2}, stitch length in millimetres of the individual guide bars and tex of yarns employed in individual beams are known, the fabric area density can be readily obtained using the above equation in any fabric state, that is, on the machine, dry relaxed or fully relaxed.

The geometry and dimensional properties of warp-knitted structures have been studied by a number of researchers including Anand and Burnip.[6]

5.7.8 End-use applications of warp-knitted fabrics

Specification for tricot machines is:

- *Type of needle*: compound or bearded
- *Machine gauge*: from 18 to 40 needles per inch (E18–E40)
- *Machine width*: from 213 to 533 cm (84–210 inches)
- *Machine speed*: from 2000 to 3500 courses per minute (HKS 2 tricot machine operates at 3500 cpm)
- *Number of needle bars*: one or two
- *Number of guide bars*: from two to eight
- *Products*: lingerie, shirts, ladies' and gents' outerwear, leisurewear, sportswear, swimwear, car seat covers, upholstery, technical fabrics, bed linen, towelling, lining, nets, footwear fabrics, medical textiles.

Specification for raschel machines is:

- *Type of needle*: latch or compound
- *Machine gauge*: from 12 to 32 needles per inch (E12–E32).
- *Machine width*: from 191 to 533 cm (75–210 inches)
- *Machine speed*: from 500 to 2000 courses per minute
- *Number of needle bars*: one or two
- *Number of guide bars*: from two to seventy-eight
- *Products*: marquisettes, curtains, foundation garments, nets, fishing nets, sports nets, technical fabrics, curtain lace, power nets, tablecloths, bed covers, elastic bandages, cleaning cloths, upholstery, drapes, velvets, carpets, ladies' underwear, fruit and vegetable bags, geotextiles, medical textiles.

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6

Technical fabric structures – 3. Nonwoven fabrics

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6.1 Introduction

It is an unfortunate fact that there is no internationally agreed definition of nonwovens, in spite of the fact that the International Standards Organization published a definition in 1988 (ISO 9092:1988). Many countries, particularly those that have played an active part in the development of nonwovens, still prefer their own national definition, which is generally wider in its scope than the very narrow definition of ISO 9092.

As it is essential to be clear on the subject matter to be included in this chapter, I have decided to use the definition of the American Society for Testing Materials (ASTM D 1117-80). This definition is as follows: 'A nonwoven is a textile structure produced by the bonding or interlocking of fibres, or both, accomplished by mechanical, chemical, thermal or solvent means and combinations thereof. The term does not include paper or fabrics that are woven, knitted or tufted.' It has to be admitted that this definition is not very precise, but it has been chosen because it includes many important fabrics which most people regard as nonwovens, but which are excluded by ISO 9092. Nonwovens are still increasing in importance; production is increasing at the rate of 11% per annum.

One of the major advantages of nonwoven manufacture is that it is generally done in one continuous process directly from the raw material to the finished fabric, although there are some exceptions to this. This naturally means that the labour cost of manufacture is low, because there is no need for material handling as there is in older textile processes. In spite of this mass-production approach, the nonwovens industry can produce a very wide range of fabric properties from open waddings suitable for insulation containing only 2–3% fibres by volume to stiff reinforcing fabrics where the fibre content may be over 80% by volume. How is this wide range of properties produced? All nonwoven processes can be divided into two stages, the preparation of the fibres into a form suitable for bonding and the bonding process itself. There are a number of different ways of fibre processing, each producing its own particular characteristic in the final fabric. Equally there are a number of different bonding methods which have an even bigger effect on the finished fabric properties. Almost all the fibre processing methods can be combined with all the bonding methods, so that the range of different possible manufacturing lines is enormous, allowing a great range of final properties.

However, this does raise a difficulty in describing the nonwoven process. We know that the process is essentially a continuous one in which the fibre processing and bonding take place in two machines tightly linked together, but it is impossible to describe the combined machines together owing to the wide number of machine combinations that are possible. Instead it is necessary to explain the methods of fibre processing and the methods of bonding separately.

In fibre processing it is common to make first a thin layer of fibre called a web and then to lay several webs on top of each other to form a batt, which goes directly to bonding. The words web and batt are explained by the previous sentence, but there are cases where it is difficult to decide if a fibre layer is a web or a batt. Nevertheless the first stage of nonwoven processing is normally called batt production.

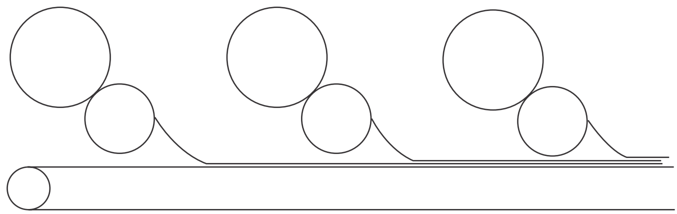
6.2 Methods of batt production using carding machines

The principles of carding and the types of carding machines have already been discussed in Chapter 3. The machines in the nonwoven industry use identical principles and are quite similar but there are some differences. In particular in the process of yarn manufacture there are opportunities for further opening and for improving the levelness of the product after the carding stage, but in nonwoven manufacture there is no further opening at all and very limited improvements in levelness are possible. It therefore follows that the opening and blending stages before carding must be carried out more intensively in a nonwoven plant and the card should be designed to achieve more opening, for instance by including one more cylinder, though it must be admitted that many nonwoven manufacturers do not follow this maxim.

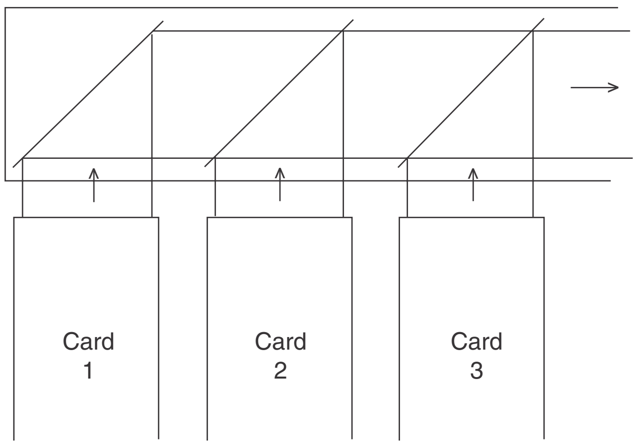
Theoretically either short-staple revolving flat cards or long-staple roller cards could be used, the short-staple cards having the advantages of high production and high opening power, especially if this is expressed per unit of floor space occupied. However, the short-staple cards are very narrow, whereas long-staple cards can be many times wider, making them much more suitable for nonwoven manufacture, particularly since nonwoven fabrics are required to be wider and wider for many end-uses. Hence a nonwoven installation of this type will usually consist of automatic fibre blending and opening feeding automatically to one or more wide long-staple cards. The cards will usually have some form of autoleveller to control the mass per unit area of the output web.

6.2.1 Parallel laying

The mass per unit area of card web is normally too low to be used directly in a nonwoven. Additionally the uniformity can be increased by laying several card webs over each other to form the batt. The simplest and cheapest way of doing this is by parallel laying. Figure 6.1 shows three cards raised slightly above the floor to allow a long conveyor lattice to pass underneath. The webs from each card fall onto the



6.1 Parallel laying.



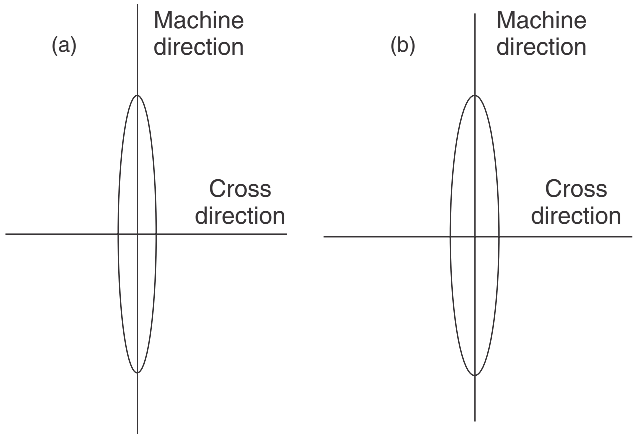
6.2 Alternative layout for parallel laying.

lattice forming a batt with three times the mass per unit area. If the cards are longer this method becomes unwieldy and instead the cards are placed side-by-side as in Figure 6.2.

The card webs are turned through a right angle by a guide at 45°, but the batt produced by this method is identical in all respects to the previous method. It is important to recognise that it is not cross laid, as in Section 6.2.2, in spite of the similarities between the layouts.

In any card web there is a marked tendency for the fibres to lie along the web rather than across it. Since in parallel laying all the card webs are parallel to each other (and to the batt), it follows that most of the fibres will lie along the batt and very few across it. At this stage it is important to introduce two terms used widely in nonwovens. The direction along the batt is called the 'machine direction' and the direction at right angles is called the 'cross direction'. Whatever method of bonding is used it is found that the bonds are weaker than the fibres. A tensile test on a bonded parallel-laid material in the machine direction will depend mainly on the fibre strength, whereas in the cross direction it will depend more on the bond strength. The effect of these facts on the relative fibre frequency and on the directional strength of a typical parallel-laid fabric in various directions is shown in Figure 6.3.

The weakness of the fabric in the cross direction has a profound effect on possible uses of the fabric. Briefly it can be used when strength is not required in either



6.3 Polar diagrams showing (a) the relative frequency of fibres lying in various directions and (b) the relative strength in various directions for a parallel-laid fabric.

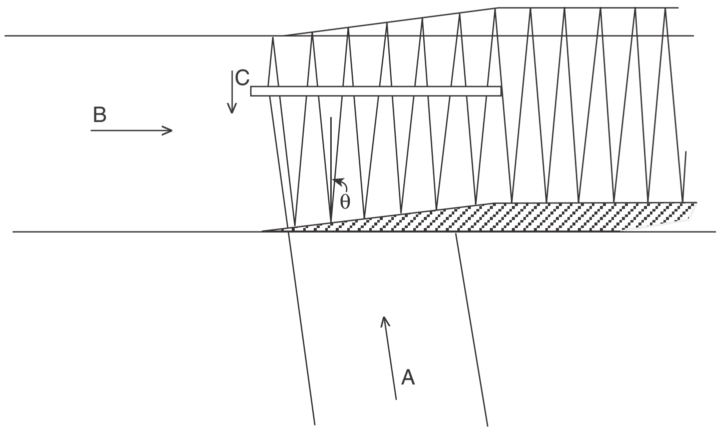
direction, for example, a filter fabric which is completely supported or as a wiping cloth. It is especially useful when high strength is required in one direction but strength in the other direction is not important, but examples of this are rare; the one usually quoted is a narrow tape cut in the machine direction and used mainly for medical purposes.

This situation has been altered by the advent of cards designed especially for the nonwoven industry. These cards are given a randomising doffer, which as its name implies, makes the fibre directions more random, together with 'scrambling rollers' that condense the card web in length, having the effect of buckling those fibres lying in the machine direction and forming segments lying in the cross direction. By using these two techniques together it is possible to bring the strength ratio of parallel-laid fabric down from the normal 10 or 20:1 to 1.5:1, which is about as isotropic as any nonwoven. It may also be worth mentioning that similar carding techniques have been expanded even further to make a card that produces a really thick web, making laying unnecessary. However, all parallel-lay processes suffer from a further fundamental problem; the width of the final fabric cannot be wider than the card web, while current trends demand wider and wider fabrics.

6.2.2 Cross laying

When cross laying, the card (or cards) are placed at right angles to the main conveyor just as in Fig. 6.2, but in this case the card web is traversed backwards and forwards across the main conveyor, which itself is moving. The result is a zig-zag as shown in Fig. 6.4.

Usually the conveyor B is moving only slowly so that many layers of card web are built up, as shown in the diagram. The thickness of the card web is very small in comparison with the completed batt, so that the zig-zag marks, which appear so prominent in the figure, do not usually show much. There are two major problems with cross layers; one is that they tend to lay the batt heavier at the edges than in the middle. This fault can be corrected by running the traversing mechanism rather slower in the centre and more rapidly at the edges, with a very rapid change



6.4 Cross laying. A, card web; B, main conveyor; C, traverse mechanism; θ, angle of cross laying.

of direction at the edge. The other problem is trying to match the input speed of the cross layer with the card web speed. For various reasons the input speed of the cross layer is limited and the speed of the card web has to be reduced to match it. Because for economic reasons the card is forced to run at maximum production, the card web at the lower speed is thicker and the cross-laying marks discussed above will tend to show more. In spite of these problems, cross layers are used much more frequently than parallel layers.

The diagram in Fig. 6.4 showing webs crossing at an angle seems to imply that the batt will be fairly isotropic. However, this is not so because the cross-laying angle (θ in Fig. 6.4) is normally less than 10°, so that the great majority of fibres lie in or near the cross direction. Cross-laid fabrics are consequently very strong in the cross direction and weak in the machine direction. In many cases this may not matter, because cross-laid fabrics are often quite heavy and may not require much strength, but in many other cases a more isotropic batt is required. The obvious solution is to combine parallel laying and cross laying together; this is done very occasionally but it is uncommon because it combines the limitations of both systems, that is, the relatively narrow width of parallel laying and the slow output speed of the cross laying. The common solution is to stretch the batt in the machine direction as it exits from the cross layer. Various machines are available for doing this; the important criterion is that the stretching should be even, otherwise it could create thick and thin places in the batt. Cross laying, with or without stretching, is much more popular than parallel laying and is probably the most widely used system of all.

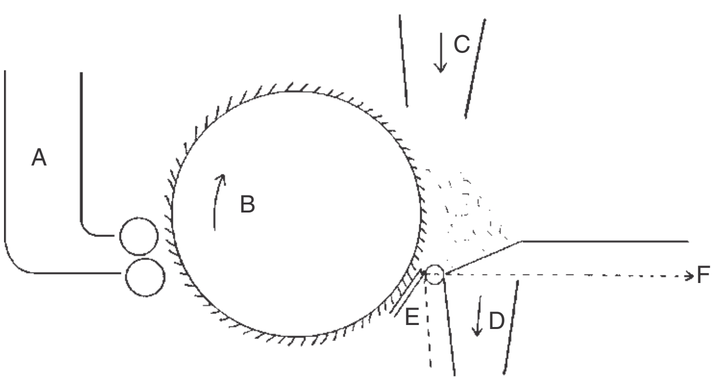
6.3 Air laying

The air-laying method produces the final batt in one stage without first making a lighter weight web. It is also capable of running at high production speeds but is similar to the parallel-lay method in that the width of the final batt is the same as the width of the air-laying machine, usually in the range of 3–4 m.

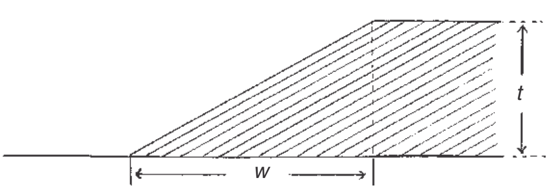
The degree of fibre opening available in an air-lay machine varies from one manufacturer to another, but in all cases it is very much lower than in a card. As a consequence of this more fibre opening should be used prior to air laying and the fibres used should be capable of being more easily opened, otherwise the final batt would show clumps of inadequately opened fibre. In the past the desire for really good fibre opening (which is needed for lightweight batts) led to a process consisting of carding, cross laying, then feeding the cross-laid batt to an air-laying machine. The only purpose of the air-lay machine in this example was to obtain the desired machine : cross-direction strength ratio, but it is a very expensive way compared to the stretching device discussed above and such a process would not be installed today.

The diagram in Fig. 6.5 shows the principle of an air-lay machine, although the actual machines may vary considerably from this outline. Opened fibre from the opening/blending section is fed into the back of hopper A, which delivers a uniform sheet of fibres to the feed rollers. The fibre is then taken by the toothed roller B, which is revolving at high speed. There may or may not be worker and stripper rollers set to the roller B to improve the opening power. A strong air stream C dislodges the fibres from the surface of roller B and carries them onto the permeable conveyor on which the batt is formed. The stripping rail E prevents fibre from recirculating round the cylinder B. The air flow at D helps the fibre to stabilise in the formation zone.

Figure 6.6 shows the formation zone in more detail. This shows that the fibres fall onto an inclined plane, and that the angle between this plane and the plane of the fabric depends on the width of the formation zone, w, and the thickness of the



6.5 Principle of air-lay machine. A, Hopper/chute feed; B, opening roller; C, air flow from fan; D, suction to fan; E, stripping rail; F, batt conveyor.



6.6 Close-up of the formation zone.

batt, t. It is possible when making thick fabrics to reduce the width, w, so that the fibres lie at a substantial angle to the plane of the batt. It is claimed that for this reason air-laid fabrics show better recovery from compression compared with cross-laid fabrics. It is often thought because the fibres are deposited without control from an air stream that they will be random in the plane of the batt. This belief is so widespread that air-laid fabrics are frequently called 'random-laid' fabrics. The use of this term should be strongly discouraged, because it gives a false impression. In fact air-laid fabrics can have strength ratios as high as 2.5:1, which is far from random. It is thought that the increase in the machine direction strength is caused by the movement of the conveyor; a fibre in the air-stream approaching the conveyor will tend to be pulled into the machine direction as it lands on the moving conveyor.

The parallel-laid, cross-laid and air-laid methods discussed so far, are collectively known as dry-laid processes. They are the most similar to traditional textile processing and currently account for slightly less than half the total nonwoven production.

6.4 Wet laying

The wet-laid process is a development from papermaking that was undertaken because the production speeds of papermaking are very high compared with textile production. Textile fibres are cut very short by textile standards (6–20 mm), but at the same time these are very long in comparison with wood pulp, the usual raw material for paper. The fibres are dispersed into water; the rate of dilution has to be great enough to prevent the fibres aggregating. The required dilution rate turns out to be roughly ten times that required for paper, which means that only specialised forms of paper machines can be used, known as inclined-wire machines. In fact most frequently a blend of textile fibres together with wood pulp is used as the raw material, not only reducing the necessary dilution rate but also leading to a big reduction in the cost of the raw material. It is now possible to appreciate one of the problems of defining 'nonwoven'. It has been agreed that a material containing 50% textile fibre and 50% wood pulp is a nonwoven, but any further increase in the wood pulp content results in a fibre-reinforced paper. A great many products use exactly 50% wood pulp. Wet-laid nonwovens represent about 10% of the total market, but this percentage is tending to decline. They are used widely in disposable products, for example in hospitals as drapes, gowns, sometimes as sheets, as one-use filters, and as coverstock in disposable nappies.

6.5 Dry laying wood pulp

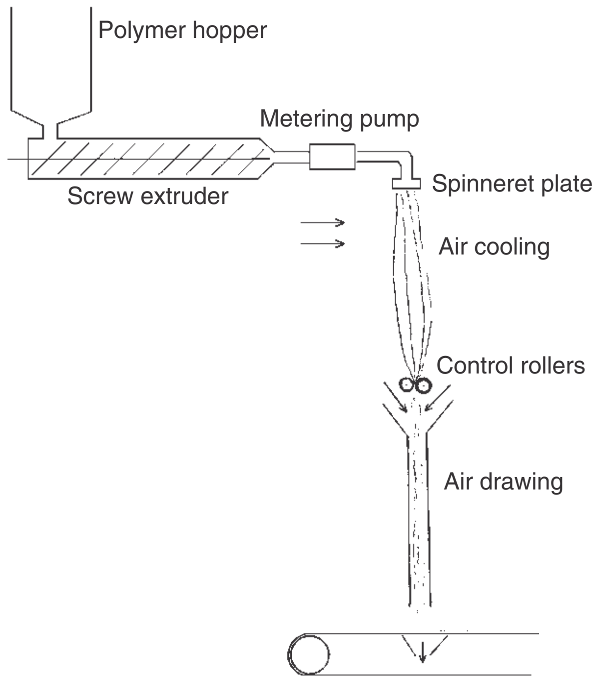
The paper industry has attempted for many years to develop a dry paper process because of the problems associated with the normal wet process, that is, the removal of very large volumes of water by suction, by squeezing and finally by evaporation. Now a dry process has been developed using wood pulp and either latex binders or thermoplastic fibres or powders to bond the wood pulp together to replace hydrogen bonding which is no longer possible. Owing to the similarity of both the bonding methods and some of the properties to those of nonwovens, these products are being referred to as nonwovens in some areas, although it is clear from the definition above they do not pass the percentage wood pulp criterion. Hence although the dry-laid paper process cannot be regarded as a nonwoven process at present, it is very likely that the process will be modified to accept textile fibres and will become very important in nonwovens in the future. It is for this reason that it has been included here.

6.6 Spun laying

Spun laying includes extrusion of the filaments from the polymer raw material, drawing the filaments and laying them into a batt. As laying and bonding are normally continuous, this process represents the shortest possible textile route from polymer to fabric in one stage. In addition to this the spun-laid process has been made more versatile. When first introduced only large, very expensive machines with large production capabilities were available, but much smaller and relatively inexpensive machines have been developed, permitting the smaller nonwoven producers to use the spun-laid route. Further developments have made it possible to produce microfibres on spun-laid machines giving the advantages of better filament distribution, smaller pores between the fibres for better filtration, softer feel and also the possibility of making lighter-weight fabrics. For these reasons spun-laid production is increasing more rapidly than any other nonwoven process.

Spun laying starts with extrusion. Virtually all commercial machines use thermoplastic polymers and melt extrusion. Polyester and polypropylene are by far the most common, but polyamide and polyethylene can also be used. The polymer chips are fed continuously to a screw extruder which delivers the liquid polymer to a metering pump and thence to a bank of spinnerets, or alternatively to a rectangular spinneret plate, each containing a very large number of holes. The liquid polymer pumped through each hole is cooled rapidly to the solid state but some stretching or drawing in the liquid state will inevitably take place. Up to this stage the technology is similar to the fibre or filament extrusion described in Chapter 2, except that the speeds and throughputs are higher, but here the technologies tend to divide. In spun laying the most common form of drawing the filaments to obtain the correct modulus is air drawing, in which a high velocity air stream is blown past the filaments moving down a long tube, the conditions of air velocity and tube length being chosen so that sufficient tension is developed in the filaments to cause drawing to take place. In some cases air drawing is not adequate and roller drawing has to be used as in normal textile extrusion, but roller drawing is more complex and tends to slow the process, so that air drawing is preferred.

The laying of the drawn filaments must satisfy two criteria; the batt must be as even as possible in mass per unit area at all levels of area, and the distribution of filament orientations must be as desired, which may not be isotropic. Taking the regularity criterion first, the air tubes must direct the filaments onto the conveyor belt in such a way that an even distribution is possible. However, this in itself is not sufficient because the filaments can form agglomerations that make ‘strings’ or ‘ropes’ which can be clearly seen in the final fabric. A number of methods have been suggested to prevent this, for instance, charging the spinneret so that the filaments become charged and repel one another or blowing the filaments from the air tubes against a baffle plate, which tends to break up any agglomerations. With regard to



6.7 Diagram of a spun-laid process.

the filament orientation, in the absence of any positive traversing of the filaments in the cross direction, only very small random movements would take place. However, the movement of the conveyor makes a very strong machine direction orientation; thus the fabric would have a very strong machine-direction orientation. Cross-direction movement can most easily be applied by oscillating the air tubes backwards and forwards. By controlling the speed and amplitude of this oscillation it is possible to control the degree of cross-direction orientation. A simplified diagram of a spun-laid plant is shown in Fig. 6.7.

6.7 Flash spinning

Flash spinning is a specialised technique for producing very fine fibres without the need to make very fine spinneret holes. It is used in making only two fabric types. Flash spinning depends on the fact that the intramolecular bonds in polyethylene and polypropylene are much weaker than similar bonds in polyester and polyamide. When a thin sheet of polyolefin is very highly drawn (10 or 12 to 1) the molecules align in the direction of drawing giving high strength in that direction, but across the drawing direction the strength is based only on the intramolecular bonds and so is very low, so low that any mechanical action such as bending, twisting or abrasion causes the sheet to split. Depending on the original thickness of the sheet and the amount of splitting, the result may be fibre-like but with a rectangular cross-section. The process is known as fibrillation.

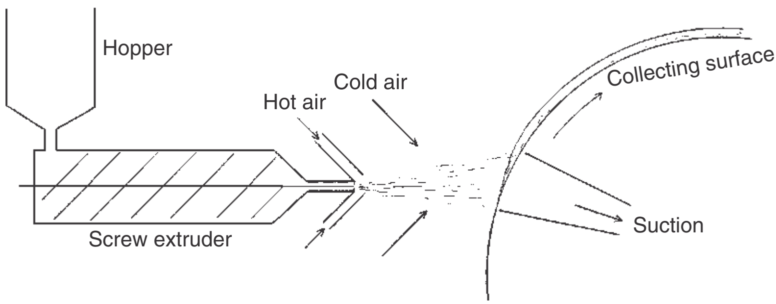
In flash spinning the polymer is dissolved in a solvent and is extruded as a sheet at a suitable temperature so that when the pressure falls on leaving the extruder the solvent boils suddenly. This blows the polymer sheet into a mass of bubbles with a large surface area and consequently with very low wall thickness. Subsequent drawing of this sheet, followed by mechanical fibrillation, results in a fibre network of very fine fibres joined together at intervals according to the method of production. This material is then laid to obtain the desired mass per unit area and directional strength.

Flash-spun material is only bonded in two ways, so that it seems sensible to discuss both the bonding and the products at this juncture. One method (discussed later in Section 6.10.3) involves melting the fibres under high pressure so that virtually all fibres adhere along the whole of their length and the fabric is almost solid with very little air space. This method of construction makes a very stiff material with high tensile and tear strengths. It is mainly used in competition with paper for making tough waterproof envelopes for mailing important documents and for making banknotes. The fact that the original fibres were very fine means that the material is very smooth and can be used for handwriting or printing. The alternative method of bonding is the same, that is, heat and pressure (see Section 6.10.4) but is only applied to small areas, say 1 mm square, leaving larger areas, say 4 mm square, completely unbonded. The bonded areas normally form a square or diagonal pattern. This material, known as Tyvek, has a lower tensile strength than the fully bonded fabric, but has good strength and is flexible enough to be used for clothing. Because the fine fibres leave very small pores in the fabric, it is not only waterproof but is also resistant to many other liquids with surface tensions lower than water. The presence of the pores means that the fabric is permeable to water vapour and so is comfortable to wear. Tyvek is used principally for protective clothing in the chemical, nuclear and oil industries, probably as protection for the armed forces and certainly in many industries not requiring such good protection but where it is found to be convenient. The garments can be produced so cheaply that they are usually regarded as disposable.

6.8 Melt blown

The process of melt blowing is another method of producing very fine fibres at high production rates without the use of fine spinnerets. Figure 6.8 shows that the polymer is melted and extruded in the normal way but through relatively large holes.

As the polymer leaves the extrusion holes it is hit by a high speed stream of hot air at or even above its melting point, which breaks up the flow and stretches the many filaments until they are very fine. At a later stage, cold air mixes with the hot and the polymer solidifies. Depending on the air velocity after this point a certain amount of aerodynamic drawing may take place but this is by no means as satisfactory as in spun laying and the fibres do not develop much tenacity. At some point the filaments break into staple fibres, but it seems likely that this happens while the polymer is still liquid because if it happened later this would imply that a high tension had been applied to the solid fibre, which would have caused drawing before breaking. The fine staple fibres produced in this way are collected into a batt on a permeable conveyor as in air laying (Section 6.3) and spun laying (Section 6.6). The big difference is that in melt blowing the fibres are extremely fine so that there are many more fibre-to-fibre contacts and the batt has greater integrity.



6.8 Diagram of melt-blown equipment.

For many end-uses no form of bonding is used and the material is not nonwoven, but simply a batt of loose fibres. Such uses include ultrafine filters for air conditioning and personal face masks, oil-spill absorbents and personal hygiene products. In other cases the melt-blown batt may be laminated to another nonwoven, especially a spun-laid one or the melt-blown batt itself may be bonded but the method must be chosen carefully to avoid spoiling the openness of the very fine fibres. In the bonded or laminated form the fabric can be used for breathable protective clothing in hospitals, agriculture and industry, as battery separators, industrial wipes and clothing interlinings with good insulation properties. Melt blowing started to develop rapidly in about 1975, although the process was known before 1950. It is continuing to grow at about 10% per annum.

6.9 Chemical bonding

Chemical bonding involves treating either the complete batt or alternatively isolated portions of the batt with a bonding agent with the intention of sticking the fibres together. Although many different bonding agents could be used, the modern industry uses only synthetic lattices, of which acrylic latex represents at least half and styrene–butadiene latex and vinyl acetate latex roughly a quarter each. When the bonding agent is applied it is essential that it wets the fibres, otherwise poor adhesion will be achieved. Most lattices already contain a surfactant to disperse the polymer particles, but in some cases additional surfactant may be needed to aid wetting. The next stage is to dry the latex by evaporating the aqueous component and leaving the polymer particles together with any additives on and between the fibres. During this stage the surface tension of the water pulls the binder particles together forming a film over the fibres and a rather thicker film over the fibre intersections. Smaller binder particles will form a more effective film than larger particles, other things being equal. The final stage is curing and in this phase the batt is brought up to a higher temperature than for the drying. The purpose of curing is to develop crosslinks both inside and between the polymer particles and so to develop good cohesive strength in the binder film. Typical curing conditions are 120–140 °C for 2–4 min.

6.9.1 Saturation bonding

Although the principles discussed above apply to all forms of chemical bonding whatever the method of binder application, this latter factor has a profound influence on the properties of the nonwoven material. As implied by the name, saturation bonding wets the whole batt with bonding agents, so that all fibres are covered in a film of binder. It is clear that saturation bonding would not be suitable for flash-spun or melt-blown batts, since it would impair the fine fibres, but it is inherently suitable for all other batts, although other methods of bonding are generally preferred for spun-laid batts.

To saturate the batt, it is carried under the surface of the bonding agent. In most cases the batt is very open and weak and care is needed to avoid distortion. The action of the liquid greatly reduces the thickness of the batt and the thickness is further reduced by the squeeze rollers which follow. Hence saturation bonded fabrics are generally compact and relatively thin. However, as in most technologies, there is an exception to this rule; if coarse fibres containing a lot of crimp are used they can spring back after being crushed by the squeeze rollers and produce a thick open fabric, but this is very rare.

The drying is often done in a dryer designed basically for woven fabric, modified by having a permeable conveyor to support and transport the nonwoven through the machine. Hot air is blown against the top and bottom surfaces to cause drying, the top air pressure being slightly greater than the bottom pressure to press and control the nonwoven against the conveyor. Because the air only penetrates the immediate surfaces of the nonwoven, drying is confined to these areas and the central layers of the nonwoven remain wet. The result is that the liquid wicks from the wet areas to the dry ones, unfortunately carrying the suspended binder particles with the water. This is the cause of the problem known as binder migration; under adverse conditions virtually all the binder can be found in the surface layers and the central layers contain no binder at all, leaving them very weak. Such a fabric can easily split into two layers, a problem known as delamination. Fortunately a number of ways have been found to control binder migration, several of them being rather complicated. Only one method will be mentioned here, through-drying. In this case only one air stream is used to blow down and through the fabric. Drying conditions are then almost the same in all parts of the fabric and no binder migration takes place. However, the air pressure may exert a significant force on the nonwoven, pressing it against the conveyor so hard that it may be imprinted with the pattern of the conveyor.

In contrast the curing stage is simpler; it should be done in a separate compartment in order to achieve the correct temperature. However, it is quite common for curing to be done in the final part of the dryer in order to keep down machinery costs.

Many of the physical properties of saturation-bonded fabric derive from the fact that all fibres are covered with a film of binder. First, the fabric feels like the binder and not the fibres it is made from. However, in some cases this can be an advantage, because by using either a hydrophobic or a hydrophilic binder the reaction of the fabric to water can be changed regardless of which fibres are used.

The mechanical properties can be explained from a model of a network of fibres bonded together at close intervals. The fabric cannot stretch without the fibres also stretching by a similar amount. Hence the fabric modulus is of the order of the fibre modulus, that is, extremely high. A high modulus in a spatially uniform material means that it will be stiff, which explains why saturation-bonded fabrics are very stiff relative to conventional textiles. At the same time tensile strength is low, because the bonds tend to break before most fibres break. Efforts to make the fabrics more flexible include using a more flexible binder and using a lower percentage of binder, but both of these reduce the tensile strength; in fact the ratio of fabric modulus to tensile strength remains remarkably constant.

One of the major uses of saturation bonded fabric turns this apparent disadvantage into an advantage. Interlining fabric for textile clothing is required to be stiff and to have a high modulus. Other uses are as some types of filter fabric, in some coverstock and in wiping cloths.

6.9.2 Foam bonding

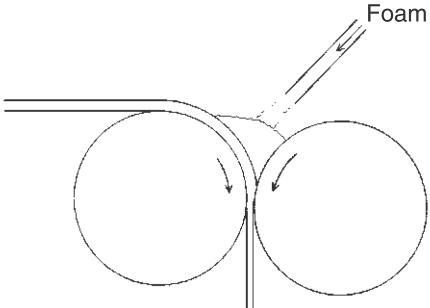
It can be inferred above that one of the problems of saturation bonding is that too much water is used. This not only increases the cost of drying but also increases the risk of binder migration. Application of chemicals as a foam was developed not only for nonwovens but also for the dyeing and finishing industry as a means of using less water during application. The binder solution and a measured volume of air are passed continuously through a driven turbine which beats the two components into a consistent foam. The foam is then delivered to the horizontal nip of the impregnating roller, as shown in Fig. 6.9. The foam delivery has to be traversed because the foam does not flow easily; end plates, which cannot be shown in the cross-section diagram prevent the foam from running out of the gap at the end of the rollers.

The rollers serve the dual purpose of metering the amount of foam applied and also of squeezing the foam into the batt. If the set-up shown in Fig. 6.9 does not give adequate foam penetration, then the batt can be entered vertically and the foam can be applied from both sides.

Foam application should only be thought of as an alternative method of saturation bonding. The properties and uses of the fabrics are identical.

6.9.3 Print bonding

Print bonding involves applying the same types of binder to the batt but the application is to limited areas and in a set pattern. The binder does not penetrate well into the dry batt so the batt is first saturated with water and then printed with either a printing roller or a rotary screen printer. The final properties of the fabric depend



6.9 Foam impregnation.

vitally on the printed/unprinted area ratio, which could be changed significantly if the binder migrated sideways from the printed area. To prevent this the binder formulation must contain some thickener.

Print-bonded fabrics are much softer in feel and also much more flexible owing to the strong effect of the free fibres in the unbonded areas. They are also significantly weaker than saturation-bonded fabrics owing to the fibres slipping in unbonded areas, but knowing the fibre length and the fibre orientation distribution it is possible to design a print pattern which will minimise the strength loss.

Print-bonded fabrics tend to be used in applications where the textile-like handle is an advantage. Examples are disposable/protective clothing, coverstock and wiping cloths, particularly domestic ones (washing-up and dusting).

6.9.4 Spray bonding

Similar latex binders may also be applied by spraying, using spray guns similar to those used in painting, which may be either operated by compressed air or be airless. On the first passage the spray penetrates about 5 mm into the top surface, then the batt is turned over for a spray application on the lower surface. Each spray application reduces the thickness of the batt slightly, but it is still left substantially lofty; the drying and curing stage also causes some small dimensional changes. The final product is a thick, open and lofty fabric used widely as the filling in quilted fabrics, for duvets, for some upholstery and also for some types of filter media.

6.10 Thermal bonding

Thermal bonding is increasingly used at the expense of chemical bonding for a number of reasons. Thermal bonding can be run at high speed, whereas the speed of chemical bonding is limited by the drying and curing stage. Thermal bonding takes up little space compared with drying and curing ovens. Also thermal bonding requires less heat compared with the heat required to evaporate water from the binder, so it is more energy efficient.

Thermal bonding can use three types of fibrous raw material, each of which may be suitable in some applications but not in others. First, the fibres may be all of the same type, with the same melting point. This is satisfactory if the heat is applied at localised spots, but if overall bonding is used it is possible that all the fibres will melt into a plastic sheet with little or no value. Second, a blend of fusible fibre with either a fibre with a higher melting point or a non-thermoplastic fibre can be used. This is satisfactory in most conditions except where the fusible fibre melts completely, losing its fibrous nature and causing the batt to collapse in thickness. Finally, the fusible fibre may be a bicomponent fibre, that is, a fibre extruded with a core of high melting point polymer surrounded by a sheath of lower melting point polymer. This is an ideal material to process because the core of the fibre does not melt but supports the sheath in its fibrous state. Thermal bonding is used with all the methods of batt production except the wet-laid method, but it is worth pointing out that the spun-laid process and point bonding (see Section 6.10.4) complement each other so well that they are often thought of as the standard process.

6.10.1 Thermal bonding without pressure

The batt may be processed through a hot air oven with just sufficient air movement to cause the fusible portion to melt. This method is used to produce high loft fabrics; the products are similar to spray-bonded materials except that in this case the bonding is uniform all the way through and there is virtually no limit to the thickness of fabric made. The uses of the thermal-bonded fabric are basically the same as those of a spray-bonded fabric but they would be used in situations where a higher specification is required. One interesting example is in the fuel tanks of Formula 1 cars to limit the rate of fuel loss in the event of a crash.

6.10.2 Thermal bonding with some pressure

This method is basically the same as the previous one, except that as the batt leaves the thermobonding oven it is calendered by two heavy rollers to bring it to the required thickness. The products could be used as insulation, as rather expensive packaging or for filtration.

6.10.3 Thermal bonding with high pressure

The batt is taken between two large heated rollers (calender rollers) that both melt the fusible fibre and compress the batt at the same time. Provided the batt is not too heavy in mass per unit area the heating is very rapid and the process can be carried out at high speed ($300\,m\,min^{-1}$). The design of calender rollers for this purpose has become highly developed; they can be 4–5 m wide and can be heated to give less than 1 °C temperature variation across the rollers. Also the rollers have to be specially designed to produce the same pressure all the way across the rollers, because rollers of this width can bend quite significantly.

The products tend to be dense and heavily bonded, although of course the amount of bonding can be adjusted by varying the percentage of fusible fibre in the blend. Typical properties are high strength, very high modulus and stiffness but good recovery from bending. The main uses are in some geotextiles, stiffeners in some clothing and in shoes, some filtration media and in roofing membranes.

6.10.4 Thermal bonding with point contact

Although it is very strong, the fabric produced with bonding all over the batt (area bonding) is too stiff and non-textile-like for many uses. It is far more common to use point bonding, in which one of the calender rollers is engraved with a pattern that limits the degree of contact between the rollers to roughly 5% of the total area. The bonding is confined to those points where the rollers touch and leaves roughly 95% of the batt unbonded. The area, shape and location of the bonding points are of great importance.

Fabrics made in this way are flexible and relatively soft owing to the unbonded areas. At the same time they maintain reasonable strength, especially in the case of the spun-laid fabrics. These fabrics have many uses, for example, as a substrate for tufted carpets, in geotextiles, as a filtration medium, in protective/disposable clothing, as a substrate for coating, in furniture and home furnishings and as coverstock.

6.10.5 Powder bonding

Thermoplastic powders may be used as an alternative to thermoplastic fibres for bonding in all the methods of thermobonding except for point bonding, where powder in the unbonded areas would be wasted and would drop out in use. Products made by powder bonding seem to be characterised by softness and flexibility but in general they have relatively low strength. Again there is a very wide range of uses covering particularly the high bulk applications, protective apparel and coverstock areas.

6.11 Solvent bonding

This form of bonding is only rarely used but it is interesting from two points of view; first, the solvent can be recycled, so the process is ecologically sound, although whether or not recycling is practical depends on the economics of recovering the solvent. Second, some of the concepts in solvent bonding are both interesting and unique. In one application of the method, a spun-laid polyamide batt is carried through an enclosure containing the solvent gas, NO_2 which softens the skin of the filaments. On leaving the enclosure bonding is completed by cold calender rolls and the solvent is washed from the fabric with water using traditional textile equipment. This is a suitable method of bonding to follow a spun-laid line because the speeds of production can be matched. The other application uses a so-called latent solvent, by which is meant one that is not a solvent at room temperature but becomes a solvent at higher temperatures. This latent solvent is used in conjunction with carding and cross laying and is applied as a liquid before carding. The action of carding spreads the solvent and at the same time the solvent lubricates the fibres during carding. The batt is passed to a hot air oven which first activates the solvent and later evaporates it. The product will normally be high loft, but if less loft is required a compression roller could be used.

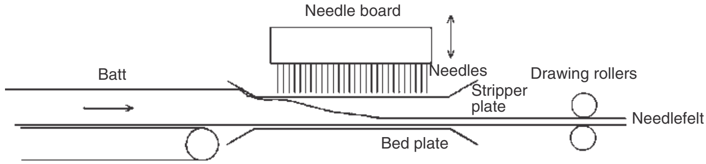
6.12 Needlefelting

All the methods of bonding discussed so far have involved adhesion between the fibres; hence they can be referred to collectively as adhesive bonding. The final three methods, needlefelting, hydroentanglement and stitch bonding rely on frictional forces and fibre entanglements, and are known collectively as mechanical bonding.

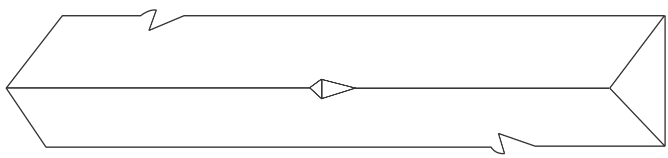
The basic concept of needlefelting is apparently simple; the batt is led between two stationary plates, the bed and stripper plates, as shown in Fig. 6.10. While between the plates the batt is penetrated by a large number of needles, up to about $4000\,m^{-1}$ width of the loom. The needles are usually made triangular and have barbs cut into the three edges as shown in Fig. 6.11.

When the needles descend into the batt the barbs catch some fibres and pull them through the other fibres. When the needles return upwards, the loops of fibre formed on the downstroke tend to remain in position, because they are released by the barbs. This downward pressure repeated many times makes the batt much denser, that is, into a needlefelt.

The above description illustrates how simple the concept seems to be. Without going into too much detail it may be interesting to look at some of the complica-



6.10 Diagram of a needleloom.



6.11 Diagram of three needle barbs on a section of a needle.

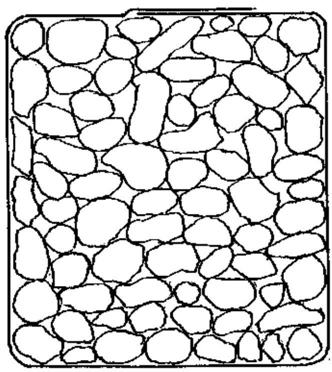
tions. First, the needles can only form vertical loops or 'pegs' of fibre and increase the density of the batt. This alone does not form a strong fabric unless the vertical pegs pass through loops already present in the horizontal plane of the batt. It follows from this that parallel-laid fabric is not very suitable for needling since there are few fibre loops present, so most needling processes are carried out with cross-laid, air-laid and spun-laid batts. Second, the amount of needling is determined partly by the distance the drawing rollers move between each movement of the needleboard, the 'advance', and partly by the number of needles per metre across the loom. If the chosen advance happens to be equal to, or even near the distance between needle rows as shown in Fig. 6.10, then the next row of needles will come down in exactly the same position as the previous row, and so on for all the rows of needles. The result will be a severe needle patterning; to avoid this the distance between each row of needles must be different. Computer programs have been written to calculate the best set of row spacings. Third, if it is necessary to obtain a higher production from a needleloom, is it better to increase the number of needles in the board or to increase the speed of the needleboard? Finally, in trying to decide how to make a particular felt it is necessary to choose how many needle penetrations there will be per unit area, how deep the needles will penetrate and what type of needles should be used from a total of roughly 5000 different types. The variations possible seem to be infinite, making an optimisation process very difficult.

There are several different types of needleloom. Figure 6.10 is called a 'down-punch' because it is pushing the fibres downwards. Similarly an 'up-punch' pushes the fibres upwards. There is some advantage in combining an up-punch with a down-punch when trying to make a dense felt, rather than to punch continually in the same direction. For this reason some looms are made 'double-punch', that is, one board punching down and one board punching up. Although this type of double punch loom is better than unidirectional punching, it has the disadvantage that all the down-punching is completed before the up-punching even starts. The up-punch and the down-punch are far from symmetrical. In order to improve this situation the modern form of double-punch loom has been developed in which both boards penetrate through the same bed and stripper plates. The normal operation is for the boards to penetrate the fabric alternately, one from above and the other from below. To all intents and purposes the two boards are now symmetrical and this appears to give optimum needling. This type of loom can often be adjusted so that both sets of needles enter and leave the batt simultaneously. (Alternate rows of needles have to be taken out of both boards to prevent serious needle damage.) This is not found to be advantageous with long fibres (50 mm upwards) because there is quite a high chance that the same fibre may be pulled upwards by one needle and pushed downwards by another, leading to serious fibre breakage. However, the very short mineral fibres used for high temperature insulation are found to consolidate better using this form of simultaneous needling.

Needlefelts have a high breaking tenacity and also a high tear strength but the modulus is low and the recovery from extension is poor. For these last two reasons any needlefelt which is likely to be subjected to a load has to have some form of reinforcement to control the extension. Needled carpets, for instance, may be impregnated with a chemical binder that gives better dimensional stability and increases the resistance to wear. In other cases thermal bonding may be used for the same object. For heavy duty applications such as filter media and papermakers' felts, yarns are used, either spun yarns or filament yarns. In some cases with a cross-laid batt the threads may run only in the machine direction, but it is also common to use a woven fabric as the foundation and to build up the nonwoven on one or both sides. In both applications the presence of the woven fabric or base fabric reduces the efficiency by restricting the liquid flow; in a few cases 'baseless' fabrics, that is nonwovens without woven supports have been made, but there are still very many situations where a base fabric is essential.

Needlefelts are used widely in gas filtration media and in some wet filtration. The principal advantage is that the nonwoven is practically homogeneous in comparison with a woven fabric so that the whole area of a nonwoven filter can be used for filtration, whereas in a woven fabric the yarns effectively stop the flow, leaving only the spaces between the yarns for filtration. In papermakers' felts the same considerations apply, but in some cases the design of the felt has also to allow for the fact that the felt is acting as an enormous drive belt to drive some parts of the machine. In both gas filtration and papermakers' felts needlefelts hold virtually the whole market. Needlefelts are used in geotextiles, but in view of the low modulus their application is mainly in removing water rather than as reinforcement. If the water is flowing through the fabric this is termed filtration. For instance a simple drain may be formed by lining a trench with a geotextile, partly filling it with graded gravel, drawing the edges of the geotextile together and back-filling the trench as shown in Fig. 6.12. The geotextile will keep the drain open for many years by filtering out fine particles. Less frequently the geotextile is required for drainage, which means water movement in the plane of the fabric. Because of the inevitable contamination of the surface layers, together with the compression of the geotextile caused by the soil pressure, only a limited part of the fabric cross-section is actually available for drainage and more complicated compound structures are frequently used in preference.

Many makers of synthetic leather have taken the view that the structure should be similar to natural leather. In these cases the backing or foundation of the synthetic leather is a needlefelt. The method of production is to include heat-shrinkable fibres which are made to shrink after intense needling in order to make the felt even more dense. After shrinking the felt is impregnated using a binder



6.12 Simple drain using geotextiles.

that fills the voids in the felt but does not adhere to the fibres, otherwise the felt would become very stiff. The leather is then finished by coating the face side with one or two layers of suitable polymer. Needlefelts are also widely used in home and commercial carpeting; in many cases the carpet may have either a velour or a loop pile surface to improve the appearance. Both velour and loop pile are produced in a separate needling operation using special needles and a special bedplate in the needleloom. Similar materials in a lighter weight are used for car carpeting, headliners and other decorative features on cars.

6.13 Stitch bonding

The idea of stitch bonding was developed almost exclusively in Czechoslovakia, in the former East Germany and to some extent in Russia, though there was a brief development in Britain. The machines have a number of variants which are best discussed separately; many possible variants have been produced but only a limited number are discussed here for simplicity.

6.13.1 Batt bonded by threads

Stitch bonding uses mainly cross-laid and air-laid batts. The batt is taken into a modification of a warp knitting machine (see Chapter 5) and passes between the needles and the guide bar(s). The needles are strengthened and are specially designed to penetrate the batt on each cycle of the machine. The needles are of the compound type having a tongue controlled by a separate bar. After the needles pass through the batt the needle hooks open and the guide bar laps thread into the hooks of the needles. As the needles withdraw again the needle hooks are closed by the tongues, the old loops knock over the needles and new loops are formed. In this way a form of warp knitting action is carried out with the overlaps on one side of the batt and the underlaps on the other. Generally, as in most warp knitting, continuous filament yarns are used to avoid yarn breakages and stoppages on the machine. Two structures are normally knitted on these machines, pillar (or chain) stitch, or tricot. When knitting chain stitch the same guide laps round the same needle continuously, producing a large number of isolated chains of loops. When knitting tricot structure, the guide bar shogs one needle space to the left, then one to the right. Single-guide bar structure is called tricot, whereas the two-guide bar structure is often referred to as full tricot.

The nature of this fabric is very textile-like, soft and flexible. At one time it was widely used for curtaining but is now used as a backing fabric for lamination, as covering material for mattresses and beds and as the fabric in training shoes. In deciding whether to use pillar or tricot stitch, both have a similar strength in the machine direction, but in the cross direction the tricot stitch fabric is stronger, owing to the underlaps lying in that direction. A cross-laid web is already stronger in that direction so the advantage is relatively small. The abrasion resistance is the same on the loop or overlap side, but on the underlap side the tricot fabric has significantly better resistance owing to the longer underlaps. However, continuous filament yarn is very expensive relative to the price of the batt, so tricot fabric costs significantly more. The decision then becomes a purely financial one; is it worth paying more for the greater abrasion resistance?

6.13.2 Stitch bonding without threads

In this case the machine is basically the same as in the previous section, but the guide bar(s) are not used. The needle bar moves backwards and forwards as before, pushing the needles through the batt. The main difference is that the timing of the hook closing by the tongues is somewhat delayed, so that the hook of the needle picks up some of the fibre from the batt. These fibres are formed into a loop on the first cycle and on subsequent cycles the newly formed loops are pulled through the previous loops, just as in normal knitting. The final structure is felt-like on one side and like a knitted fabric on the other. The fabric can be used for insulation and as a decorative fabric.

6.13.3 Stitch bonding to produce a pile fabric

To form a pile fabric two guide bars are usually used, two types of warp yarns (pile yarn and sewing yarn) and also a set of pile sinkers, which are narrow strips of metal over which the pile yarn is passed and whose height determines the height of the pile. The pile yarn is not fed into the needle's hook so does not form a loop; it is held in place between the underlap of the sewing yarn and the batt itself. It is clear that this is the most efficient way to treat the pile yarn, since any pile yarn in a loop is effectively wasted. This structure has been used for making towelling with single-sided pile and also for making loop-pile carpeting in Eastern Europe. The structure has not been popular in the West owing to competition with double-sided terry towelling and tufted carpets. Equally it has not been used in technical textiles, but it could be a solution in waiting for the correct problem. Strangely a suitable problem has been proposed. Car seating usually has a polyester face with a foam backing, but this material cannot be recycled, because of the laminated foam. It has been suggested that a polyester nonwoven pile fabric could replace the foam and would be 100% recyclable.

6.13.4 Batt looped through a supporting structure

In this technique the needles pass through the supporting fabric and pick up as much fibre from the batt as possible. Special sinkers are used to push fibre into the needle's hook to increase this pick-up. The fibre pulled through the fabric forms a chain of loops, with loose fibre from the batt on the other surface of the fabric. The fabric is finished by raising, not as one might expect on the loose side of the fabric but instead the loops are raised because this gives a thicker pile. This structure was widely used in Eastern Europe, particularly for artificial fur, but in the West it never broke the competition from silver knitting, which gives a fabric with similar properties. The method could be used for making good quality insulating fabrics.

6.13.5 Laid yarns sewn together with binding threads

Two distinct types of fabric can be made using the same principle. The first is a simulated woven fabric in which the cross-direction yarns are laid many at a time in a process a bit like cross laying. The machine direction yarns, if any are used, are simply unwound into the machine. These two sets of yarns are sewn together using chain stitch if there are only cross-direction threads and tricot stitch if machine-direction threads are present, the underlaps holding the threads down. Although fabric can be made rapidly by this system this turns out to be a situation in which speed is not everything and in fact the system is not usually economically competitive with normal weaving. However, it has one great technical advantage; the machine and cross threads do not interlace but lie straight in the fabric. Consequently the initial modulus of this fabric is very high compared with a woven fabric, which can first extend by straightening out the crimp in the yarn. These fabrics are in demand for making fibre-reinforced plastic using continuous filament glass and similar high modulus fibres or filaments.

The alternative system makes a multidirectional fabric. Again sets of yarns are cross-laid but in this case not in the cross direction but at, say, 45° or 60° to the cross direction. Two sets of yarns at, say, +45° and –45° to the cross direction plus another layer of yarns in the machine direction can be sewn together in the usual way. Again high modulus yarns are used, with the advantage that the directional properties of the fabric can be designed to satisfy the stresses in the component being made.

6.14 Hydroentanglement

The process of hydroentanglement was invented as a means of producing an entanglement similar to that made by a needleloom, but using a lighter weight batt. A successful process was developed during the 1960s by Du Pont and was patented. However, Du Pont decided in the mid-1970s to dedicate the patents to the public domain, which resulted in a rush of new development work in the major industrial countries, Japan, USA, France, Germany and Britain.

As the name implies the process depends on jets of water working at very high pressures through jet orifices with very small diameters. A very fine jet of this sort is liable to break up into droplets, particularly if there is any turbulence in the water passing through the orifice. If droplets are formed the energy in the jet stream will still be roughly the same, but it will spread over a much larger area of batt so that the energy per unit area will be much less. Consequently the design of the jet to avoid turbulence and to produce a needle-like stream of water is critical. The jets are arranged in banks and the batt is passed continuously under the jets held up by a perforated screen which removes most of the water. Exactly what happens to the batt underneath the jets is not known, but it is clear that fibre ends become twisted together or entangled by the turbulence in the water after it has hit the batt. It is also known that the supporting screen is vital to the process; changing the screen with all other variables remaining constant will profoundly alter the fabric produced.

Although the machines have higher throughputs compared with most bonding systems, and particularly compared with a needleloom, they are still very expensive and require a lot of power, which is also expensive. The other considerable problem lies in supplying clean water to the jets at the correct pH and temperature. Large quantities of water are needed, so recycling is necessary, but the water picks up air bubbles, bits of fibre and fibre lubricant/fibre finish in passing through the process and it is necessary to remove everything before recycling. It is said that this filtration process is more difficult than running the rest of the machine.

Fabric uses include wipes, surgeons' gowns, disposable protective clothing and backing fabrics for coating. The wipes produced by hydroentanglement are guaranteed lint free, because it is argued that if a fibre is loose it will be washed away by the jetting process. It is interesting to note that the hydroentanglement process came into being as a process for entangling batts too light for a needleloom, but that the most recent developments are to use higher water pressures (400 bar) and to process heavier fabrics at the lower end of the needleloom range.

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