6 Yarn Formation Structure and Properties

6.1 SPINNING SYSTEMS

There is an extensive range of different spinning systems, not all of which are in wide commercial use; many are still experimental or, having reached the commercial stage, have been withdrawn from the market. A classification of the better known spinning systems is given Table 6.1, in which the various techniques are grouped according to five basic methods. In the first section of this chapter, we will consider the fundamental principles of these listed spinning systems. In the sections that follow, we will deal with the yarn structure and properties of only those that still have commercial significance. Often, two or more yarns are twisted together to improve yarn properties or to overcome subsequent processing difficulties in, for example, weaving and knitting. The operating principles of the more common plying systems will also be described in this section.

The conventional ring spinning technique is currently the most widely used, accounting for an estimated 90% of the world market for spinning machines. The remaining systems in Table 6.1 are often referred to as *unconventional spinning processes* and, of these, rotor spinning has the largest market share. The more knowledgeable reader will notice that mule and cap spinning have been omitted. Although in commercial use, these two processes are very dated traditional systems, limited to a very small market segment and well described elsewhere.[1,2]

Important aspects of any spinning system are the fiber types that can be spun, the count range, the economics of the process, and — very importantly — the suitability of the resulting yarn structure to a wide range of end uses. Except for the twistless-felting technique, all of the systems listed in Table 6.1 will spin man-made fibers, but because of processing difficulties and/or economic factors, the commercial spinning of 100% cotton yarns is mainly performed on ring and rotor spinning. Wool is principally ring spun, the main reason being that the yarn structure gives the desired fabric properties, although a number of unconventional systems are used to produce wool yarns. With regard to process economics, the number of stages required to prepare the raw material for spinning, the production speed, the package size, and the degree of automation are key factors in determining the cost per kilogram of yarn, i.e., the unit cost.

Figures 6.1 and 6.2 show that, although ring spinning has the widest spinnable count range, it has comparatively a very low production speed and therefore, even

TABLE 6.1
Classification of Spinning System

Spinning methods	Common feature	Technique	Type of twisting action during spinning	Type of yarn structure produced for fiber consolidation	Trade names
Ring spinning	Ring and traveler	Single strand twisting	Real	Twisted: S or Z	Various
		Double-strand ply twisting	Real	Twisted: S or Z	Sirospun/Duospun
OE spinning	Break in the fiber mass flow to the twist insertion zone	Rotor spinning	Real	Twisted: Z + wrapped	Various
		Friction spinning	Real	Twisted: Z + wrapped	Dref II
Self-twist spinning	Alternative S and Z folding twist	False twisting of two fibrous strands positioned to self-ply	False	S and Z twisted	Repco
Wrap spinning	Wrap of fibrous core by either (a) filament yarn	Alternating S and Z twist plus filament wrapping	False	S and Z + filament wrapped	Selfil
	(b) staple fibers	Hollow spindle wrapping	False	Wrap	Parafil
		Air-jet fasciated wrapping	False	Wrapped + twisted	(Dref III, MJS, Plyfil)
Twistless	Coherence of the yarn constituents achieved by adhesive bonding or felting	Water-based adhesive	False	Bonded	Twilo
		Resin-based	False	Bonded	Bobtex
		Liquid felting	Zero	Felted	Periloc

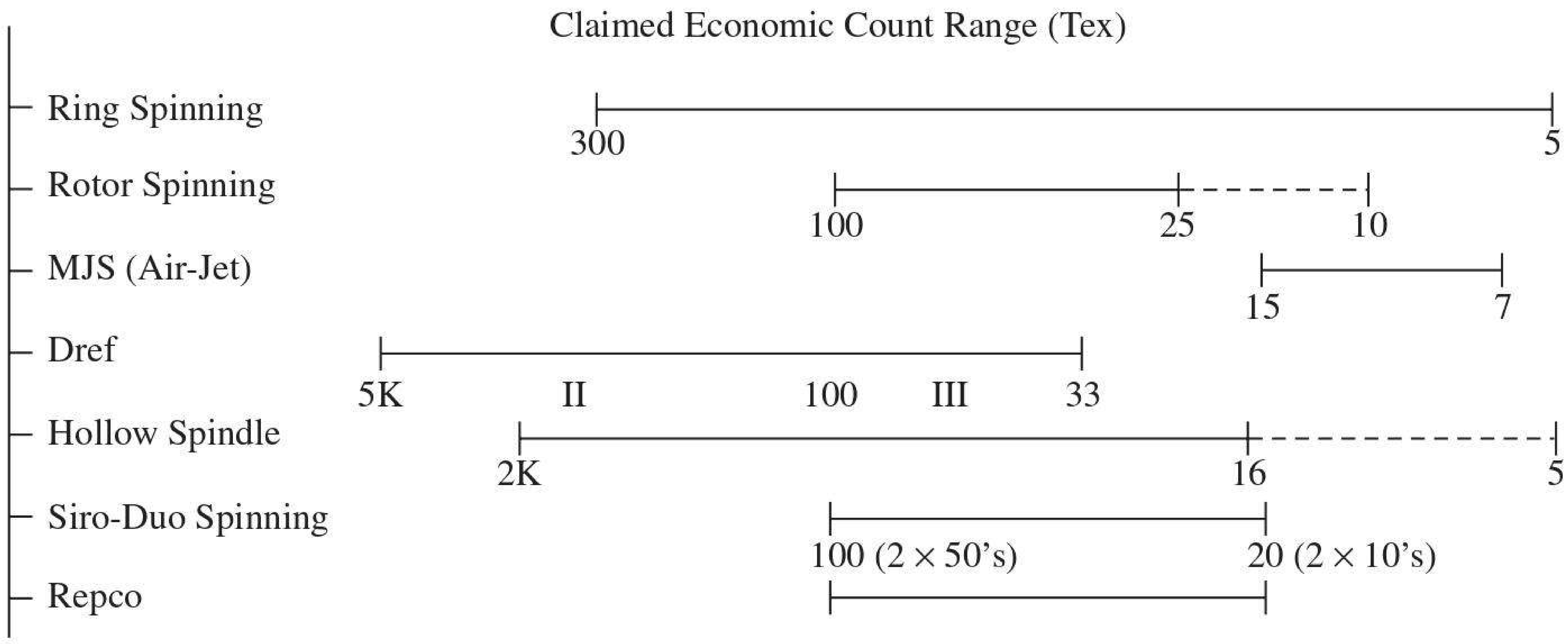


FIGURE 6.1 Economic count range of spinning systems.

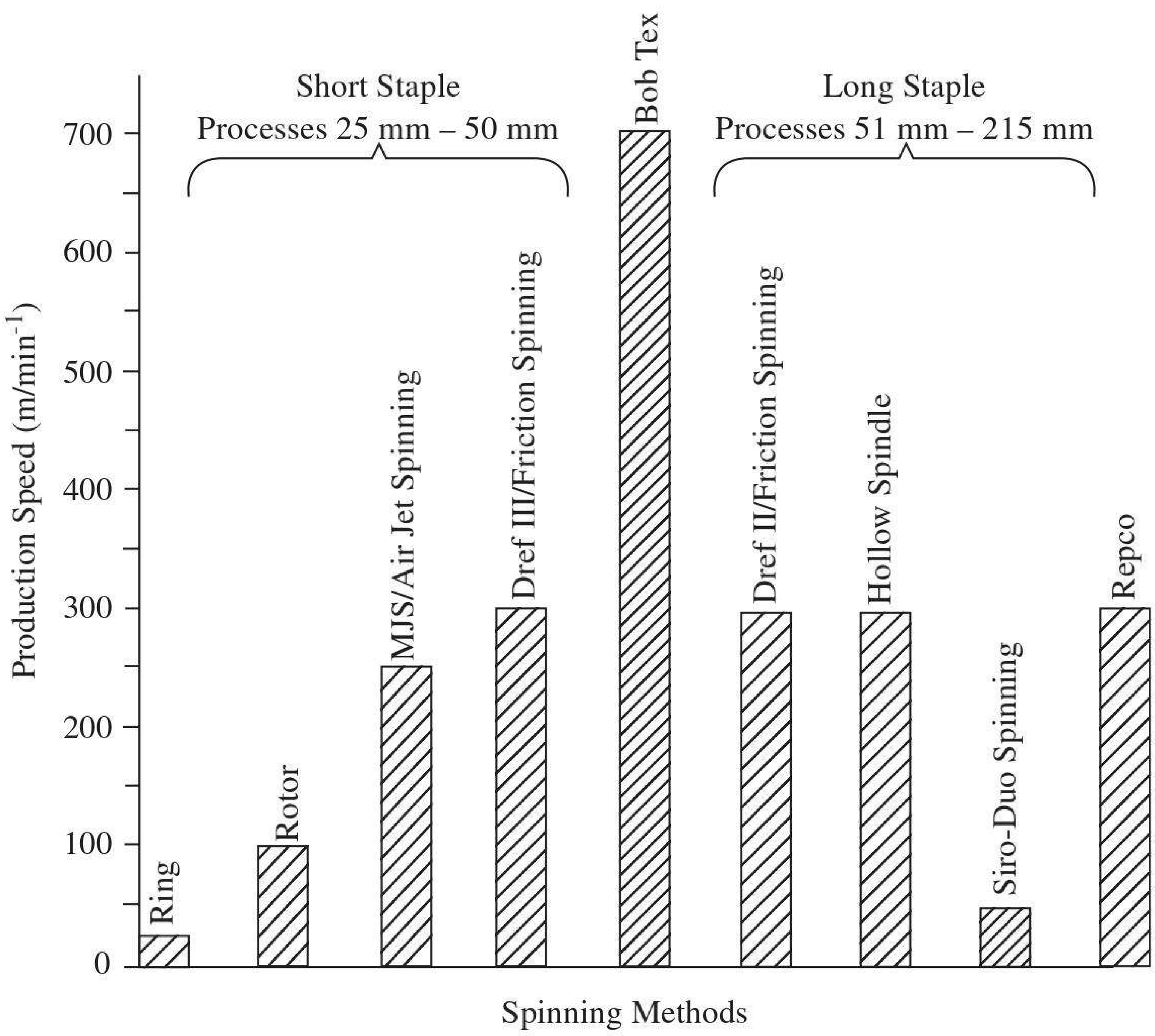
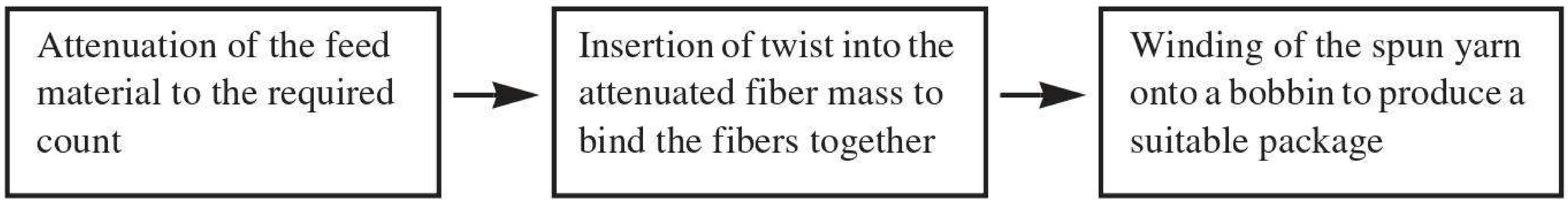


FIGURE 6.2 Production speeds of spinning systems.

with automation, does not always offer the best process economics. The key to its dominance of world markets is the suitability of the ring-spun yarn structure and properties to a wide range of fabric end uses.

Before explaining the operating principles of the listed spinning systems, it is useful to consider the technological equations applicable to all of them. All spinning systems have the three basic actions shown below for producing staple yarns:

Basic Actions in Spinning Yarns



It was explained in Chapter 1 that to spin a yarn from a given fiber type, certain specifications are required, such as the yarn count and, in particular, the level of twist. The concept of twist factor was also explained. These parameters are key variables in the technological equations that give us the production rate of any spinning system.

With respect to the yarn count, the required level of attenuation or total draft, D_T, of the system should allow for twist contraction as described in Chapter 1. To do so in practice, a sample of yarn is spun to the required twist level, the resulting increase in count is determined, and the total draft is readjusted to give the specified count. Similar to the drafting considerations in Chapters 1 and 2, the total draft is calculated as the ratio of the count of the feed material to the spinning machine and the count of the yarn. This value is then used to set the relative speeds of the drafting components of the machine.

$$D_T = \frac{\text{Sliver tex}}{\text{Yarn tex}} = \frac{\text{Delivery roller surface speed}(V_d)}{\text{Feed roller surface speed}(V_f)}$$

If N_I is the rotation speed of the twisting device used in spinning the yarn, then, as we saw in Chapter 1, the twist factor, TF, the yarn count, C_Y, the level of twist, t, and N_I have the relation

$$TF = tC_y^{1/2} \tag{6.1}$$

$$t = \frac{N_I}{V_d} \tag{6.2}$$

Assuming that a machine has N_M number of spinning positions, commonly referred to as the number of spindles, and an operating efficiency of ε%, then the production per spindle, P_S, in kg/h^{-1} is

$$P_S = \frac{V_d C_Y 60}{10^6} \tag{6.3}$$

and the production per machine, P_M (again, in kg/h^{-1}) is

$$P_M = \frac{V_d C_Y 60 N_M \varepsilon}{10^8}$$

Substituting for V_d (Equations 6.1 and 6.2),

$$P_M = \frac{N_I C_Y^{3/2} 60 N_M \varepsilon}{TF\ 10^8} \tag{6.4}$$

The above equations are applicable to any spinning system. However, with some systems, the rotational speed of the yarn cannot be readily determined. It then may be estimated from twist (or some similar parameter, e.g., twist angle) and delivery speed measurements using Equation 6.2.

6.1.1 Ring and Traveler Spinning Systems

Definition: The ring and traveler spinning method is a process that utilizes roller drafting for fiber mass attenuation and the motion of a guide, called a *traveler,* freely circulating around a ring to insert twist and simultaneously wind the formed yarn onto a bobbin.

The ring and traveler combination is effectively a twisting and winding mechanism.

6.1.1.1 Conventional Ring Spinning

Figure 6.3 illustrates a typical arrangement of the ring spinning system. The drafting system is a 3-over-3 apron-drafting unit. The fibrous material to be spun is fed to the drafting system, usually in the form of a roving. Similar to the roving frame, the back zone draft is small, on the order of 1.25, and the front zone draft is much higher, around 30 to 40. The aprons are used to control fibers as they pass through the front zone to the nip of the front rollers. Chapter 5 describes the principles of roller drafting. It is nevertheless important to note here that apron drafting systems are suitable for use only where the fiber length distribution of the material to be processed is not wide (i.e., not a significant amount of very short and very long fibers). When the standard distribution is higher, the material is more commonly drafted with a false-twister, which essentially replaces the drafting apron as depicted in Figure 6.4. This is typical of the ring spinning system for producing woolen yarns in which the slubbings from the woolen card are fed through the false-twister to the front rollers of the drafting system.

As Figure 6.3 shows, a yarn guide, called a *lappet,* is positioned below the front pair of drafting rollers. The ring, with the spindle located at its center, is situated below the lappet. Importantly, the lappet, the ring, and the spindle are coaxial. The traveler resembles a C-shaped metal clip, which is clipped onto the ring. A tubular-shaped bobbin is made to sheath the spindle so as to rotate with the spindle. The ring rail is geared to move up and down the length of the spindle; its purpose is to position the ring so that the yarn is wound onto the bobbin in successive layers, thereby building a full package, which is fractionally smaller in diameter than the ring. The yarn path is therefore from the nip of the front rollers of the drafting system, through the eye of the lappet and the loop of the traveler, and onto the bobbin.

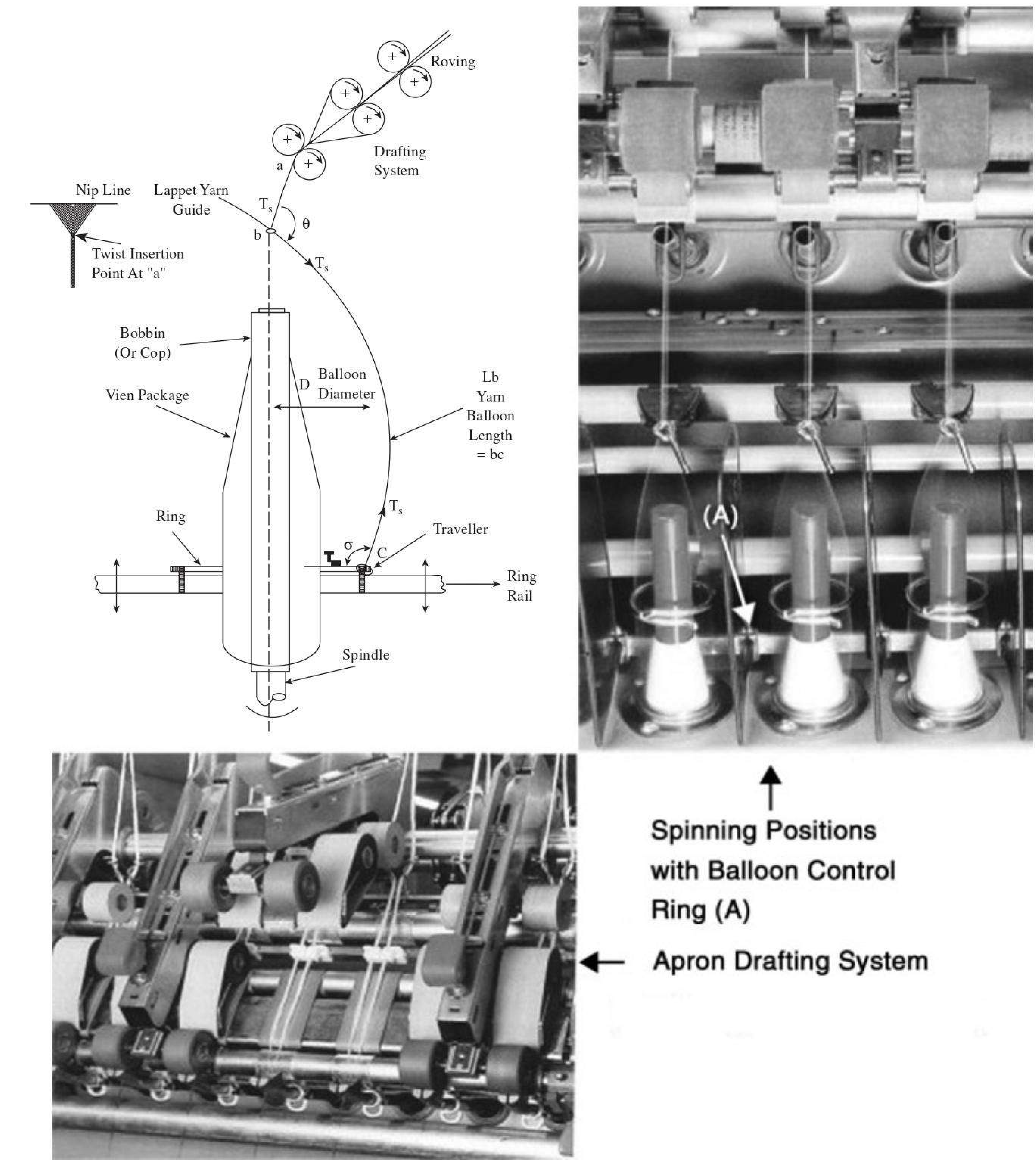


FIGURE 6.3 (See color insert following page 266.) Example of ring spinning system. (Courtesy of Spindelfabrik Suessen Ltd.)

Essentially, the drafting system reduces the roving or slubbing count to an appropriate value so that, on twisting, the drafted mass of the required yarn count is obtained. As the front rollers push the drafted material forward, twist torque propagates up the yarn length (i.e., from *c* to *a*) and twists the fibers together to form a new length of yarn. The tensions and twist torque cause the fibers to come together to form a triangular shape between the nip line of the front drafting rollers and the twist insertion point at *a*. This shape is called the *spinning triangle.* The differing tensions between the fibers in the spinning triangle are considered to be responsible for an intertwining of the fibers during twisting, termed migration. The degree of migration strongly influences the properties of the spun yarn, and this feature of the yarn will be discussed in the later section.

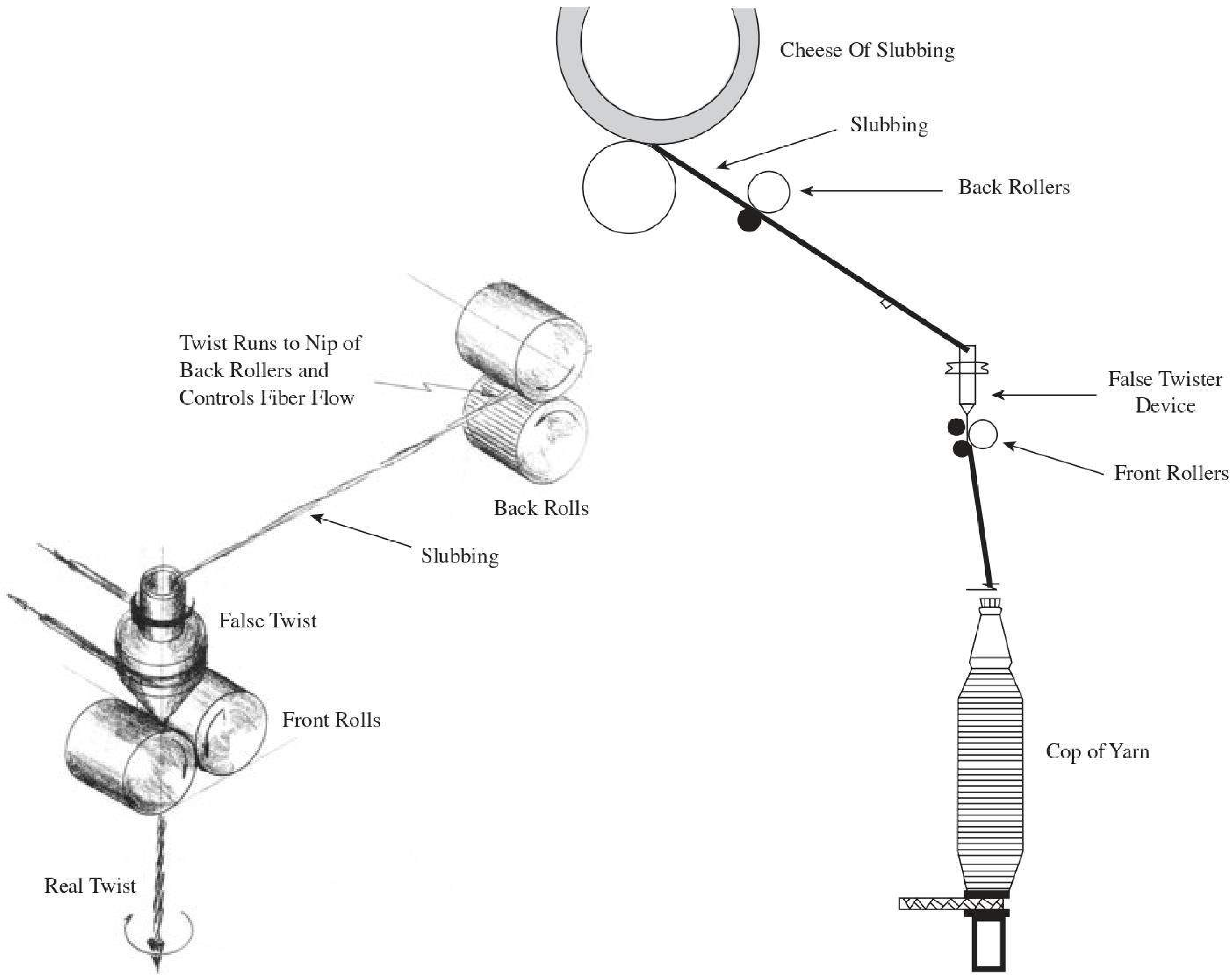


FIGURE 6.4 False-twist drafting of woolen slubbing. (Courtesy of Lord, P. R., *Economics, Science & Technology of Yarn Production,* North Carolina State University, 1981.)

6.1.1.2 Spinning Tensions

The bobbin rotates with the spindle and, because the yarn passes through the traveler and onto the bobbin, the traveler will be pulled around the ring and the yarn pulled through the traveler and wound onto the bobbin. As the traveler circulates the ring, it carries with it the yarn length, L_b (= bc), extending from the lappet to the traveler. While L_b circulates the ring, the circular motion causes it to arc outward away from the bobbin. Air drag and the inertia of L_b result in the arc length having a slight spiral as it circulates with the traveler (see Chapter 8). The rotational speed of the spindle can be up to 25,000 rpm. The three-dimensional visual impression given by the circular motion of L_b is of an inflated balloon, termed the *spinning balloon* or *yarn balloon.* Hence, L_b is called the *balloon length, H* is the balloon height (the vertical distance from the plane of the ring to the plane of the lappet), and D is the balloon diameter. The forces generated by the motion of the traveler and the pulling of the yarn through the traveler result in yarn tensions that govern the actual shape of the spinning balloon. Chapter 8 discusses in more detail yarn tensions and spinning balloons in relation to the physical parameters of spinning.

The tensions generated in the yarn are indicated in Figure 6.3 and are related according to the following equations:

$$T_O = T_S\, e^{K\theta} \tag{6.5}$$

$$T_W = T_R\, e^{P\alpha} \tag{6.6}$$

where T_S = the spinning tension
T_O, T_R = the tensions in the balloon length at the lappet guide and at the ring and traveler, respectively
T_W = the winding tension
K = the yarn-lappet coefficient of friction
θ and α = the angles shown in the figure
P = yarn-traveler coefficient of friction

T_O and T_R are related by (see Chapter 8)

$$T_O = T_R + mR^2\omega^2 \tag{6.7}$$

where m = mass per unit length

These tensions are important to twist insertion and the winding of the yarn onto the bobbin, and also to end breaks during spinning.

Consider first the winding action. As the traveler is pulled around the ring, the centrifugal force, C, on the traveler will lead to a friction drag, F, where

$$F = \mu\, C \tag{6.8}$$

$$C = MR_R\omega^2 \tag{6.9}$$

where M = traveler mass
R_R = ring radius
ω = angular velocity of the traveler (= $2\pi\, N_t$)

The yarn must be wound onto the bobbin at the same linear speed, V_F, as the front drafting rollers are delivering fibers to be twisted. This means that F must be sufficient to make the traveler's rotational speed lag that of the spindle. Hence, if D_B is the bobbin diameter, then

$$N_s - N_t = \frac{V_F}{\pi D_B} \tag{6.10}$$

where N_s = spindle speed (rpm)
N_t = traveler speed (rpm)

The wind-up speed is therefore the difference between the spindle and traveler speed. It is evident that, as the bobbin diameter increases with the buildup of the yarn, the traveler speed increases. The traveler speed will also change with the movement of the ring rail to form successive yarn layers on the bobbin. The common way of layering the yarn on the bobbin is known as a *cop build* in which each layer is wound in a conical form onto the package. The top of the cone is called the *nose* and the bottom the *shoulder*. In practice, it is found that the conical shape gives easy unwinding of the yarn without interference between layers, as the yarn length is pulled from the nose over the end of the bobbin. To make a cop build, the ring rail cycles up and down over a short length of the bobbin, with a slow upward and a fast downward motion. This increases the size of the shoulder more quickly than the nose. This cycling action of the ring rail progresses up the bobbin length in steps, each step taken when the shoulder size reaches almost the ring diameter.

6.1.1.3 Twist Insertion and Bobbin Winding

Let us consider now the action of twist insertion. From the definition, it is clear that one revolution of the traveler around the ring inserts one turn of twist into the forming yarn. However, for a fuller understanding of the twist insertion, we need to consider where the twist originates, the twist propagation, and twist variation caused by the cop build action.

Imagine two yarns of contrasting colors passed through the nip of the front drafting rollers and threaded along the yarn path to the bobbin. With the front drafting rollers and the ring rail stationary, and only the spindle driven, using high-speed photography, we would see that, within the first few rotations of the traveler, the twisting of the two yarns together originates in the balloon length between the lappet guide and the traveler.[4] The action of twisting the two yarns together is called *plying* or *doubling*, so no ply twist would be seen in the length between the traveler and the spindle or between the lappet guide and the front drafting rollers. It should be clear from Equation 6.10 that no yarn would be wound onto the bobbin and that the rotational speed of the traveler would be equal to the spindle speed.

If the above experiment is repeated, but this time with the front drafting rollers and the ring rail operating, then the following would be observed. The initial length wound onto the bobbin will be of the two yarns in parallel and not twisted together. As above, the ply twist originates in the balloon length and, as it builds up in the balloon length, it propagates toward the delivery rollers. The frictional resistance at the lappet opposes the twist torque propagation, reducing the amount of twist passing the guide. The forces acting at the point of contact of the yarn and traveler prevent the twist torque propagating past the traveler toward the bobbin. However, as sections of the yarn leave the region of the balloon length and are pulled through the traveler and wound onto the bobbin, they retain the nominal twist given by Equation 6.2. Hence, under steady running conditions, the twist level in the balloon length will be greater than in the length above the lappet and slightly larger than in the length wound onto the bobbin.

The up-and-down movement of the ring rail gives a cyclic change in the balloon length during spinning. The length is shortest when the ring rail forms the nose of the cop build and longest at the shoulder. As the ring rail moves from the shoulder to the nose, the difference in length has to be quickly wound onto the bobbin. The velocity, V_R, of the ring rail should be therefore included in Equation 6.10.

Hence,

$$N_s - N_t = [V_F - V_R]/\pi\, D_B \tag{6.11}$$

when the ring rail moves up toward the nose of the cop, and

$$N_s - N_t = [V_F + V_R]/\pi\, D_B \tag{6.12}$$

when moving downward toward the shoulder. It is evident then that N_t will vary cyclically with the movement of the ring rail. The increase in the bobbin diameter as the yarn is wound onto the bobbin will increase N_t, and this will be superimposed on the ring rail effect. Clearly, then, there will be some variation in the twist per unit length along the yarn length wound onto a bobbin. In practice, the variation is small and often falls within the random variation of measurements. Furthermore, the difference between N_s and N_t is also small, and therefore, for practical purposes, N_s is used in calculating the nominal or machine twist.

From the above discussion, it should be evident to the reader that the size of the ring diameter limits the diameter of the yarn package that can be built in ring spinning. Package size is an important factor in machine efficiency, since each time a package is changed, the spinning process is disrupted, adding to the stoppage or downtime of the spindles. In modern high-speed weaving (i.e., shuttle-less looms) and knitting processes, yarn package sizes of approximately 2.5 to 3 kg are required; therefore, the yarn packages from ring and traveler processes have to be rewound to make larger packages. Chapter 7 describes the principles involved in the rewinding of spun yarns. However, here, it is important to point out that, when many ring-spun yarn packages are involved in making a full rewound package for subsequent processes, the quality of the fabric can be affected. This is because yarns from different spindles on a machine may vary in properties, owing to small differences in the machine elements from one spinning position to another. More detrimentally, there unknowingly may be a few incorrectly functioning spinning positions, i.e., *rogue spindles.* When the yarns from the different spindles are pieced together, they provide a continuous length on a large rewound package, and the variations in this continual length will eventually be incorporated into the fabric. If yarn from the rogue spindle is part of the pieced length, it may lead to a degrading fault in fabric. The larger the ring-yarn packages, the fewer for rewinding onto larger packages. There is also an advantage for the rewinding process, as there would be few piecings and less stoppage time to replace empty ring bobbins with full ones.

Increasing the ring diameter to produce larger cops has its limitations and disadvantages. We can see from Equations 6.8 and 6.9 that the frictional drag of the ring on the traveler increases with the square of the rotational speed of the traveler and with increased radius of the ring. Travelers are available in various forms (i.e., shape, base material and weight), but steel travelers are probably the most widely used. The frictional drag by a steel ring on a steel traveler during spinning will generate heat at the ring-traveler interface. In spite of high average temperatures (up to 300°C) being reached, the surrounding air removes only 10 to 20% of the total frictional heat by cooling; most of the heat needs to be conducted away through the ring.[5] With the small contact area between the C-shaped traveler and ring, the heat can build up locally to much higher temperatures. Increased spindle speed and/or ring diameter, and thereby traveler speed, may then lead to a situation in which localized melting of the traveler occurs, and the traveler can no longer be effectively used for spinning. This is usually referred to as *traveler burn,* because, visually, the place on the traveler that makes contact with the ring becomes the blue-black color of heated metal.

In addition to the factor of traveler burn, there is the aspect of wear on both traveler and ring. The faster the traveler speed, the shorter the traveler life. The cautious spinner tends to quote a maximum practical speed for steel travelers to be within 35 to 40 m/s. However, research and development work by ring and traveler manufacturers, aimed at either reducing frictional wear and improving conduction of the heat generated at the ring-traveler interface, has resulted in new designs of the ring and traveler combination,[6] the use of carbon rich steels, lubricated rings (oil impregnated sintered),[7] and, in some cases, ceramic rings[8] and special finishes. Certain developments have involved slowly rotating the ring while retaining the relative speed of the traveler. This process is called *the living ring*.[9]

Claims have been made for maximum traveler speed of 50 to 60 m/s.[10,11] Figure 6.5 shows an example of an improved design, compared with the conventional ring-traveler geometry, and it can seen the greater surface contact would be beneficial.

We can reason from the above that increasing the yarn package size by using large diameter rings may mean reducing spindle speed and thereby production speed. Another means of increasing package size is by using a longer package length over which the yarn is wound. This is called the *lift*, and it inevitably means that the spinning position has a longer balloon height and balloon length. Two main factors, however, control the maximum balloon height: (1) balloon collapse caused by the

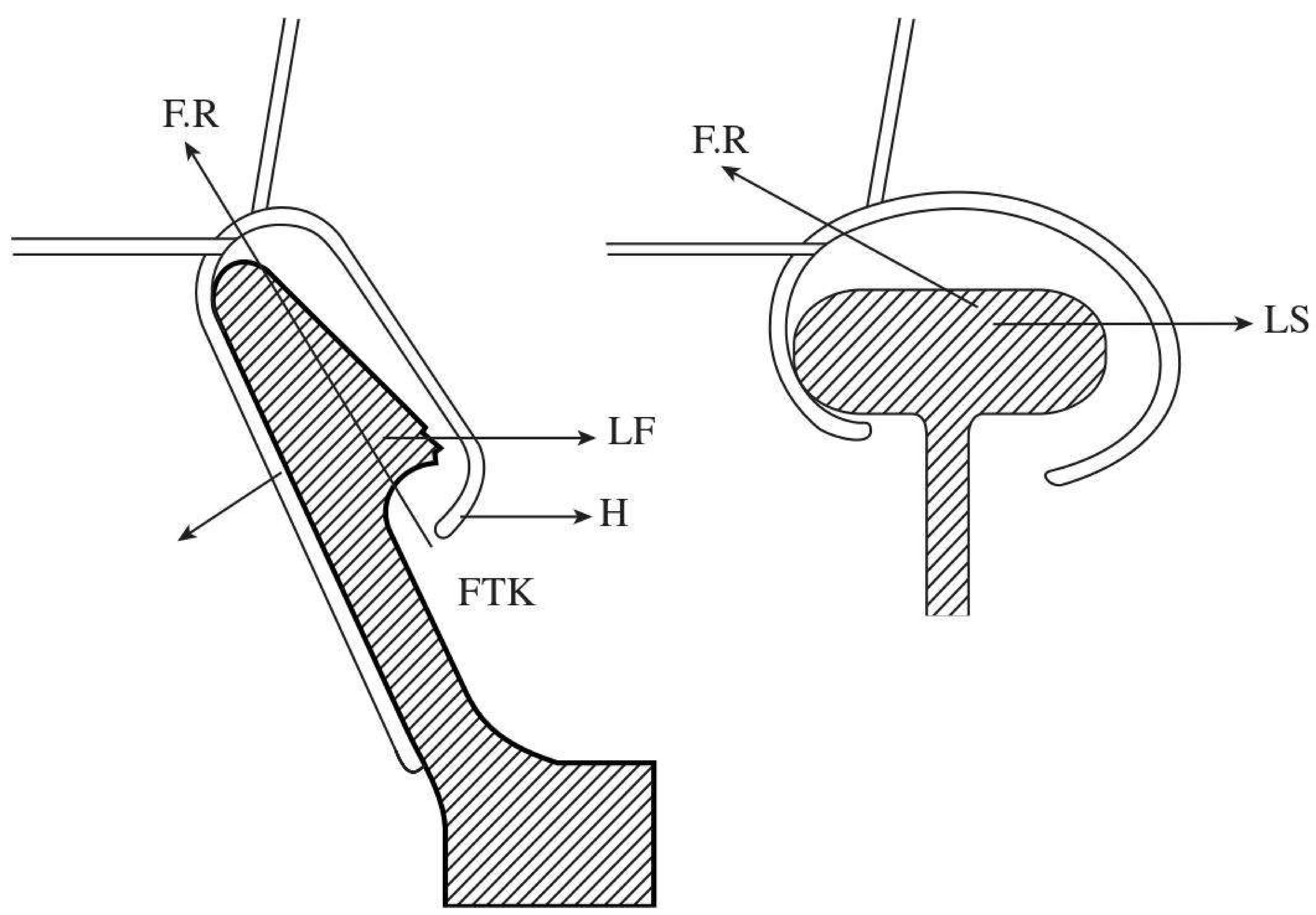


FIGURE 6.5 Orbital ring and traveler: conventional T-flange system. (Courtesy of Rieter Machine Works.)

formation of a node in the yarn balloon during spinning and (2) increased yarn tension and thereby increased interruptions of the spinning by yarn breaks (i.e., end breaks) resulting in a lower machine efficiency, ε%.

From the simple theory of a vibrating string, it can be shown that the balloon height, *H,* balloon tension, T_B, the spindle speed, N_S, and the yarn count, C_Y, are related by

$$H = C\left\{\frac{T_B}{(C_Y N_S^2)}\right\}^{\frac{1}{2}} \tag{6.13}$$

where C = the constant of proportionality

For a given yarn count and spindle speed, there must be a minimum balloon tension below which the balloon length, L_b, has the tendency to form a nodal point between the lappet and the traveler, resulting in balloon collapses. If we therefore wish to increase the balloon height for a given count and spindle speed, the balloon tension must be increased. However, as was stated earlier, too high a tension could result in increased end breaks and low machine efficiency. Since the traveler is pulled around the ring circumference by the yarn, the drag of the traveler mass, *M*, influences the tension in the yarn. Also, if *H* is large, the required *M* could result in a spinning tension greater than the strength of the yarn being spun. To circumvent the use of too heavy a traveler, balloon control rings (see Figure 6.3) are used to prevent a nodal point from forming in the balloon profile (see Chapter 8). The lightest traveler mass, *M*, for a given balloon height, yarn count, and ring diameter D_R is given by

$$M = \frac{KH^2 C_Y}{D_R} \tag{6.14}$$

where K = the constant of proportionality

With medium to coarse count yarns, say 40 to 100 tex, building sizeable packages requires the use of a balloon control ring. For very coarse counts, such as in the area of carpet yarns, it becomes necessary to spin with a collapsed balloon in order to produce a useful size spinning package for rewinding. See Figure 6.6. As the figure shows, the yarn balloon length partially wraps around the spindle, but such coarse yarns have sufficient strength to overcome the frictional drag of the spindle without breaking. The frictional contact with the spindle will resist the twist propagation toward the front drafting rollers, this is additional to the effect of the lappet. A false-twisting device fitted on the end of the spindle is therefore used to prevent spinning beaks because of low twist reaching the spinning triangle.

6.1.1.3.1 Spinning End Breaks

The weakest part of a forming yarn will be at the point of twist insertion. In ring spinning, this is the spinning triangle, just below the front drafting rollers (see Figure 6.3). During ring spinning, most end breakages will occur here. Three factors are

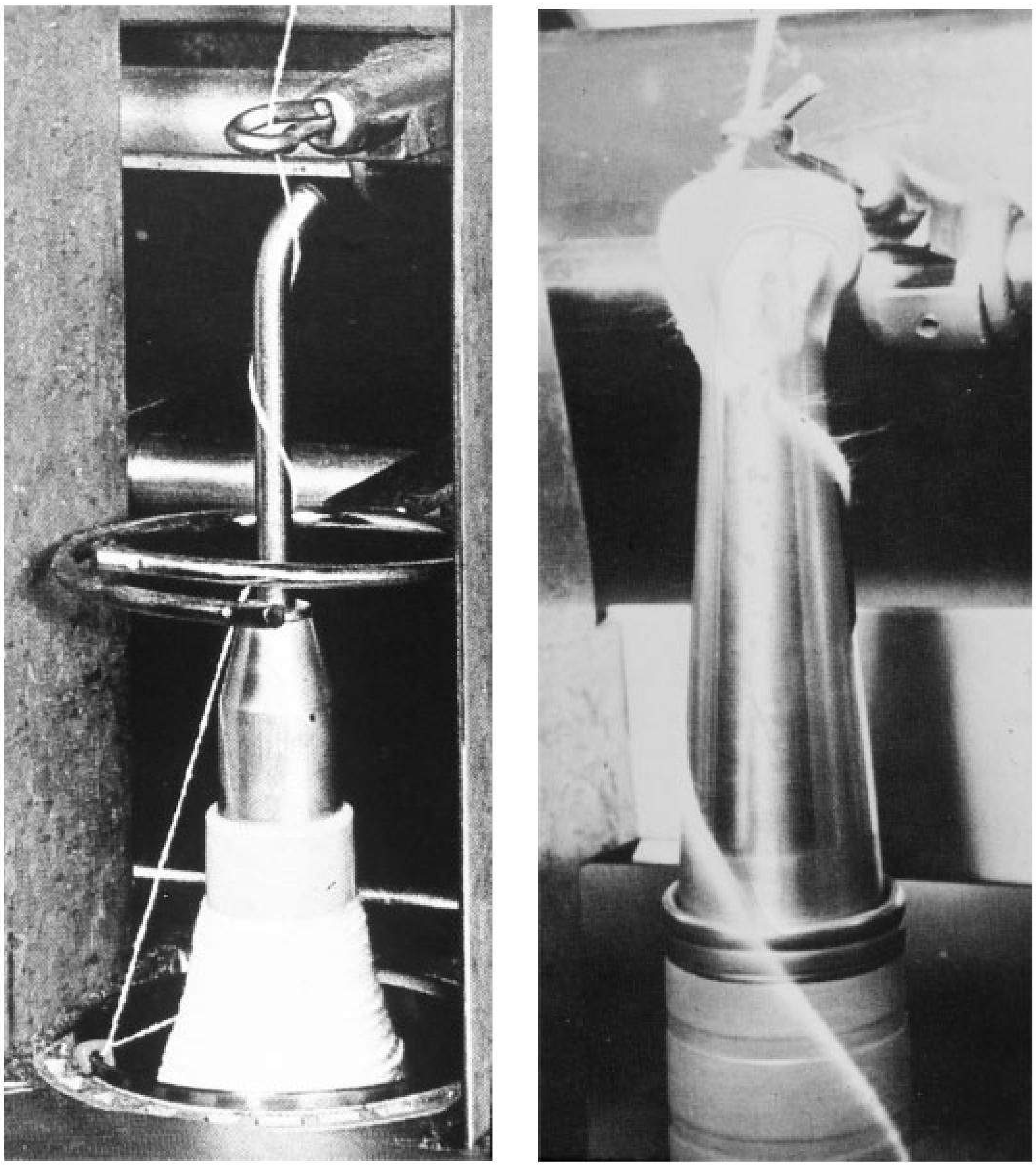


FIGURE 6.6 Examples of collapse balloon spinning. (Courtesy of Rieter Machine Works Ltd.)

therefore of importance: (1) the number of fibers in the triangle and the variation of this number, (2) the propagation of twist to the apex of the triangle, and (3) the mean tension and tension fluctuation.

Clearly, the greater the number of fibers in the cross section of the forming yarn, the stronger the yarn will be to withstand the spinning tension and tension fluctuations, provided that the mean spinning tension is kept well below the breaking load of the yarn (typically 30% below mean yarn strength). End breakage problems will arise when the number of fibers in the cross section of the fiber ribbon varies significantly and/or the peak value of tension fluctuation is too high.

The variation of the number of fibers in the cross section causes thin and thick places in the fiber ribbon. As these pass through the twist insertion point at the apex of the spinning triangle, the thin places are more easily twisted than thick places; thin parts of the ribbon will tend to have more twist than thicker parts. A very thin part of the ribbon will become over twisted and weak (see), and this will make the yarn susceptible to peak tension fluctuations.

From Equation 6.5, it is evident that the friction μ and the angle θ are important factors to the mean spinning tension, T_S, and the fluctuation of this tension. It can be seen from Figure 6.3 that θ will vary as the balloon length, *H*, rotates with the traveler. The spinning geometry therefore must ensure that fluctuation in T_S is kept small.

T_S is also dependent on the winding tension. Consequently, it is directly proportional to the mass of the traveler and inversely proportional to the bobbin radius; the spinning tension is usually high at the start winding and decreases as the package builds up. The appropriate traveler mass must be used in accordance with the yarn count (i.e., number of fiber in the yarn cross section), and the bobbin radius must not be smaller than 40% the ring radius (see Chapter 8).

6.1.1.4 Compact Spinning and Solo Spinning

These two systems are essentially modifications to the conventional ring spinning process with the aim of altering the geometry of the spinning triangle (see Figure 6.7) so as to improve the structure of the ring-spun yarn by more effective binding-in of surface fibers into the body of the yarn. This reduces yarn hairiness, and in the case of Solo spinning, makes single worsted/semi-worsted yarns suitable for use as warps in weaving and therefore dispensing with ply twisting.

As the name implies, with compact spinning (also called *condensed spinning*), the fibers leaving the front drafting roller nip are tightly compacted, making any

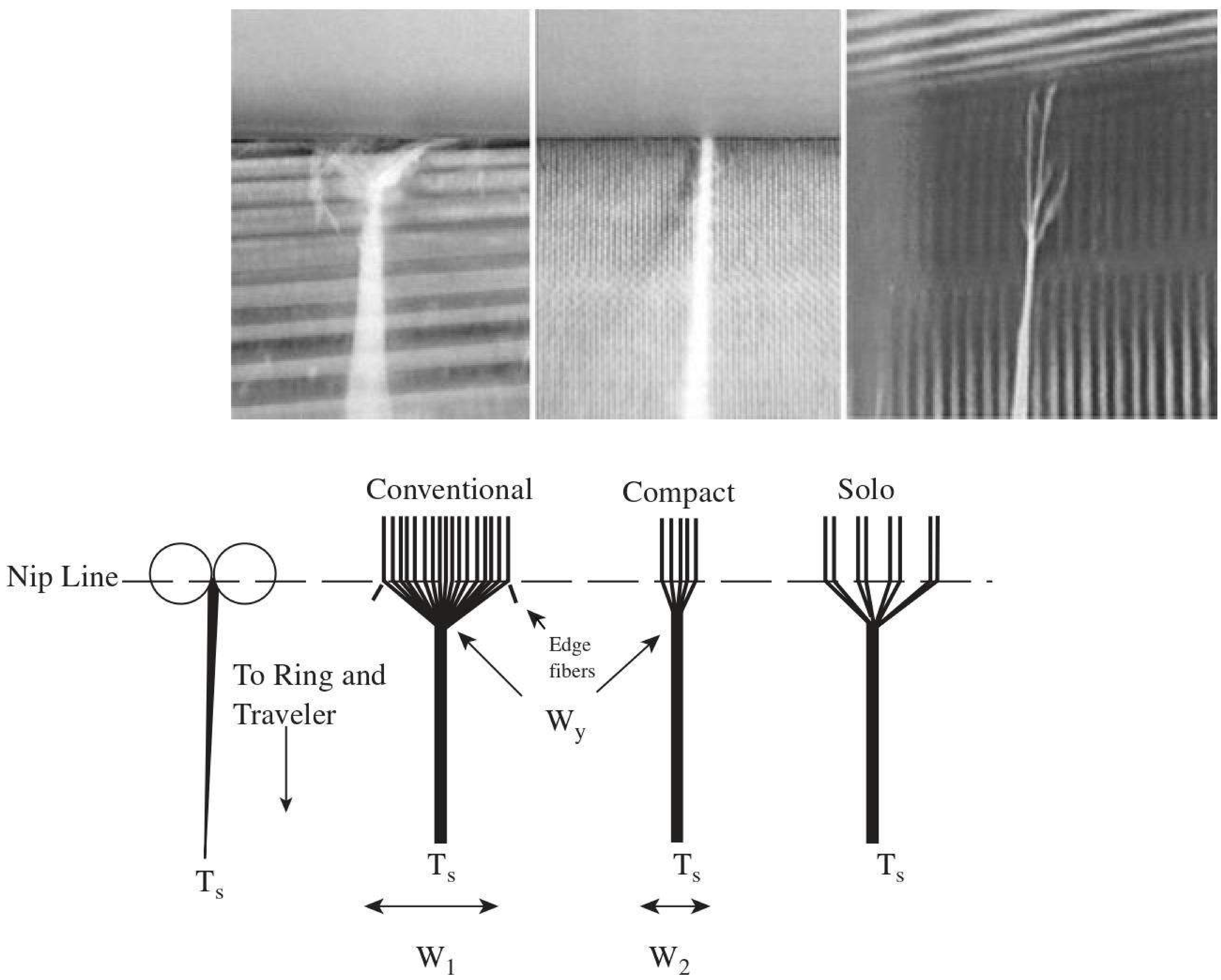


FIGURE 6.7 Compact and Solo spinning. (Courtesy of Rieter Machine Works and Prins, M., Lamb, P., and Finn, N., Solospun: The long staple weavable singles yarn, *Proc. Textile Institute 61st World Conference*, Melbourne, Australia, April 2001, 1–13.)

sign of a spinning triangle at the twist insertion point virtually imperceptible. The importance of compaction can be explained with reference to Figure 6.7. In the conventional system, the fibers are fed at width W_1 into the zone of twist insertion. This width is the result of the attenuation by roller drafting and is dependent on such factors as the count of the in put material to the drafting system, i.e., of sliver or roving, the twist level in the roving feed, and the level of draft. The first two factors govern the width of the material fed into the drafting system, and W_1 is directly proportional to this width. The level of drafting has a strong effect in that the higher the draft, the wider W_1.[13] The acuity of angle of the spinning triangle in the twist insertion zone is directly proportional to W_1, twist level, and the spinning tension T_S, but it is inversely proportional the yarn count. That is to say, these factors govern the difference between W_1 and the yarn diameter, W_Y, at the apex of the spinning triangle. Because of this difference, the leading ends of fibers at the edges of the ribbon are not adequately controlled and twisted into the yarn structure. The result is that these fibers either have a substantial part of their length projecting from yarn surface as hairs, and thereby contributing little to the yarn strength, or they escape twisting all together as fly waste. In Chapter 1, we saw that yarn hairiness can be a problem in downstream processes and to fabric appearance.

Reducing W_1 to W_2 greatly improves the control and twisting into the yarn structure of the edge fibers. It should also be noted that, with the problem of incorporating edge fibers into the forming yarn and the resistance to twist propagation from the yarn balloon zone, the strength at the apex of the spinning triangle is generally only one-third of the yarn strength. This makes the spinning triangle a potential weak spot at which breaks occur during spinning. The reason is that the tension induced into fibers by the spinning tension is very small at the center of the spinning triangle as compared with at the edges. Therefore, when spinning fine yarns or yarns with low twist levels, the loss or the poor incorporation into the yarn of edge fibers means insufficient strength to withstand the spinning tension, and breaks occur. By greatly narrowing the width of the spinning triangle, compact spinning should improve both spinning efficiency and the structure and properties of ring-spun yarn. The structure-property relation of yarns is discussed in Section 6.2.

In Solo spinning, the drafted ribbon, instead of being compacted, is divided into sub-ribbons or strands that form the spinning triangle. At the apex of the triangle, the strands are twisted together, similar to plying of several yarns. This confers better integration of the edge fibers as fibers are trapped within and between strands.

Table 6.2 lists the basic features of the four techniques currently used to compact the spinning triangle. All utilize air suction and are essentially either a modification or an attachment to the front of a conventional type drafting system.

With the ComforSpin process (Figure 6.8), a perforated drum (A) replaces the conventional grooved bottom-front roller of a 3-over-3, double-apron (DA) drafting unit. A second top-front roller (C) makes a second nip line with the perforated drum, below which the compacted spinning triangle is formed. The nip line of the front drafting zone is made by the contact of the top-front roller (B) with the drum, enabling the fiber mass to be attenuated in the normal way, producing ribbon width

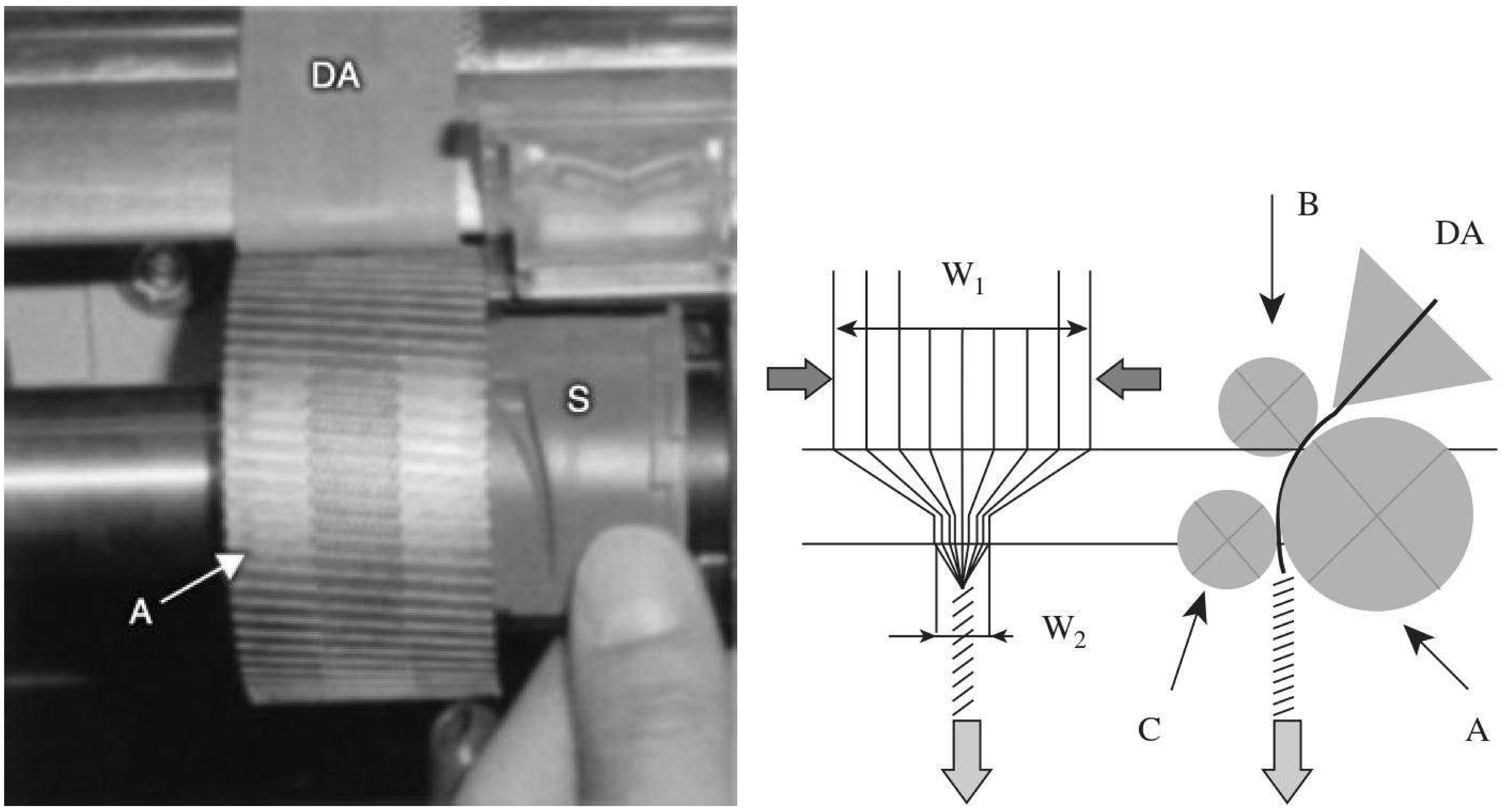


FIGURE 6.8 ComforSpin compacting system. (Courtesy of Stalder, H., and Rusch, A., Successful compact spinning process, *Int. Text. Bull.,* 1, 42–43, 2002.)

TABLE 6.2
The Compacting Systems in Ring Spinning

Manufacturer	Trade names	Basic features
Rieter Machine Works Ltd.	Com4Spin or ComforSpin	4-over-3 double apron drafting system with perforated bottom front roller and two top rollers; drafted ribbon compacted by air suction through bottom front roller
Spindelfabrik Suessen	EliTe	3-over-3 double drafting system with addition roller and special lattice apron, {moving around slotted, air suction tube (*tubular profile*) for compaction of drafted ribbon
Zinser Textilmaschinen GmbH	Air-Com-Tex 700	4-over-4 double apron drafting system with perforated apron circulating around top front roller; drafted ribbon in front zone compacted by suction through perforated apron
Maschinen-und Anlagenbau Leisnig GmbH	P4	4-over-4 double apron drafting system with perforated apron circulating around bottom front rollers; drafted ribbon in front zone compacted by suction through perforated apron

W_1 (see Figure 6.7). Suction is applied from within the drum through a slotted tubular screen (S) so that, as the perforated drum rotates, the screen enables a controlled airflow through the perforations passing over the slot to firmly hold the drafted fiber ribbon to the drum surface, leaving the nip line at roller B. The slot is specially shaped for the drafted ribbon to become compacted from width W_1 to W_2 by the time it reaches the final nip line at roller C. Beyond this, twist is inserted as in conventional ring spinning.

In the Elite system, the basic drafting rollers are retained with an additional unit fitted at the front (see Figure 6.9). The added unit consists of a transport apron of lattice weave — 3,00 pores/cm^2, which passes closely over the surface of a specially shaped, slotted, suction tube — *tubular profile.* Suction occurs at the interstices of the apron moving across the slot of the tubular profile. The plan view shows that the slot can be inclined at 30° to the center line of the apron, which thereby causes the motion of the apron to effect a rolling of the drafted ribbon as the ribbon is being compacted. This is useful when spinning uncombed cotton, i.e., *carded cotton,* as the very short fibers become more embedded in the final yarn. The additional top roller is geared to the top front drafting roller at a slightly higher surface speed. The additional top roller drives the transport apron via friction contact at the nip line. The drafted ribbon is therefore under tension, straightening fibers, during compaction.

The Air-Com-Tex 700 and CSM units use an alternative apron arrangement to the Elite unit for compaction, but, similar to the latter, compacting occurs after the front drafting rollers. The alternative arrangement is simply an added conventional

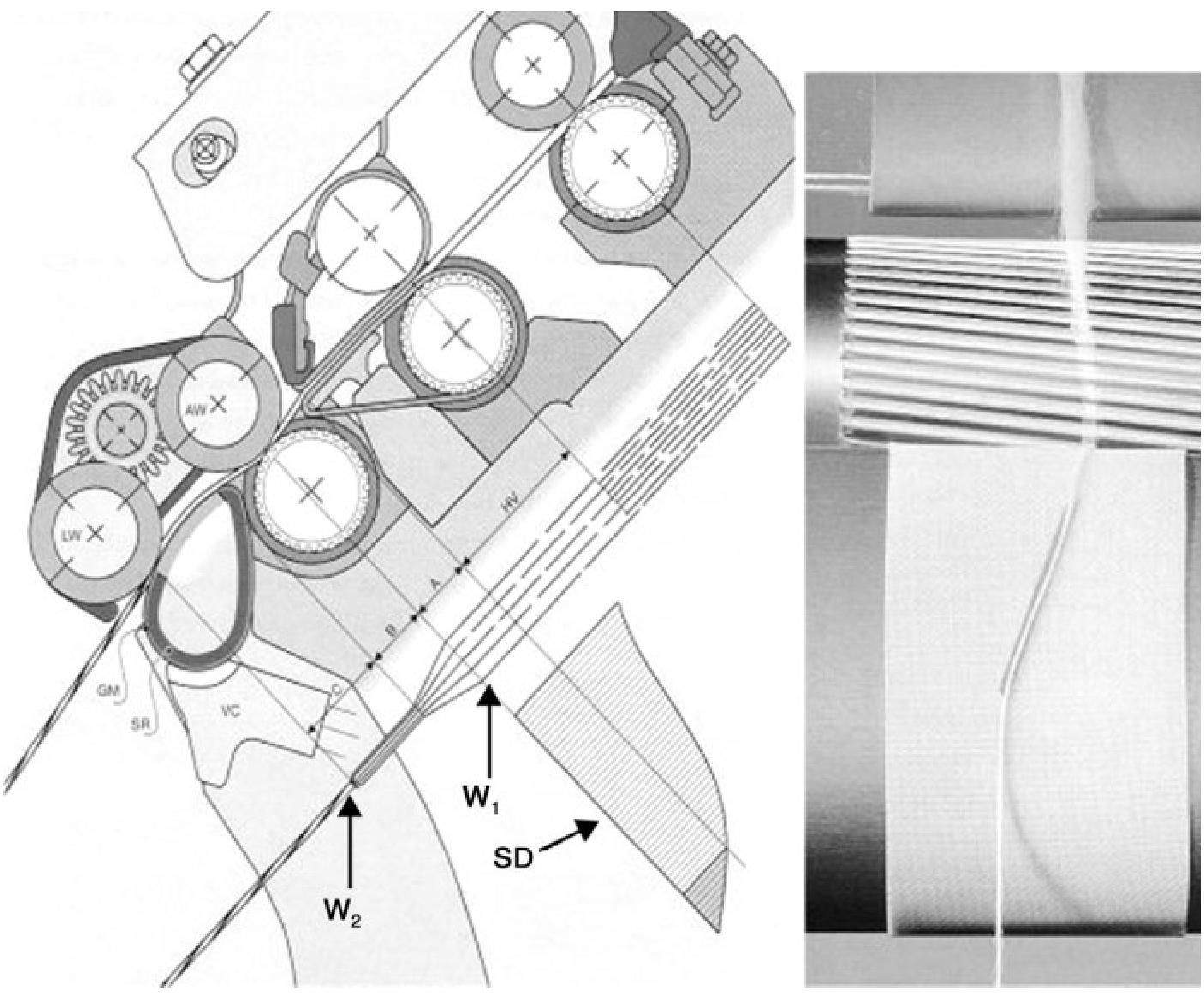


FIGURE 6.9 (See color insert.) The Elite compacting system; SD = staple diagram showing control of short fibers. (Courtesy of Spindelfabrik Suessen.)

apron-drafting zone with a line of perforations down the middle of the apron width through which suction is applied. The Air-Com-Tex 700 has only a perforated bottom apron, whereas the CSM has double aprons, of which only the top one is perforated.

Figure 6.10 shows the attachment at the front pair of drafting rollers used for the Solo spinning process. This consists of an addition roller (F), the Solospun roller, mounted via a bracket clip (C) onto the top front-drafting roller shaft (E) of the drafting arm. The Solospun roller has a series of circumferential grooves along its length, and it forms a nip line with the bottom front-drafting roller. It is the presence of the grooves in the Solospun roller that results in the drafted ribbon being divided into a number of strands that are twisted together to form the Solospun yarn.

6.1.1.5 Spun-Plied Spinning

A singles conventional ring-spun yarn of low twist will be hairy and have low abrasion resistance but, if woven or knitted, would give the fabric a soft feel. The above Solo and compact ring spinning systems produce singles yarns with much lower hairiness than conventional ring-spun yarns; however, these systems have yet to become widely used. To weave or knit low twisted conventional ring-spun yarns, it becomes necessary to trap the surface fibers by producing a twofold yarn. The conventional way of producing a twofold yarn is to ply together two single yarns using one of various techniques to be described later. There are economic advantages to be obtained if spinning and plying can be achieved as one process, and Figure 6.11 shows how this may be done.

Figure 6.11 shows two strands of roving passing through the same drafting unit but separated so that they emerge from the front drafting rollers a fixed distance apart. They then converge to a point at which the twist torque propagating from the

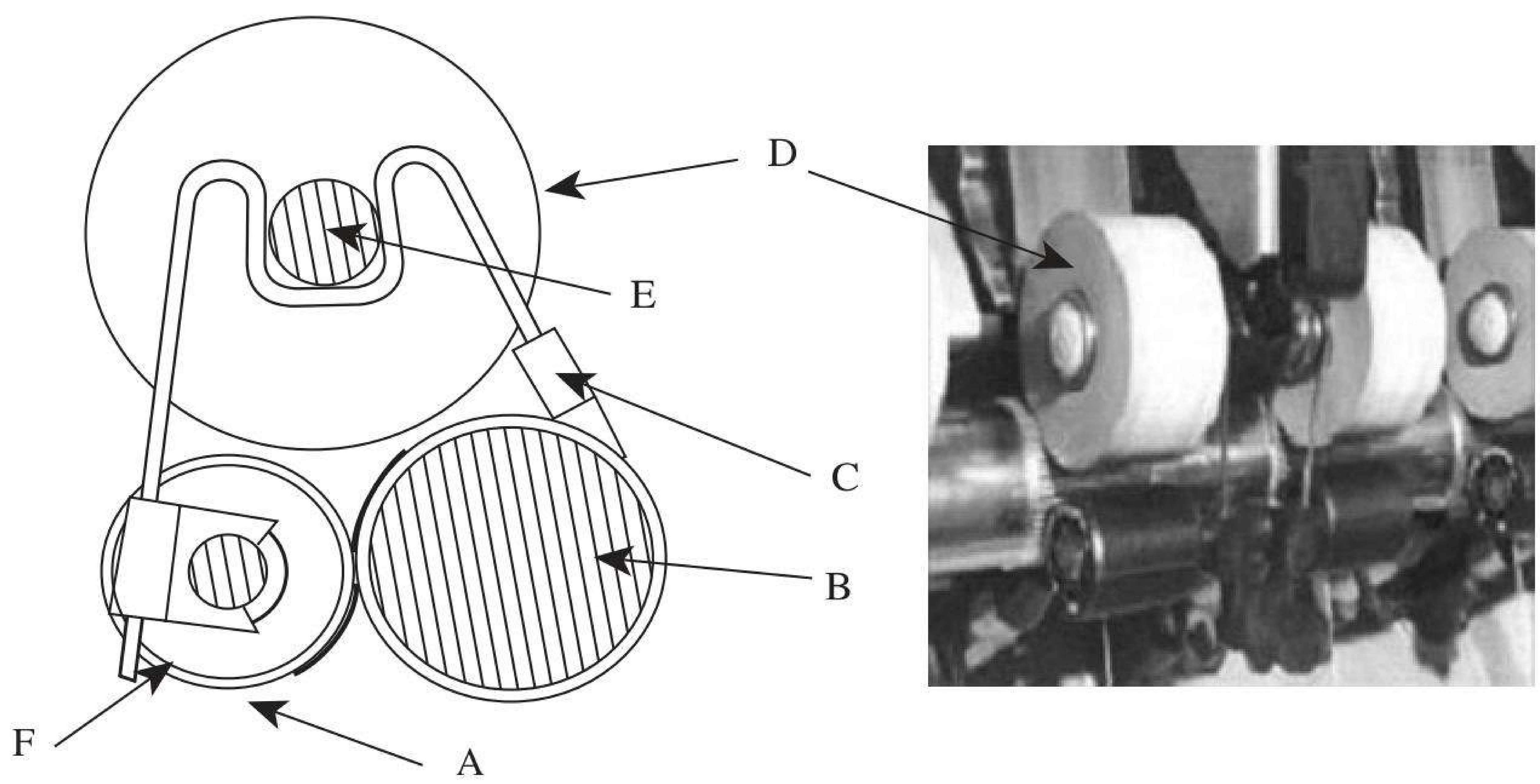


FIGURE 6.10 Solo spinning system: A = yarn, B = bottom front rollers, C = clip, D = top front roller, E = top roller shaft, F = Solo roller. (Courtesy of Prins, M., Lamb, P., and Finn, N., Solospun: The long staple weavable singles yarn, *Proc. Text. Inst. 61st World Conference*, Melbourne, Australia, April 2001, 1–13.)

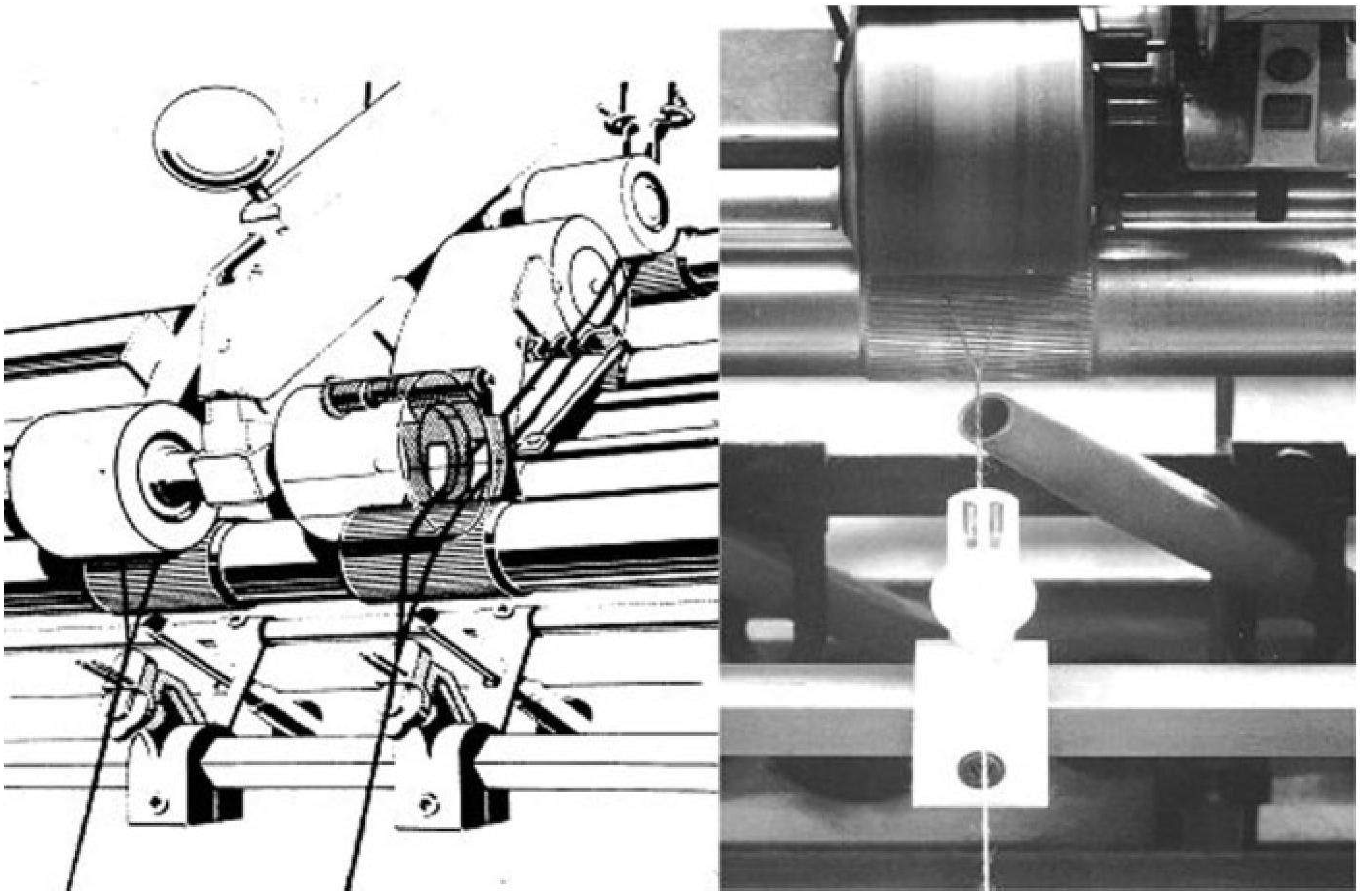


FIGURE 6.11 Sirospun system. (Courtesy of Morgan, W. V., Sirospun on long-staple spinning, I. W. S. *Text. Eng. and Process. Tech. Inf. Lett.,* 2, 1–10, 1981.)

yarn ballooning region inserts twist into the separate strands and plies the twisted strands together to form the twofold yarn. The strand twists propagate to form two very small, almost imperceptible, spinning triangles at the front drafting rollers. The strand and ply twists are of the same twist direction (see Figure 6.12). In case one of the strands breaks during spinning, the yarn guide below the front rollers has the function of breaking the remaining strand, and the suction tube (termed a *pneumafil*) is positioned near the front roller to collect the fibers that would still be issuing from the front rollers. Figure 6.13 shows a variation of the spun-plied arrangement, called *Duospun*,[14] where a specially designed suction nozzle replaces the yarn guide and pneumafil.

It is important to note that twist must be present in the individual strands if the surface fibers are to be suitably held in the twofold yarn structure. With only ply twist to hold fibers into the yarn structure, there will still be many fibers having much of their length projecting from the plied structure. With strand and ply twist, the fibers are more effectively trapped by every turn of ply twist, and for twist to be inserted into the strands, they must be spaced apart.

As fibers leave the front drafting rollers, they are incorporated into the strands in a similar way to conventional ring spinning. Therefore, unless the strand twist is high, there will be some fiber lengths projecting from the strands. The propagation of strand twist toward the nip of the front rollers means that a given projecting length will be rotating about the axis of the strand into which the remaining length of the fiber is twisted. Owing to the geometrical arrangement of the strands, as they converge, many of the projecting lengths will eventually strike the neighboring stand,

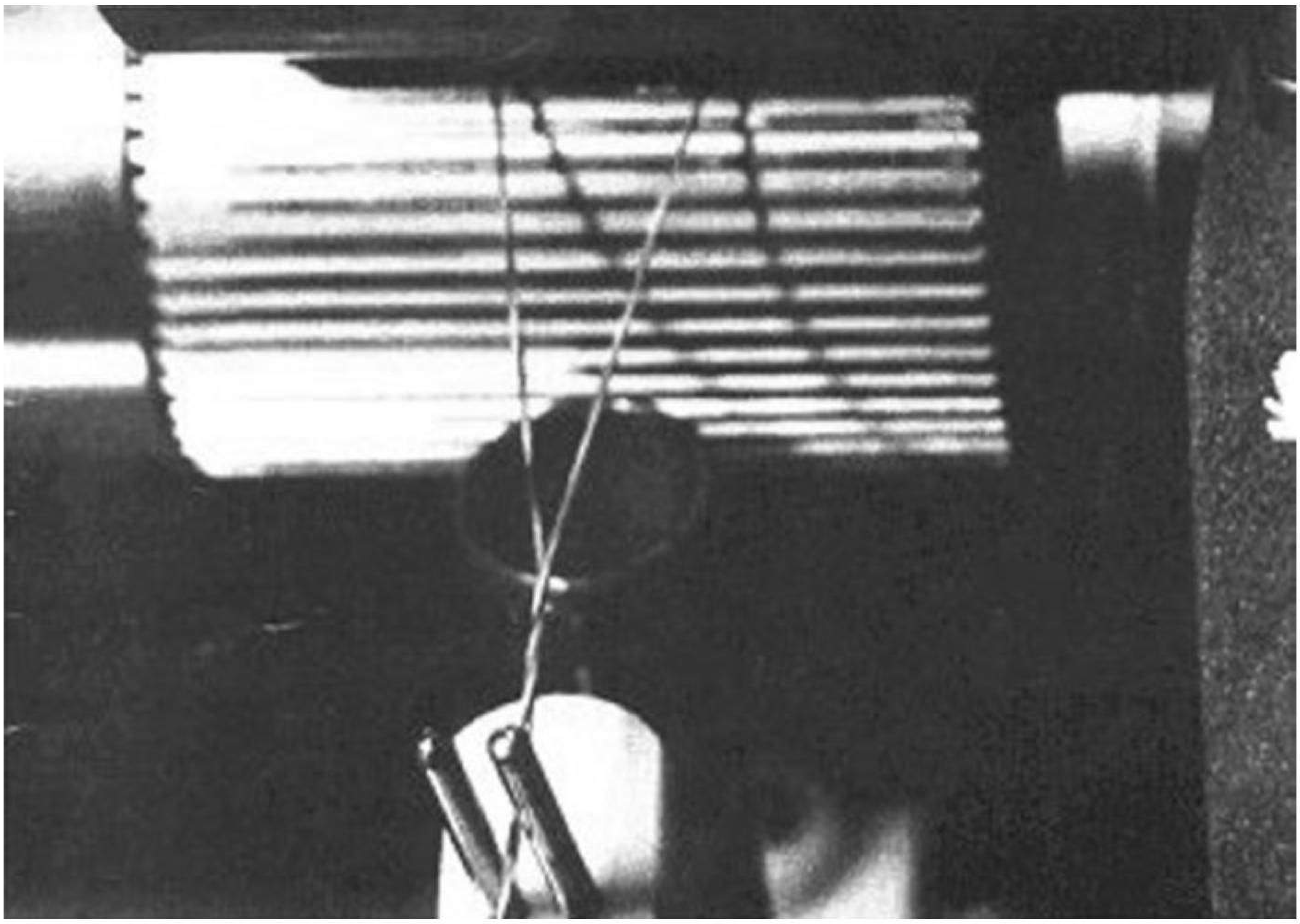


FIGURE 6.12 Strand and ply twist. (Courtesy of Zinser Ltd.)

which prevents them from rotating further. As the strands become plied, these fiber lengths are trapped between the two strands. This mechanism of trapping is called *yarn-formation trapping.* However, most surface fibers will have their lengths twisted into a strand prior to being trapped by the ply twist. This mode of trapping is called *strand-twist migration trapping.*

There is a balance of tensions at the convergence point, where the strand twist angle will almost coincide with the ply twist angle. Better trapping of the fibers occurs with greater differences between the twist angles. By varying the spinning tension, the twist propagating into the strands will vary, and so will the twist angle.

Variations in spinning tension occur with the cyclic up-and-down motion of the ring rail. When the convergence point is in its top position, the twist in the strand is at a maximum. As the tension in the plied yarn increases with the downward movement of the ring rail, the frictional contact between the strands at the convergence point increases, decreasing the amount of twist propagating into each strand and the strand twist angle. There is a resulting decrease in twist contraction of the strands, and the convergence point moves downward with the associated increase in strand lengths.

With the upward movement of the ring rail, the tension in the plied yarn decreases, enabling the strand twist and twist angle to increase; the strand lengths shorten with twist contraction, and the convergence point moves upward. The cyclic motion of the ring rail causes the convergence point to also cycle up and down and effects better trapping of fibers in the spun-plied structure.

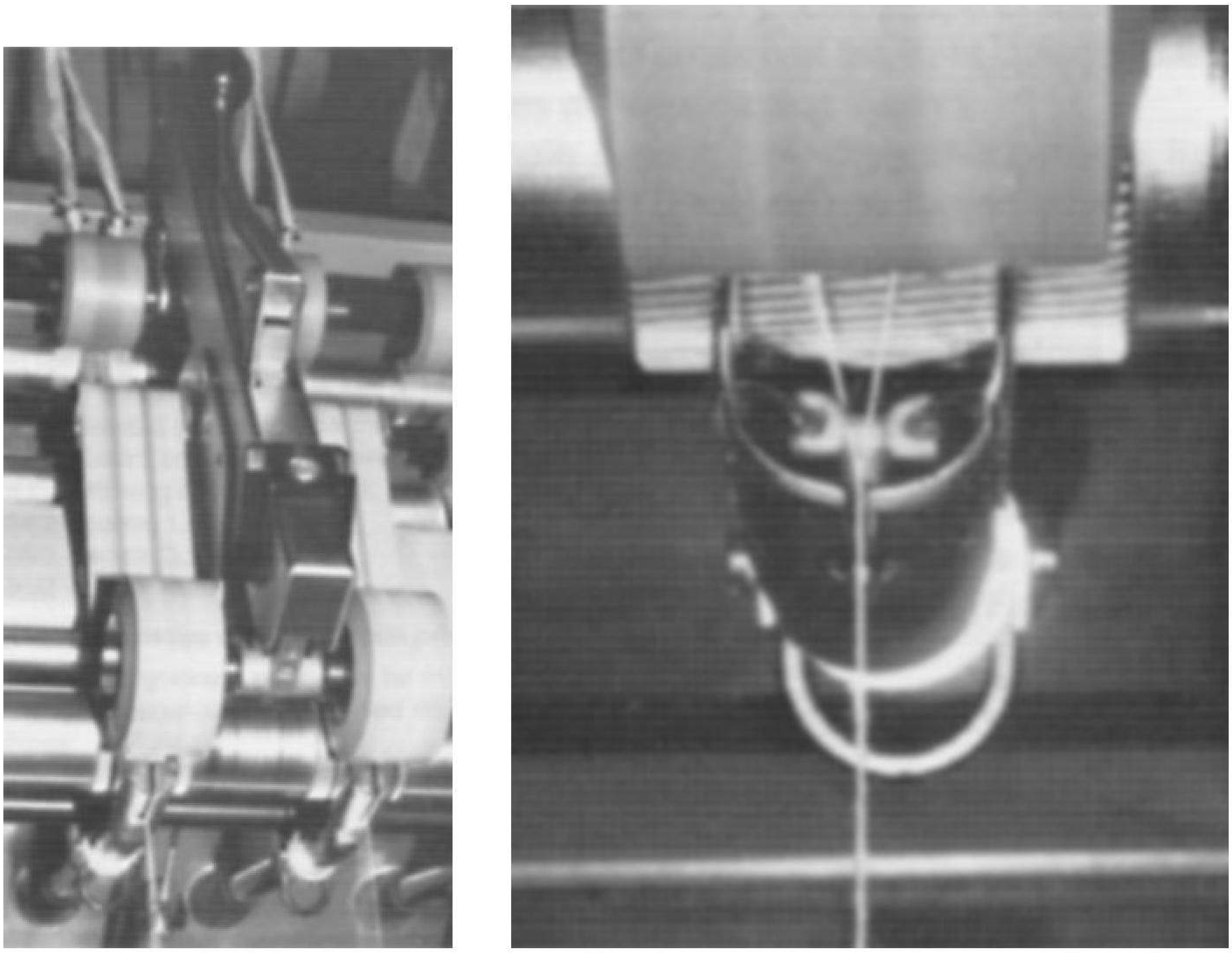


FIGURE 6.13 Duospun spun-plied unit. (Courtesy of Berkol Unicomb.)

This tension fluctuation causes only small imbalances in the tensions at the convergence point and gives only up to 20 turns per meter of strand twist level.[15,16] Deliberate cyclic perturbation of the convergence point[17] can be done with a pair of rollers profiled to nip and then release the plied yarn just below the convergence point. When the plied part of the yarn is nipped, the ply twist and the strand twist above the nip point will decrease, and the strand lengths increase. The ply twist below the nip point increases to a higher than normal value. When the nip is released, the converse occurs, and the flow of twist in the strand is then higher than the normal value. Deliberate cyclic perturbation gives more extreme twist variation, where the strand twist levels then can be up to 60 to 100 turns per meter. At the higher strand twist levels, there are few fiber lengths projecting from the strands. Therefore, strand-twist migration trapping becomes the dominant mode. Without deliberate cyclic perturbation, yarn formation trapping is the dominant mode.

The length of the individual strands above the convergence point increases with stand spacing, and the amount of twist that is available for trapping as strand twist also increases. Thus, at low strand spacing, trapping of fiber ends by the yarn-formation mode is dominant.

Yarn abrasion resistance, low hairiness, and adequate strength are important factors affecting weavability. The yarn hairiness decreases, and abrasion resistance increases, with stand spacing.

6.1.1.6 Key Points

Generally, ring and traveler systems have the following technical advantages and disadvantages.

6.1.1.6.1 Advantages

- They offer a wide spinning count range, e.g., 5 to 300 tex.
- They provide the ability to process most natural and man-made fibers and fiber blends.
- They produce staple yarns of tensile strength and handling aesthetics suitable for the majority of fabric end uses. The properties of ring-spun yarns are therefore used as a standard against which new yarns are compared.

6.1.1.6.2 Disadvantages

- Even in the ideal situation of no end breaks, spinning is still discontinuous, because it has to be interrupted for doffing.
- To attain high twisting rates and thereby high production speed, the yarn package must be reduced in size, resulting in frequent stoppages for doffing.
- The maximum mechanical speed is restricted by the frictional contact of ring and traveler and yarn tension.
- Bobbin size is restricted by the ring diameter.
- Yarn has to be rewound to produce larger size packages (see Chapter 8).
- Usually, the preparatory processes have to include roving production; spinning from sliver would be more economical.

It is important to note that the first four of the above limitations arise because, in ring spinning, twisting and winding of the yarn onto a bobbin are combined in the one action of the traveler being pulled around the ring.

The alternative spinning methods listed in Table 6.1 enable twisting and package building to occur as separate, simultaneous actions. Some of these methods retain twist in the spun yarn. With others, the twisting action is a temporary means of imparting integrity to the attenuated fiber mass forming the yarn bulk while this mass is either helically wrapped with a filament or staple fibers or bonded chemically or mechanically to obtained final integrity and strength. By separating twisting from package building, larger size packages can be made but, importantly, higher twisting rates also can be achieved to give faster production speeds as Figure 6.2 shows.

6.1.2 Open-End Spinning Systems

With the open-end (OE) spinning method, twisting and package building are separated by employing the false-twist principle (see Chapter 1). Real twist is, however, achieved in the yarn by forming a break in the attenuated mass at the point of twist insertion. The break is obtained by drafting the fiber mass to the point of individual fiber separation (see Figure 6.14). An alternative description is that the free end of the yarn (i.e., the open end) is rotated while individual fibers are collected and twisted

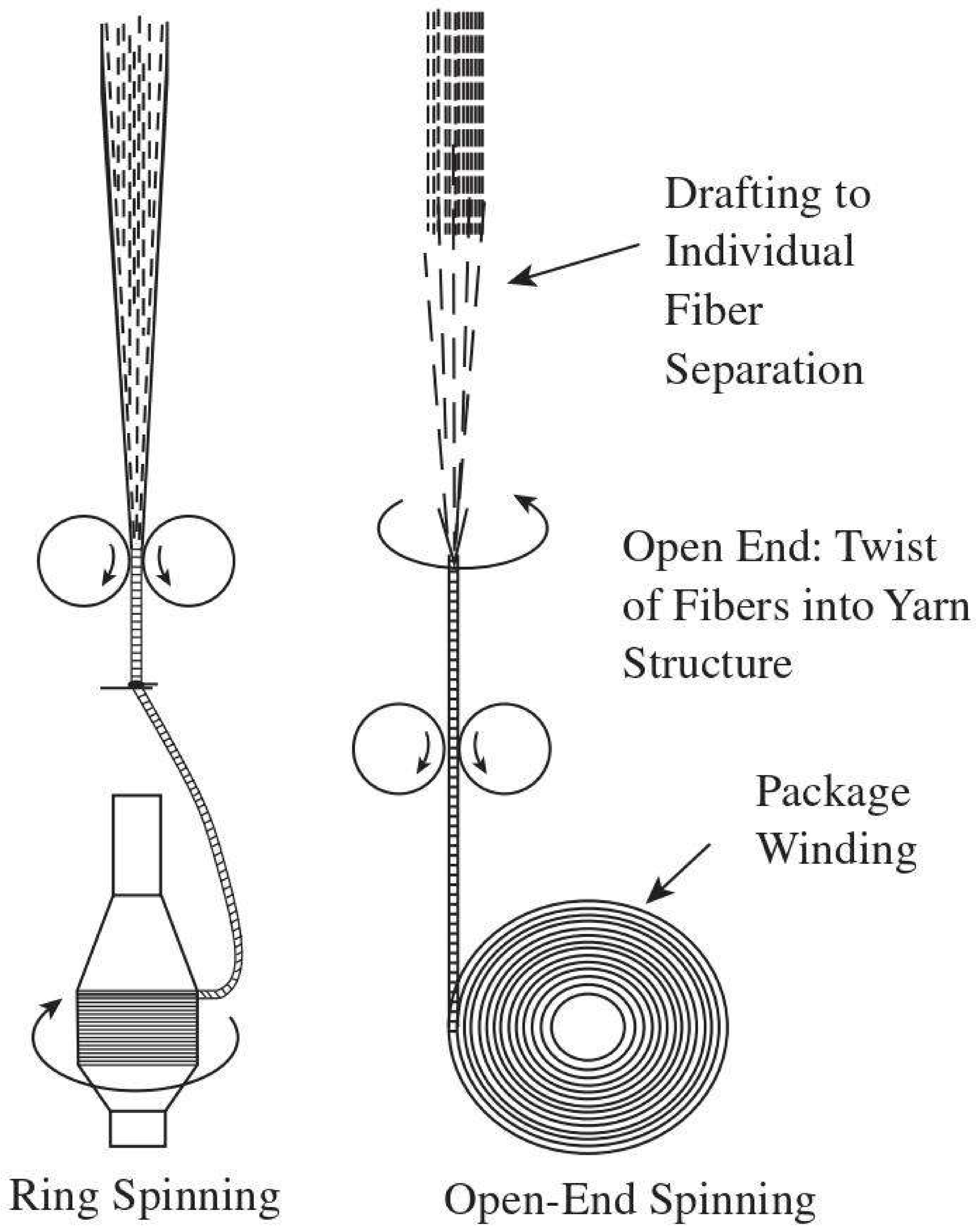


FIGURE 6.14 Comparison of ring spinning and open-end spinning principles. (Courtesy of Rohlena, V., *Open-End Spinning*, Chap. 7, Elsevier Science, New York, 1975.)

onto the end to increase the yarn length. Hence, the term *open-end spinning* or, based on the first description, *break spinning.*

Definition: Open-end spinning or break spinning is a process in which fibrous material is highly drafted, ideally to the individual fiber state, creating a break in the continuum of the fiber mass. The individual fibers are subsequently collected onto the open end of a yarn that is rotated to twist the fibers into the yarn structure to form a continuous yarn length. The length of yarn spun is then wound to form a package. Thus, the twisting action occurs simultaneously but separately from winding.

This definition outlines the basic requirements for any OE spinning system. Such a system would comprise the following:

1. A device for drafting the fibrous mass into individual fibers
2. A means of transporting the fibers and depositing the fibers onto the yarn end
3. A device for collecting the separated fibers onto the yarn end in a manner that enables the correct yarn count to be obtained
4. A device for rotating the yarn end to insert twist into the collected fibers
5. A means of winding the yarn into a package

A number of spinning techniques exploit the OE method,[18] but only two have achieved commercial success: rotor spinning and friction spinning. Of the two, rotor spinning is the more widely used commercially, because a wider range of yarn counts can be spun with suitable yarn properties.

6.1.2.1 OE Rotor Spinning

Figure 6.15 illustrates the essential features of a rotor spinning system. These are

- The feed roller and feed plate
- A saw-tooth or pin covered roller called an opening roller
- A tapered tube termed the fiber transport channel
- A shallow cup, called a *rotor* (A groove is cut into the circumference at the maximum internal radius of the rotor and is referred to as the *rotor groove.*)
- A flanged tube facing the rotor base and coaxial to the rotor, termed the *doffing tube*
- A pair of delivery rollers that feed the spun yarn to the package build device

The opening in the opening roller housing enables trash particles to be ejected from the process into a trash box, thereby providing additional cleaning of the fiber mass. In practice, most of the rotor unit components can be varied to alter the properties of the yarns and/or increase production speed. This aspect will be considered later, in Section 6.2, where the effect of machine variables on yarn properties will be described in detail. Here, a general description of the principle is given.

Fibers are presented to the rotor system in the form of a sliver. The feed roller and feed plate push the sliver into contact with the opening roller. The opening roller

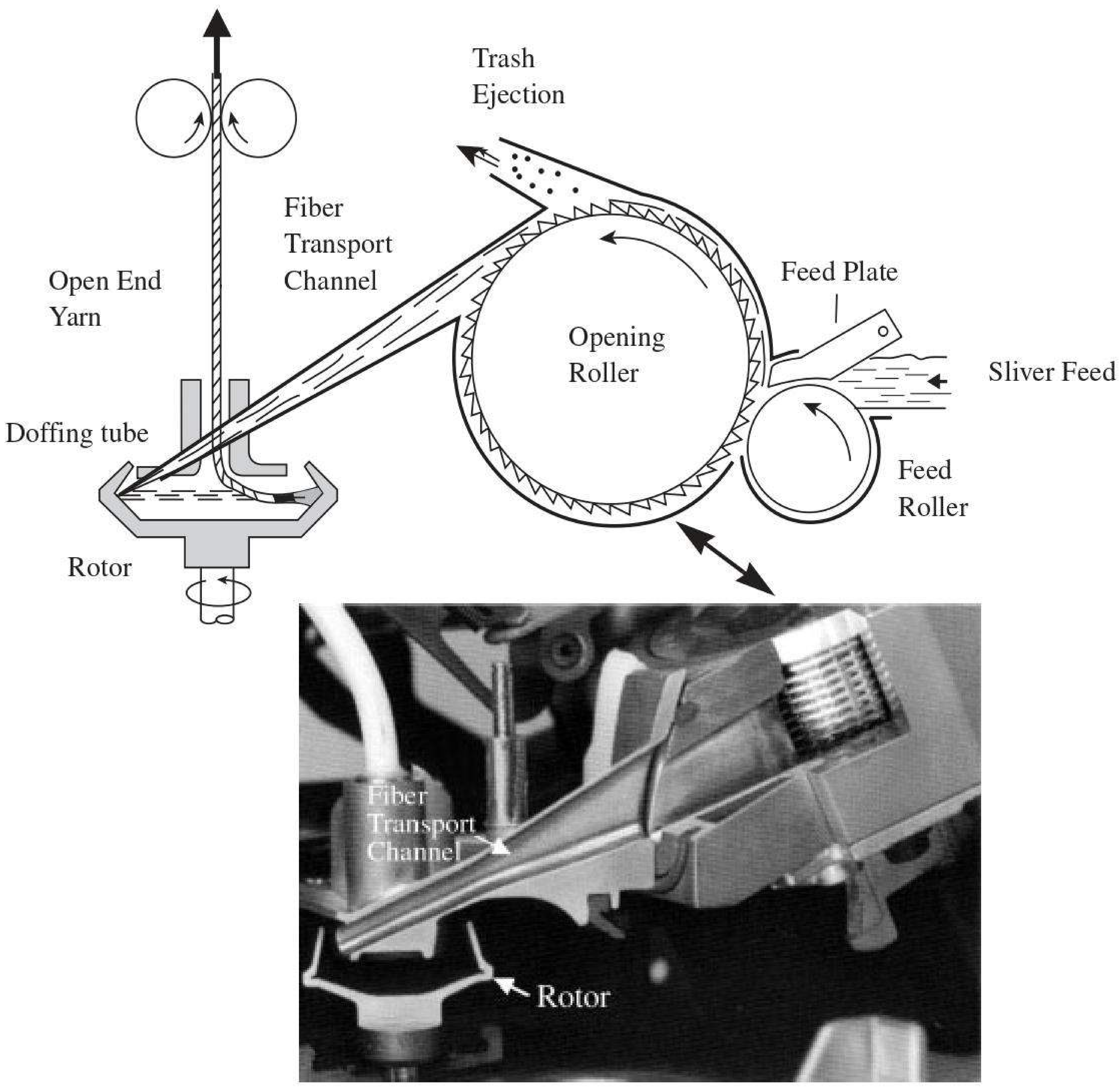


FIGURE 6.15 **(See color insert.)** Main features of a rotor spinning system. (Courtesy of W. Schlafhorst AG & Co.)

rotates much faster than the feed roller. This means fibers in the sliver are hooked by the sawteeth or pins and separated under a high draft ratio into individual fibers by the opening roller. The separated fibers are removed from the opening roller clothing by air suction flowing down the transport channel and into the rotor; the suction is generated externally to the rotor. The rotor is therefore under a partial vacuum.

The separated fibers are further drafted during their transportation in the airflow to the rotor. The fibers are individually deposited onto the internal wall of the rotating rotor and slide down the wall and into the rotor groove. Here, they accumulate to form a ribbon of fibers. To initiate spinning, the tail end of a yarn length (seed length) already wound onto the package by the package build device is threaded through the nip of the delivery rollers and into the doffing tube. The partial vacuum in the rotor sucks the tail end of the yarn into the rotor. The rotation of the rotor develops air drag and centrifugal forces on the yarn, pulling the yarn end into contact with the collected fiber ribbon. Simultaneously, the tail end is twisted with each revolution of the rotor. This twist propagates toward the tail end of the yarn and binds the ribbon onto the yarn end. Once the yarn tail enters the rotor, the delivery rollers are set in motion to pull the tail out of the rotor. The pulling action on the tail results in the peeling of the fiber ribbon from the rotor groove. The degree of twist that is inserted into the tail will propagate into each length of ribbon peeled from the groove, thus forming the next length of yarn. The process is continuous because of the conservation of mass flow; i.e., the following rates of mass flow are equal:

- Sliver feed rate
- Buildup of the fiber ribbon to give the required yarn count
- Rate at which the ribbon is peeled from the groove and twisted to form the yarn
- Rate at which the formed yarn is pulled from the rotor and wound onto the package

In Section 6.2, a detailed description is given of the buildup of the fiber mass into a ribbon of fibers and the conversion of the fiber ribbon into the rotor yarn structure. Here, we will consider more fully the insertion of twist into the fiber ribbon.

6.1.2.1.1 Twist Insertion

Figure 6.16a and b shows the side elevation and plan view of the yarn path in the rotor. The point at which the ribbon is pulled from the rotor groove is called the *peel-off point*, P. Since the ribbon is pulled at the delivery roller speed, V_d, the peel-off point circulates the circumference of the rotor at a rotational speed of $V_d/\pi D_R$, where D_R is the rotor diameter. This means that, relative to the doffing tube, the peel-off point rotates faster than the rotor such that

$$N_P = N_R + V_d/\pi D_R \qquad (6.15)$$

where N_P and N_R = the peel-off point and the rotor rotational speeds

To insert twist into the fiber ribbon to produce the yarn, sufficient twist torque must be present at point P in Figure 6.16. This keeps the forming yarn from breaking

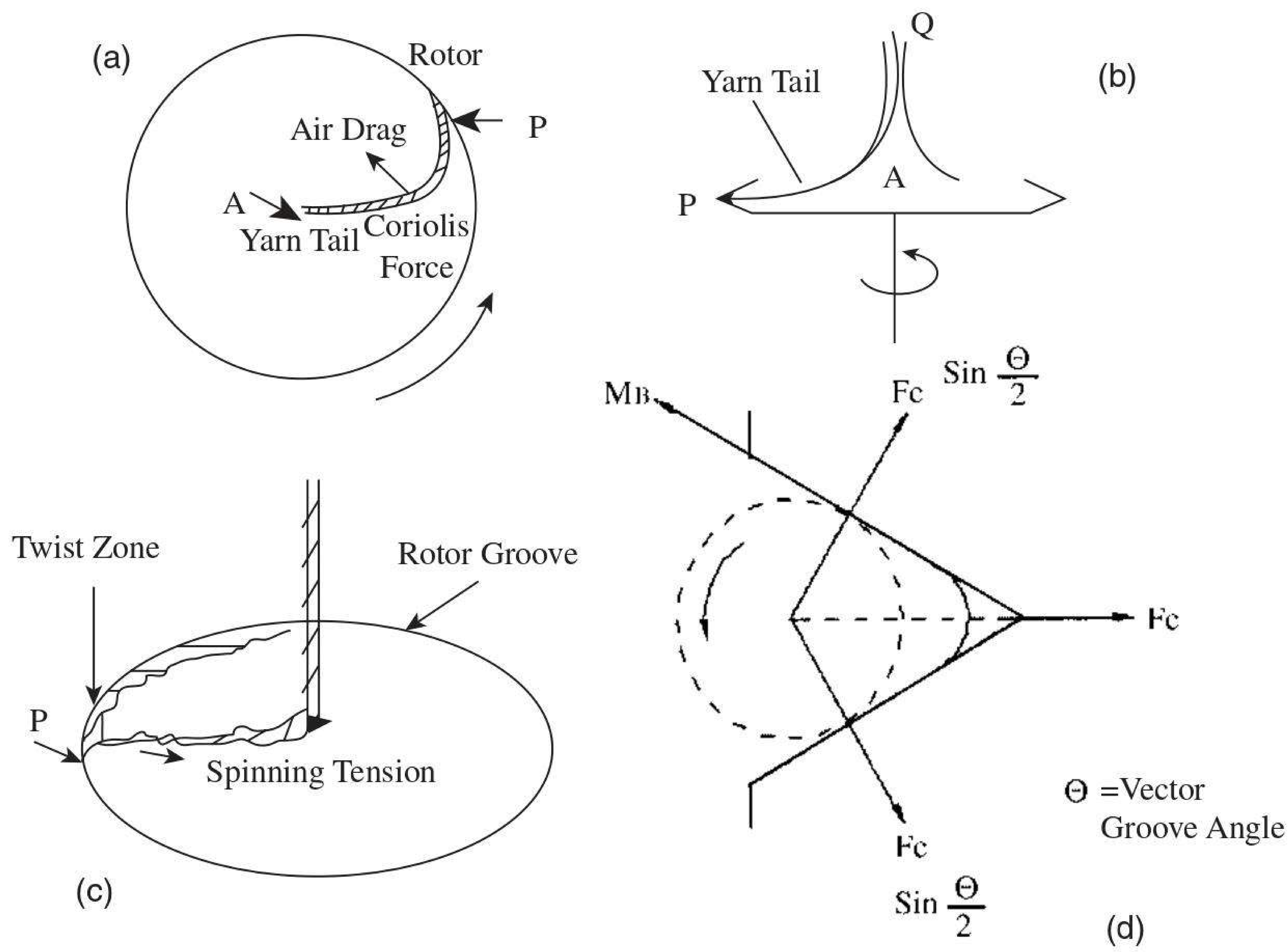
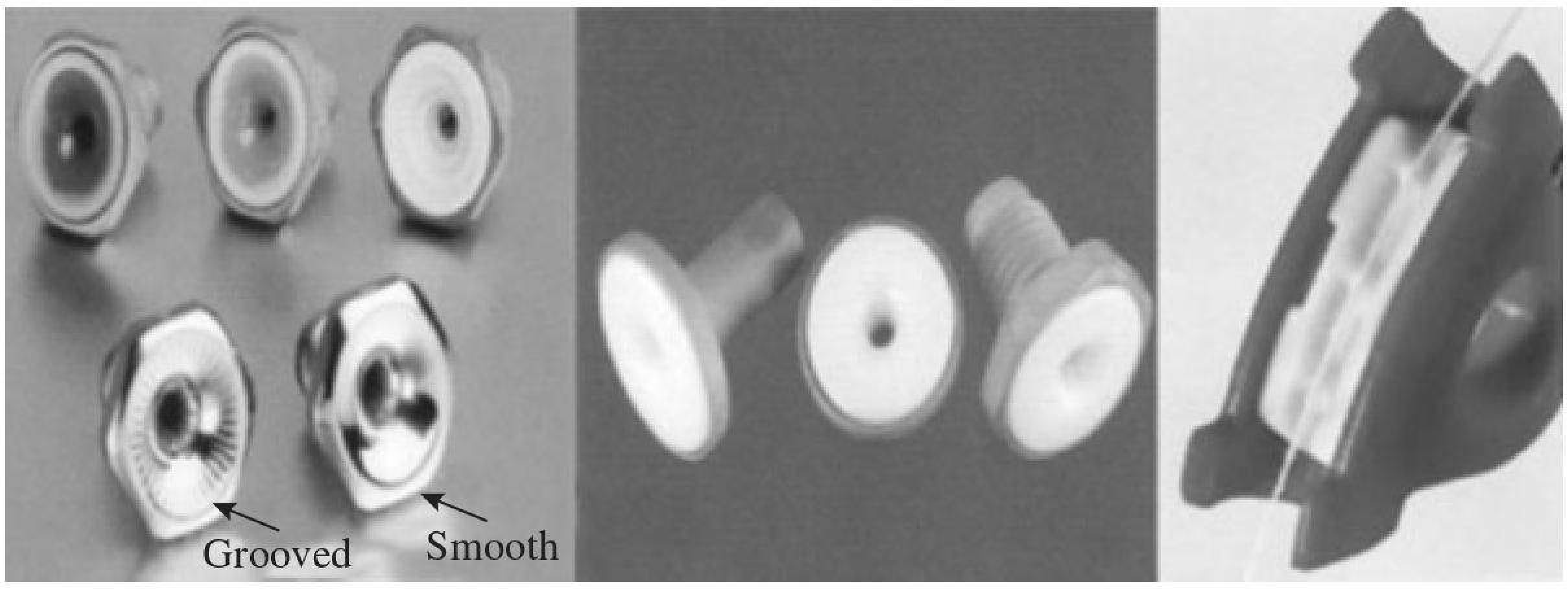


FIGURE 6.16 Yarn tail inside the rotor. (Courtesy of Zhu, R. and Ethridge, M. D., A Method for estimating the spinning-potential yarn number for cotton spun on the rotor-spinning system, *J. Text. Inst.*, 89(2), 275–280, 1998.)

at P as a result of the high tension induced in AP by centrifugal forces. The rotor generates the twist torque as it carries the yarn tail AP through each revolution; QAP is, therefore, similar to a crank. The cranking action induces twist in the length QA. The twist torque builds up and propagates to P. In doing so, it has to overcome the barrier, at A, of the doffing tube and that caused by the narrowness of the rotor groove (See Figure 6.16d). The spinning tension and the doffing tube geometry are therefore important factors. Surmounting the twist barriers requires a higher machine twist setting than is used in ring spinning. However, the central area at A, termed the *doffing tube navel,* can be altered to assist in reducing the twist level required to spin. There are many differing types of doffing tube navels that may be used (see Figure 6.17). The most contrasting effect is obtained between the smooth and the grooved navels. Essentially, the grooved navel gives a false-twist effect at A in Figure 6.16. Thus, if the yarn is being spun with Z twist, say $Z_{1,}$ then the grooved navel will give additional Z twist, say Z_2, in the yarn tail AP. As this yarn length with $Z_1 + Z_2$ twist subsequently passes A and becomes AQ, the Z_2 twist is removed by S_2 twist, leaving only the nominal Z_1 twist in the yarn. The additional Z_2 twist enables twist propagation into a small but important part of the fiber ribbon length within the rotor groove. With the use of the smooth doffing tube, the twist stops at the peel-off point, P. Because of fluctuations in spinning tension, this is therefore a point most likely to break with peak tensions. The grooved doffing tube inserts twist up to 10 mm in the fiber ribbon length beyond the peel-off point, P; that is to say, the twist insertion and peel-off points do not coincide; there is a twist insertion point beyond the peel-off point. This



Doffing Tube Navels Torque Stop

FIGURE 6.17 (See color insert.) Examples of doffing tube navels and twist block device. (Courtesy of W. Schlafhorst AG & Co.)

extended twisted length in the rotor groove is referred to as the *peripheral twist extent* (see Figure 6.16c). It strengthens the peel-off point and enables spinning at lower machine twist settings. Figure 6.17 shows what is termed a *torque stop*. If this is positioned to contact the yarn length AQ, then the twist flow along AQ will be restricted, causing a build up of twist at A and thereby increasing the twist level in AP.

Even though the above developments improve twist flow along the yarn tail, AP, a minimum of 100 fibers in the yarn cross section is required to efficiently spin on the open-end rotor system. This gives a physical limit to the fineness of count that can be rotor spun.[19] Except for very short fibers (e.g., comber waste and blends), which would have to be spun at coarse counts, the minimum figure is almost independent of fiber length. For ring spinning, because twist usually flows readily to the spinning triangle, the minimum figure is within 40 to 90, depending on fiber length, strength, and twist level. In ring spinning long-staple fibers, the forming yarn is more able to withstand tension fluctuations than is the case for spinning short-staple fibers. Therefore, for a given fiber fineness, the longer the fiber, the smaller the minimum number of fibers required in the yarn cross section for ring spinning.

6.1.2.1.2 End Breaks during Spinning

From the above explanation of the twist insertion, it can be seen that fluctuation in the rotor spinning tension and variation of the number of fibers in the cross section at the peel–off point, P, are very important to a low-end breakage rate during spinning. However, a more critical factor is the buildup of impurities in the rotor groove, as these block the twist flow into the fiber ribbon. Since the occurrence of rotor deposits is related to fiber deposition, the topic is deferred to Section 6.2.3.4.

6.1.2.2 OE Friction Spinning

The fundamental difference between open-end friction spinning and open-end rotor spinning is the way in which fibers are collected and twisted onto the tail end of the seed yarn. In friction spinning, the fibers are not collected to form a fiber ribbon that is then twisted. Instead, the fibers are individually collected and twisted onto the yarn. Two rotating, perforated, cylindrical rollers insert the twist by frictional rolling of the yarn tail while simultaneously twisting fibers onto the yarn tail. The rollers are often referred to as the *spinning drums* or *friction drums.* Figure 6.18 illustrates the commercial process known as Dref-2.

Commonly, two pairs of feed rollers feed four or five slivers in parallel to an opening roller. The objective is to process a wide range of staple lengths, i.e., up to 120 mm. Therefore, for simplicity, a feed plate is not incorporated, the opening roller is much larger than in rotor spinning, and the fibers are blown off the saw-tooth clothing of the opening roller and into the collecting zone for twisting.

The collecting zone is formed by the close positioning of the two spinning drums. This effectively gives a V-shaped groove parallel to the rotation axes of the drums. A rotating disc with projections around its circumference may be used to assist in

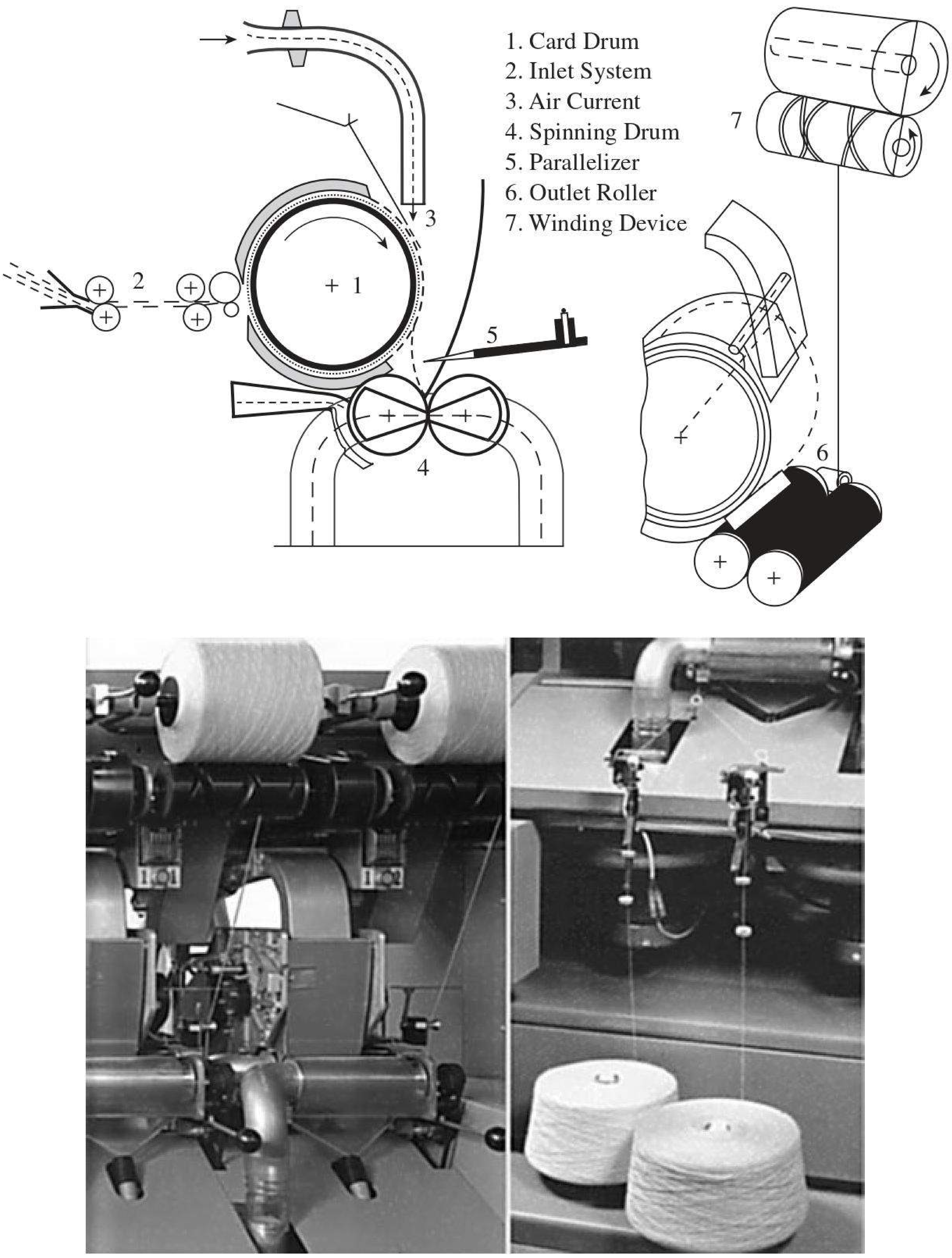


FIGURE 6.18 (See color insert.) Dref-2 open-end friction spinning system. (Courtesy of Fehrer AG.)

aligning fibers parallel to the groove axis just before their deposition. Its purpose is to get the full fiber lengths contributing to yarn length and to attain a parallel assembly of fibers in the spun yarn, as these two factors are critical to yarn strength. As the drums rotate, suction is applied through the holes at the V-shaped groove, enabling compaction of the fibers as the yarn structure is formed. The tail end of the yarn being spun is held in the groove by the suction force. The drums have the same directions of rotation. Hence, as well as being compacted, the depositing fibers are twisted onto the tail end by frictional contact with the drums. As the yarn length is spun, it is pulled along the groove by the delivery rollers and, finally, wound onto a bobbin to make a yarn package.

The Dref-2 system can be used to advantage in the spinning of core spun yarns. The deposition and twist of fibers onto the yarn tail provide the opportunity for the yarn tail to be replaced by a filament core, which would then become fully covered by a staple sheath as fibers are deposited and twisted onto the filament. In this situation, the continuous filament yarn would pass from a filament package, through a thread tensioning guide, along the V-shaped grooved formed by the spinning drums, and via delivery rollers to the package build device. (See Figure 6.18.)

The fiber deposition in the Dref-2 system does not result in a straight and parallel arrangement of the fibers in the spun yarn (see Section 6.2). As a result, the Dref-2 is only suitable for spinning very coarse count yarns (see Figure 6.1). The aspect of fiber straightening during deposition in OE spinning systems has been a focus of much research over the years, particularly with regard to OE friction spinning of finer yarn counts. However, no suitable fine-count OE friction system has yet reached commercial success. An alternative to OE friction spinning is friction wrap spinning, which has enabled the spinning of yarns within the coarse- to medium-count range. This system is described in Section 6.1.4.

The technological equations for total draft and twist factor are applicable to the friction spinning process. However, the equation for computing machine twist, t, must account for the relative diameters of the yarn and the spinning drum and the factors controlling the friction mechanism of twist insertion. Thus, it would be given by

$$t = \frac{KDN_D}{dV_d} \tag{6.16}$$

where K = a twist efficiency factor (<<1) that is indicative of the frictional contact between yarn and drums

D, d = drum and yarn diameters, respectively

N_D = rotational speed of the drums

V_d = yarn delivery speed

It is evident that fiber-metal friction and fiber torsional rigidity will significantly influence K. Generally, it is not often practicable to alter these properties, particularly if processing natural fibers. With continuous operation, the running machine temperature rises, and components can expand and alter settings. The size of the V-shaped groove, and also the fiber-metal friction, may change. Experimental studies have shown that, as a result of such changes, friction slippage can occur as illustrated in Figure 6.19. Because of slippage, K can be as low as 0.1 to 0.3. Suitably designed components can minimize the problem of altered settings with running time, and appropriate suction can be used to reduce the effect of twist slippage resulting from changes in fiber-metal friction. The suction applied can be measured as negative pressure in millimeters of water. Figure 6.19 also shows that twist slippage decreases linearly with negative pressure over the available range for Dref-2 system.[20] However, as the figure also shows, the yarn count, the drum speed, and the delivery speed also influence twist slippage. In practice, the equation of t is of little use, and twist setting of the machine is usually set by yarn measurement and experience.

Figure 6.2 shows that, compared with other spinning processes, OE friction spinning is one of the fastest production systems. However, as stated previously, the process is currently suitable only for spinning yarns at the coarse end of the yarn count range. Much research and development work has been carried out in trying to commercialize machines for the medium to fine end of the count range — so far without success. The principal reason for the lack of success has been the poor yarn properties as compared to ring- and rotor-spun yarns.

6.1.3 Self-Twist Spinning System

Definition: Self-twist spinning is a process in which two fibrous strands are separately false-twisted to give alternating S and Z twist along their lengths. Both strands are then brought together in frictional contact for the untwisting torque of the S–Z twist to ply the strands, producing an alternating Z and S twisted twofold yarn.

The alternating S-Z twist in each strand is obtained by false-twisting the strands up to the point on an S-Z false-twist curve at which the near-maximal twist value is obtained for both twist directions. Figure 6.20 illustrates this. For a continuous

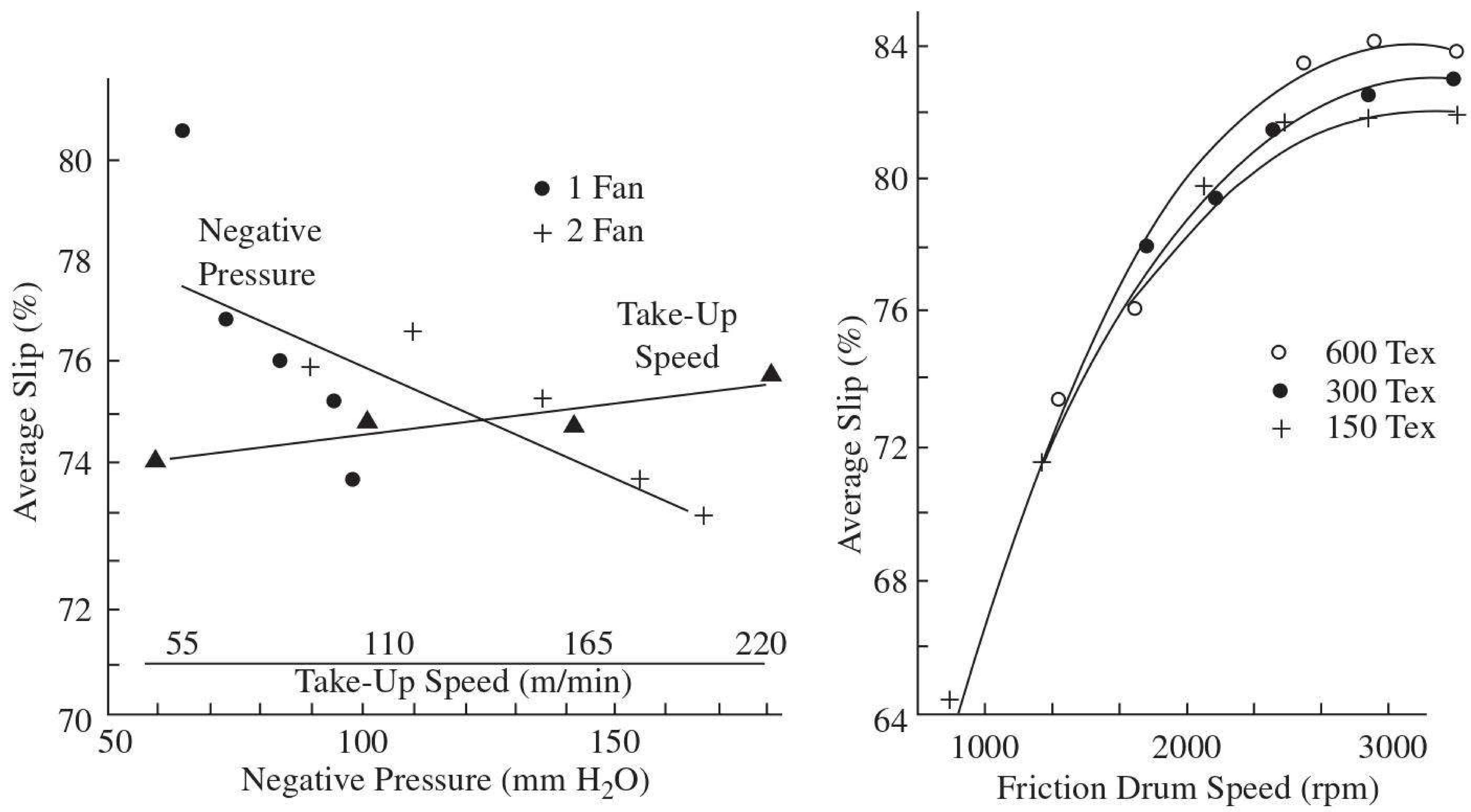


FIGURE 6.19 Friction slippage in Dref-2 spinning.

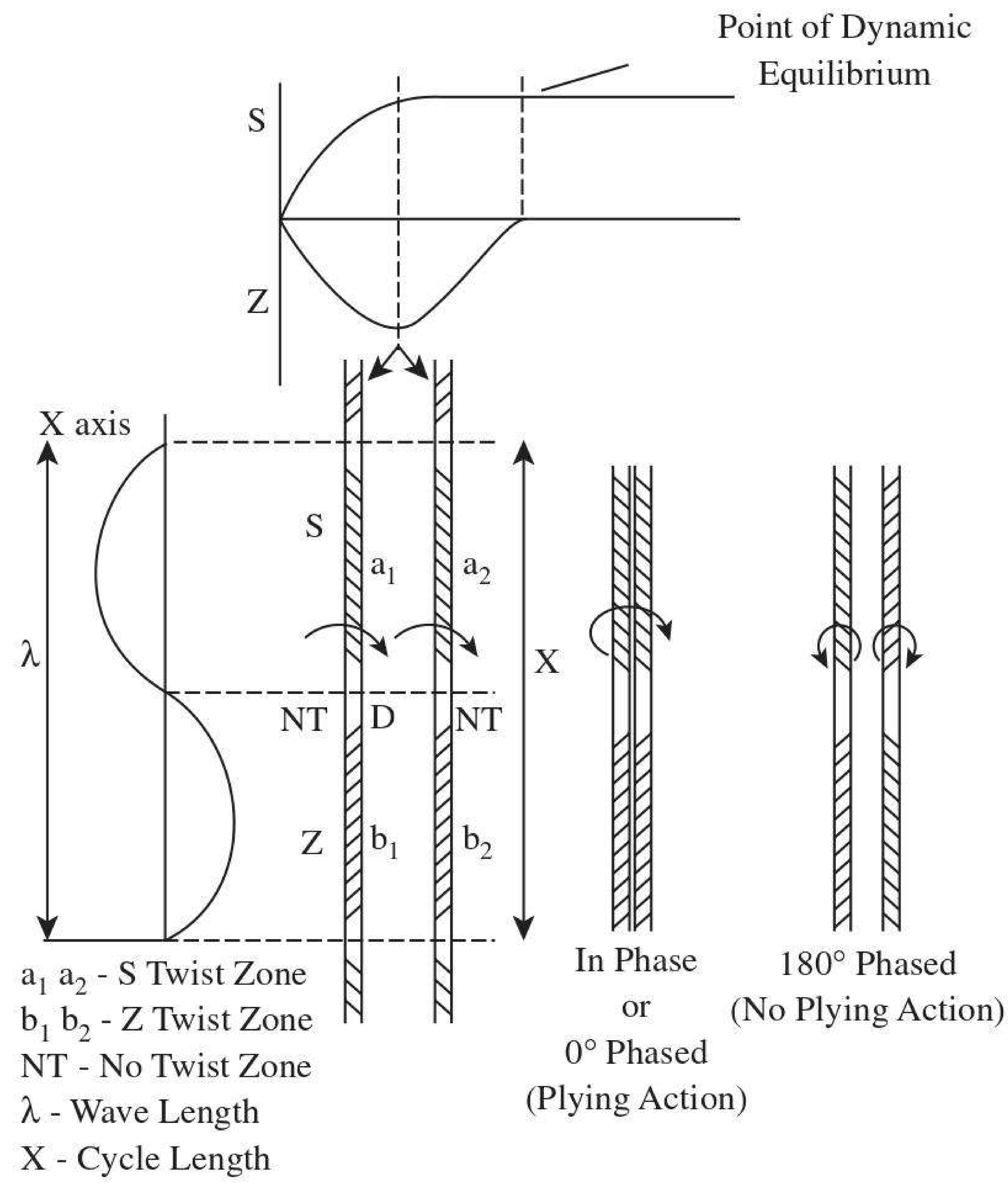


FIGURE 6.20 Principle of self-twisting.

twisting process, the twisting device would have to be repeatedly rotated clockwise then counterclockwise, the change in direction being made when the maximal twist value is reached.

We can see from the figure that each S-Z twisted strand can be related to a sinusoidal wave plotted on Cartesian axes, where the twist level and directions are along the y-axis and the twisted length along the x-axis. Thus, λ represents the wavelength, and in terms of the yarn length is called the cycle length, X. Making the sinusoidal wave analogy allows us to consider the relative positions of lengths in the strands with the same twist direction in terms of the phasing of waves. Let us consider the two extremes of phasing. As shown in the figure, two strands having their S and Z lengths and no-twist zones coincident are in phase or are zero-degree phased. If the lengths are displaced such that the S lengths coincide with the Z lengths (i.e., a_1 now faces b_2), then the strands would be 180° out of phase or 180° phased. When the twisted strands are phased by 180°, they have opposing untwisting torque, the self-twist action cannot take place, and no yarn will be formed. Theoretically, the optimal phasing is 90°, because this should give the maximal yarn strength. Figure 6.21 illustrates the 0 and 90° phased yarns. It can be seen that the former has the no-twist zones of the strands and the ply coming together at the same place in the yarn, whereas the latter has the no-twist zones coinciding with the Z-twist (and S-twist) regions of one or the other strand.

Various false-twisting arrangements can be used to produce self-twist (ST) yarns.[21] However, the commercial process known as Repco spinning utilizes friction twisting by a pair of reciprocating rollers. Figure 6.22 illustrates the Repco ST

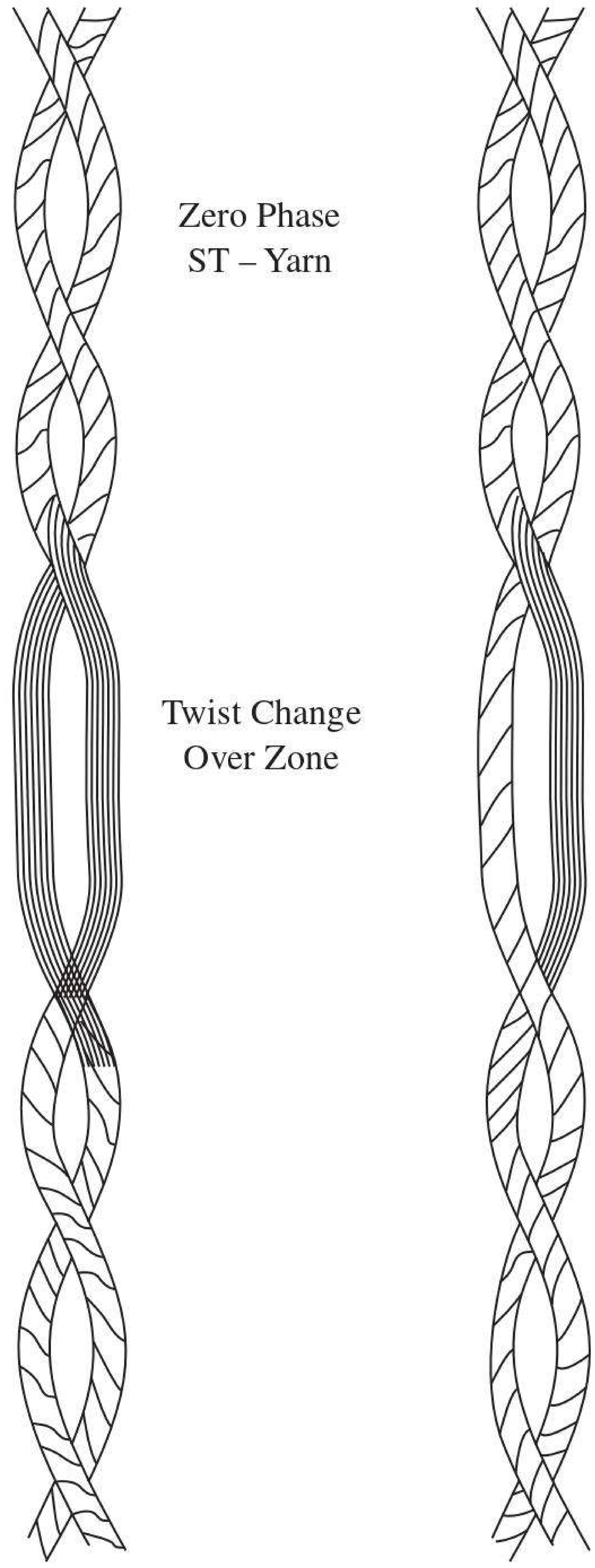


FIGURE 6.21 Self-twist yarns of 0 and 90° phasing.

system. Since two rovings have to be fed to each spinning position, the apron drafting system is designed to attenuate eight separately spaced rovings. The reciprocating rollers are placed immediately after the front drafting rollers. As well as reciprocating, these rollers move the alternating S-Z twisted strand to the phasing zone. The region between the front drafting roller and the reciprocating rollers is termed zone I. Zone II is the region from the reciprocating rollers to the phasing zone, zone III. At any instant in time, the strand lengths in zone I will have the opposite twist direction to the lengths in zone II.

In zone III, there are a pair of guides at each spinning position, which enables the phasing and self-twisting of the strands. From Figure 6.23, it can be seen that phasing is achieved by one strand, S_2, moving through a slightly longer path (d–e–f) than the other, S_1, c–f. Phasing therefore occurs through the corresponding lengths of the strands, with the same twist directions being displaced by the distance, e–f, i.e., the separation distance of the guide. If y is the separation distance and X the cycle-length corresponding to 360°, then the phasing, θ, can be obtained from the expression

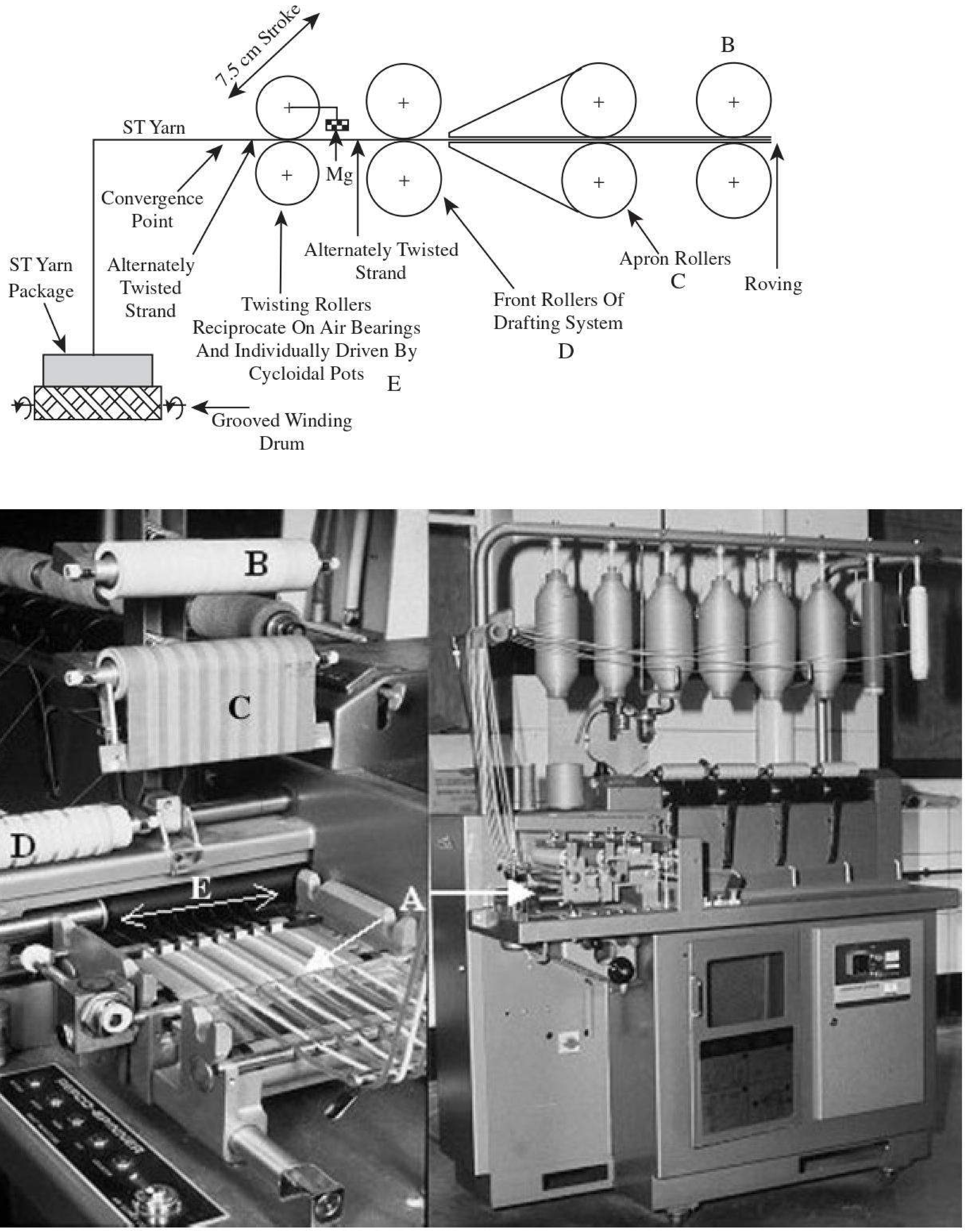


FIGURE 6.22 **(See color insert.)** Repco ST spinning system. A. Roving feed, bottom drafting rollers, and apron. B. Top rear, drafting roller. C. Top apron of drafting system. D. Special grooved top, front drafting roller. E. Reciprocating friction rollers.

$$\frac{y}{X} = \frac{\theta}{360}$$

For the Repco system X = 22 cm, and y = 1.85 cm. Therefore, the strands have a 30° phasing. A major disadvantage in using displacement to phase the alternately twisted strands is that they will begin untwisting before coming together. The twist loss will be greater with a higher degree of phasing and, consequently, so will the strength of the ST yarn. Thus, 30° phasing is the optimum for maximum strength of Repco ST yarns.

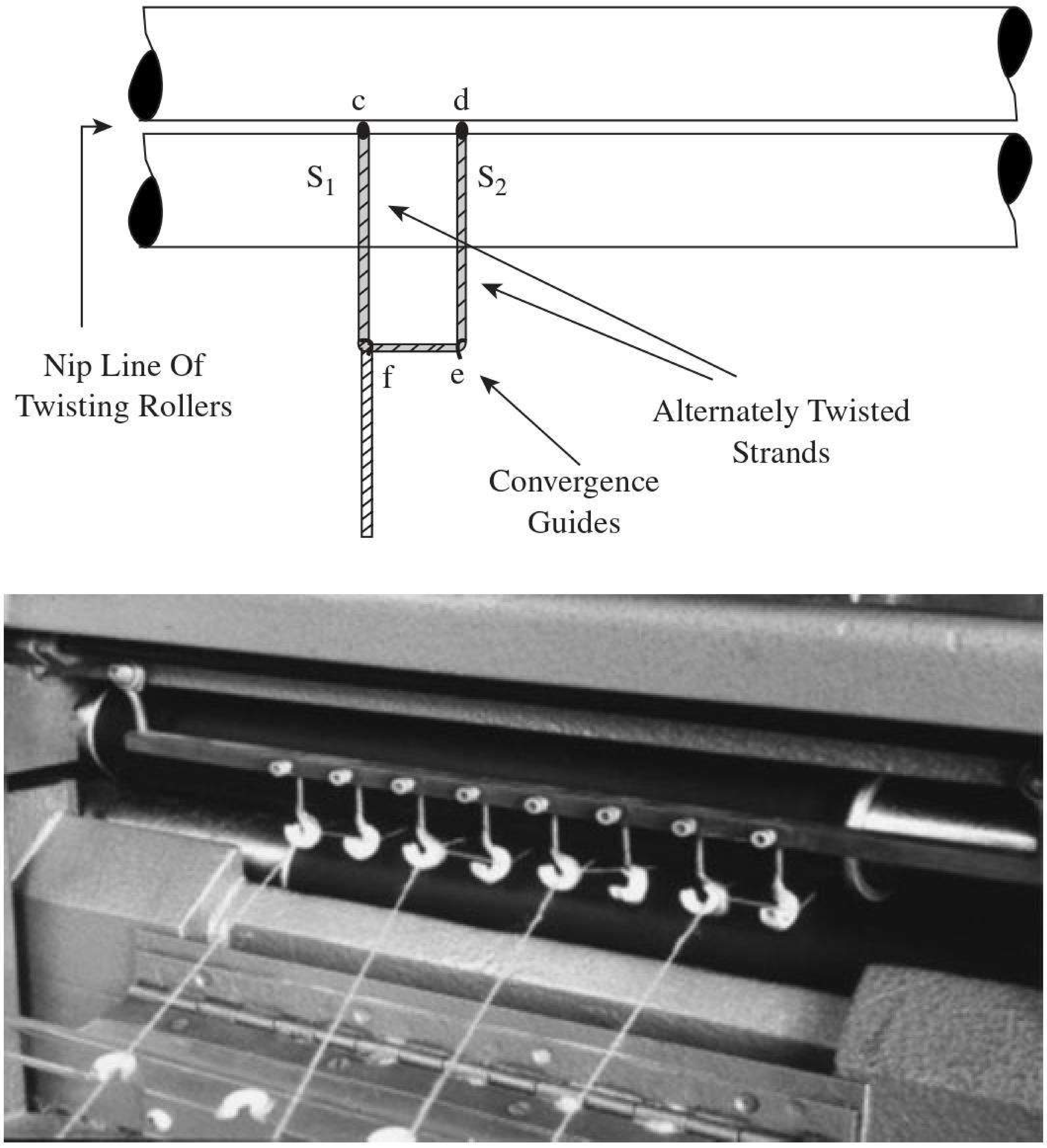


FIGURE 6.23 Self-twist yarn phasing on Repco system.

The combined action of the twist-inserting rollers of reciprocation and feeding the strands to the phasing zone is achieved with a cycloidal drive arrangement.[21] The twist inserted by the reciprocating rollers is dependent on the applied normal load, *N*, to the reciprocating or ST rollers; the stroke length; the effective strand diameter; the surface friction coefficient, μ, between fiber and ST roller; and the oscillating frequency. The number of twists per cycle of oscillation is given by

$$\text{Turns per oscillation} = \frac{\Omega 2L}{d} \tag{6.17}$$

where Ω = a twist efficiency factor dependent on μ and N
L = the stroke length = 7.6 cm for the Repco system
d = the effective diameter of the strands

Using the sinusoidal wave analogy, it can be shown theoretically[21] that the total number of twist in the strand length in zone I is

$$Y_u = \frac{\text{Lu} \sin[(2\pi x/X) - \alpha]}{d\sqrt{[X^2 + 4\pi^2 u^2]}} \tag{6.18}$$

And, in zone II is

$$Y_v = \frac{2\pi uvXL\sin[(2\pi x/X) - \gamma]}{d\sqrt{[X^2 + 4\pi^2 u^2]}\sqrt{[X^2 + 4\pi^2 v^2]}} \tag{6.19}$$

where u, v = the respective lengths of zones I and II

$$\alpha = 2\pi u/X \text{ and } \gamma = \tan\{[X^2 - 4\pi^2 uv]/[2\pi X(u + v)]\}$$

With alternating twist, it is more convenient to consider twist per half cycle (i.e., half-cycle length) than total twist or twist per unit length. If f is the oscillation (or reciprocating) frequency, and V is the speed at which the strands are fed to the phasing zone, then the cycle length, X, is given by

$$X = V/f$$

and the twist per half cycle is given by

$$t_{(1/2)} = \frac{4\Omega L}{dX} = \frac{4\Omega Lf}{dV}$$

The twist factor (TF) is then

$$TF = \frac{2t_{(1/2)}T_t^{-1/2}}{X} \tag{6.20}$$

In practice, values for Ω and d are not easily obtained for predicting $t_{(1/2)}$, so the strand and plied twists are measured. Figure 6.24 shows a graph of $t_{(1/2)}$ vs. $T_t^{-1/2}$ for various values of L.[21] As would be expected, $t_{(1/2)}$ increases with L. However, importantly, for a fixed X, TF remains constant for all yarn counts without the need to alter the rate of twisting as is required in ring and rotor spinning when differing counts are needed to be spun with the same twist factor.

6.1.4 Wrap Spinning Systems

Definition: Wrap spinning is a process whereby a drafted ribbon of parallel fibers that constitutes the bulk of the spun yarn is wrapped by either surface fibers protruding from the ribbon or by a continuous filament or filaments so as to impart coherence and strength to the resulting yarn.

Table 6.1 indicates that there are two systems that utilize surface fiber wrapping, and two that employ filament wrapping.

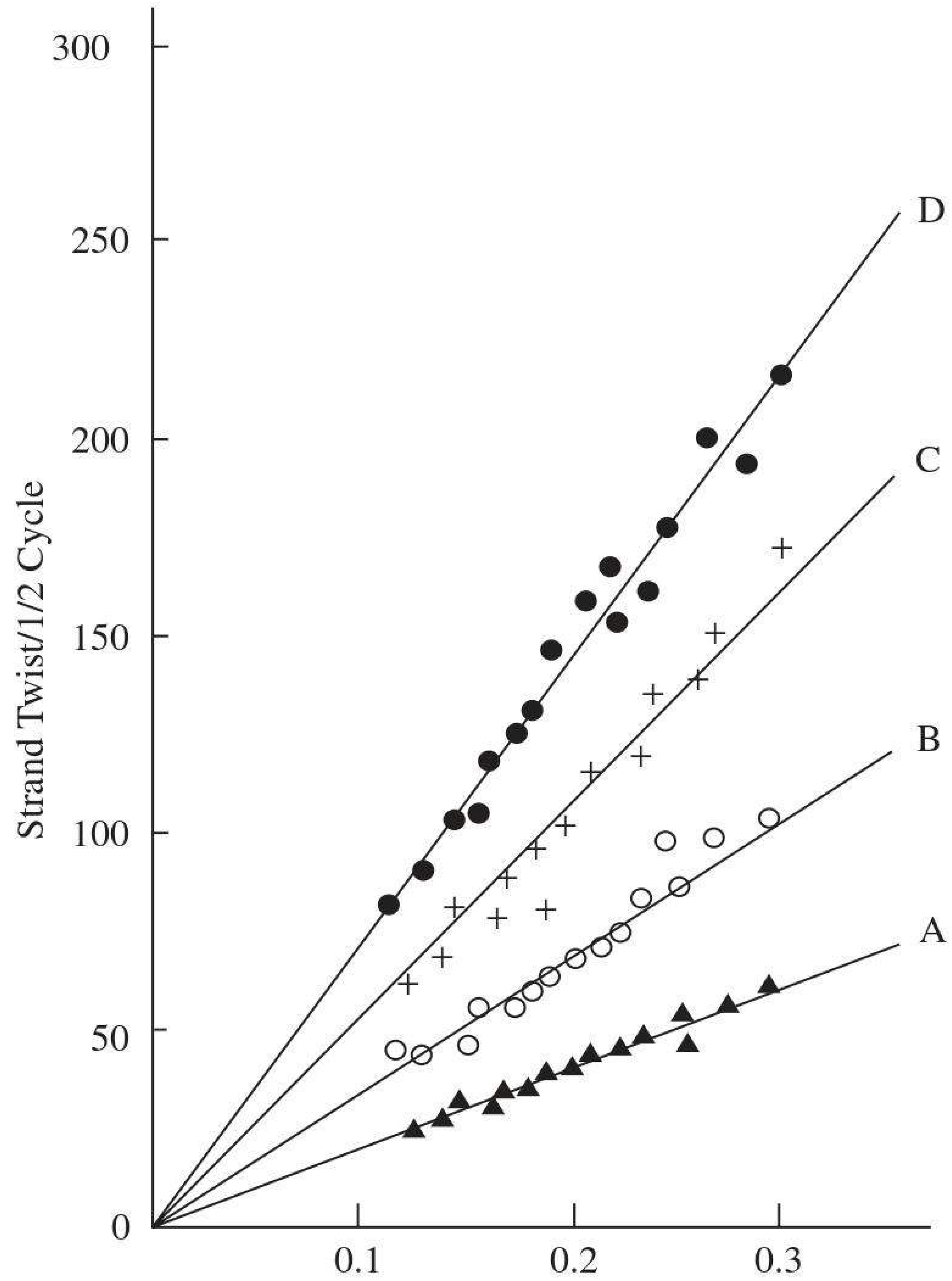


FIGURE 6.24 Strand twist per half cycle vs. reciprocal strand count.

6.1.4.1 Surface Fiber Wrapping

6.1.4.1.1 Dref-3 Friction Spinning

The Dref-3 spinning system[22] is a friction spinning process that is effectively based on the core-yarn spinning technique of the Dref-2 system. Figure 6.25 shows that a staple fiber ribbon is fed from a roller drafting unit (drafting unit I) into the V-shaped groove formed by the spinning drums (spinning unit). Fibers traveling from the opening rollers (drafting unit II) are deposited onto the drafted ribbon of fibers. Twin opening rollers are used to obtain a high degree of fiber separation. The drums generate false twist into the fiber ribbon while wrapping the deposited individual fibers around the fiber ribbon.

6.1.4.1.2 Air-Jet Spinning

Tandem Jet System

A second technique of surface fiber wrapping is generally known as fasciated yarn spinning,[23,24] and the commercial process, which used to produce 100% polyester and polyester-cotton/polyester-viscose blends, is widely referred to as air-jet spinning or Murata jet spinning (MJS, named after the machine manufacturer, Murata Co.).[25,26]

This spinning system consists of a 3-over-3 high-speed roller drafting unit, two compressed-air twisting jets arranged in tandem, a pair of take-up rollers, and a yarn package build unit (see Figure 6.26). The basic design of a jet (not a commercial

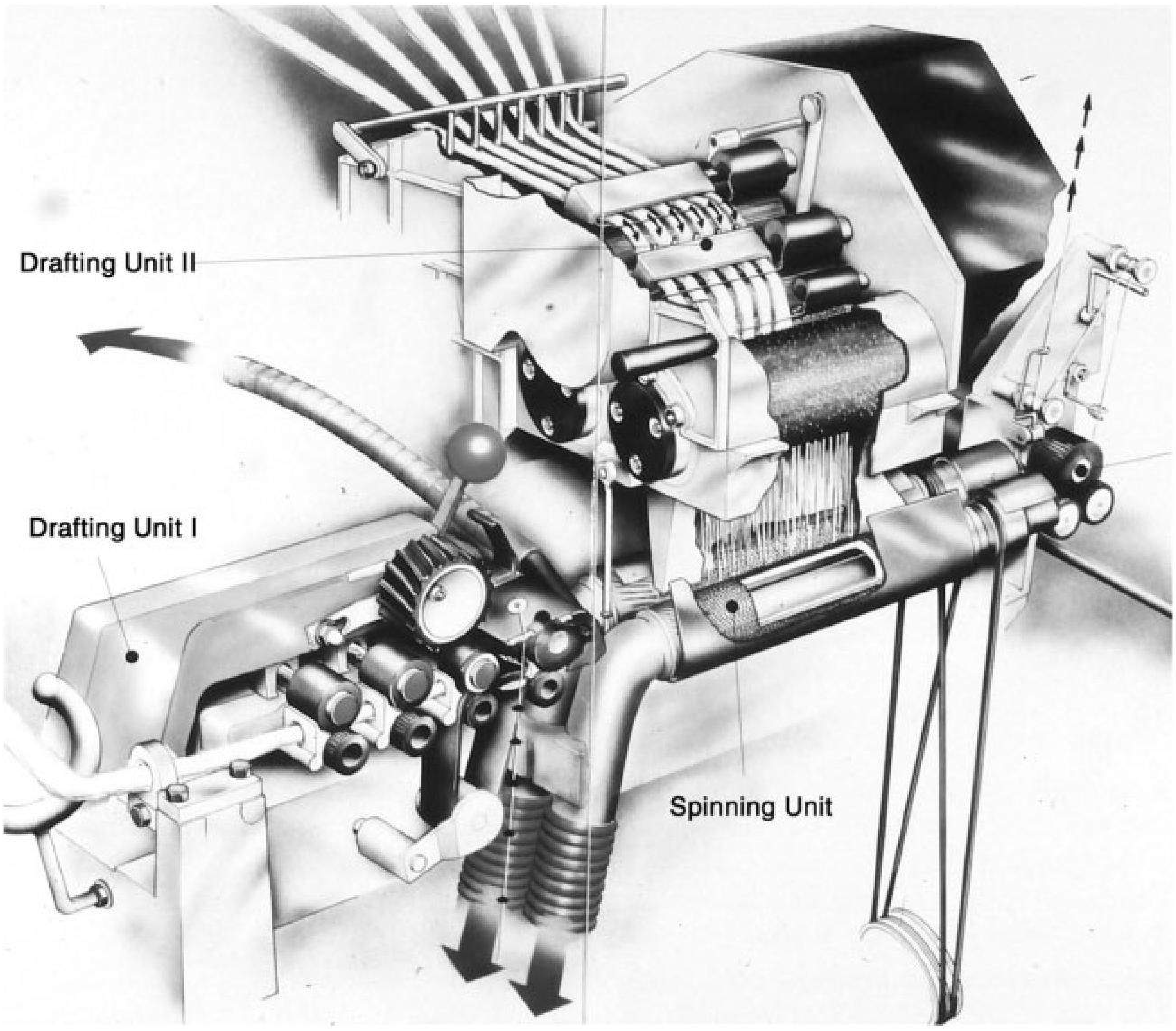


FIGURE 6.25 **(See color insert.)** Dref-3 friction (wrap) spinning system. (Courtesy of Fehrer AG.)

design) is illustrated in Figure 6.27. As shown, there is a central tubular channel (the spinning channel) through which the ribbon issuing from the front roller of the drafting unit passes.

Inclined to the spinning channel axis, but tangential to the circumference, are four nozzles through which compressed air is injected into the channel to create a vortex flow. Each compressed air jet entering and expanding into the channel has two velocity components of airflow: V_1, a circular motion of the air around the channel circumference, and V_2, the movement of the air to the channel outlet. The suction at the jet inlet created by V_2 gives automatic threading up of the spinning process. Provided the drafted ribbon is not taut within the channel, the V_1 component of flow rotates it, inducing a false-twist action and a spinning balloon (i.e., a rotating standing waveform) while V_2 assists movement of the twisted ribbon through the channel.

Referring to Figure 6.26, the surface speed ratio of take-up rollers to front drafting rollers is within 0.9 to 1.0. A counterclockwise vortex is set up in jet 1 to give a Z-S false-twisting action, and a clockwise vortex in jet 2 gives an S-Z action. The pressures applied to the jets are such that $P_2 >> P_1$; i.e., jet 2 has the higher twisting vortex.

Although the jets impart false twist, while doing so they do not have a positive hold on the ribbon being twisted. High-speed photographic studies[27,28] have shown that the absence of a positive hold enables S twist from jet 2 to propagate along the

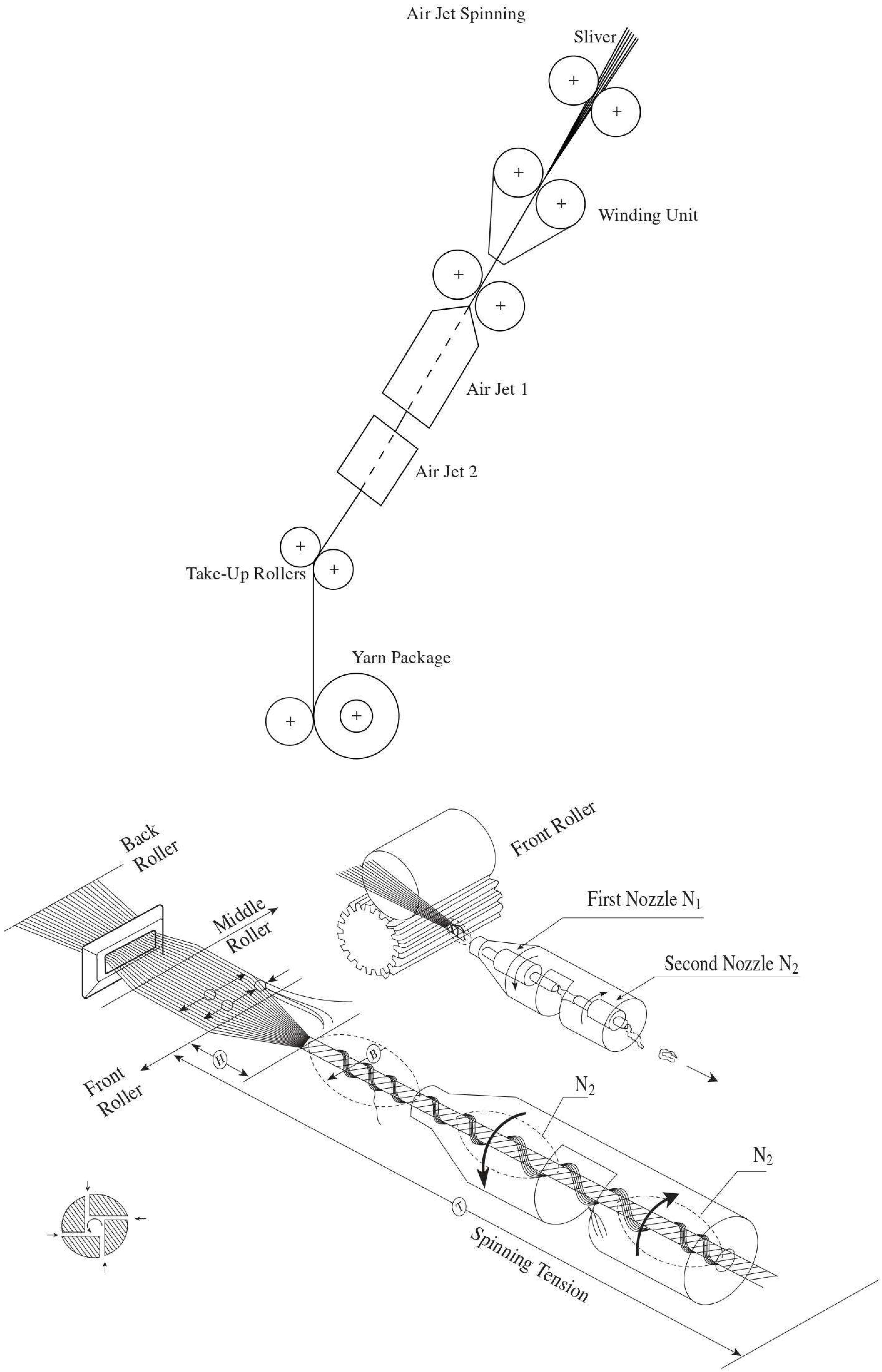


FIGURE 6.26 Murata air-jet spinning system. (Courtesy of Murata Co.)

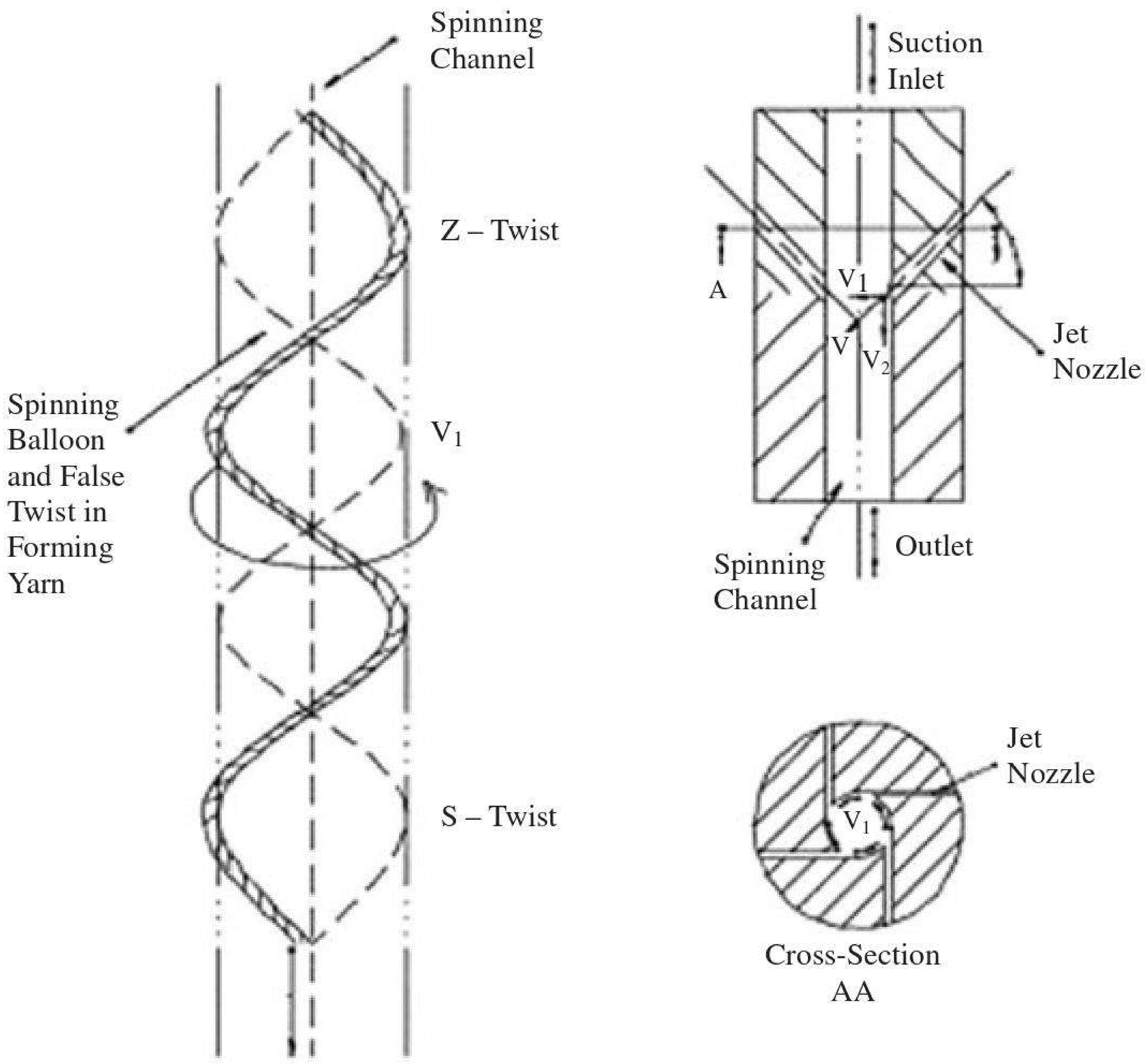


FIGURE 6.27 Basic design features of a twisting jet.

twisted ribbon and null the Z twist of jet 1, leaving some S-twist to travel toward the nip line of the front rollers. As in ring spinning, a spinning triangle will form just below the nip line of the front roller. The ballooning of the thread line tends to keep the edge fibers of the spinning triangle from being twisted together with the main bulk of fibers that subsequently form the yarn core. Consequently, the leading ends of the edge fibers are not controlled by the S-twist propagating from jet 2, and they are free to move with the vortex of jet 1, in the opposite direction (Z-direction) to the twist in the core. The vortex of jet 1 is therefore able to wrap the edge fibers around the twisted core of fibers.

Figure 6.28 illustrates the twist and wrap actions. The solid lines represent the false-twisting actions of the jets, and the dotted and dashed lines show the twist in the core and the helical wraps of the edge fibers. We can see that, at the front drafting rollers, the twist in the core would be the difference of S_2 and Z_1. As the core moves through jet 1 and into jet 2, its twist increases to S_2 until it enters the Z-twist zone of jet 2. Here, the S_2 twist in the core is removed by the opposing twist Z_2, leaving an untwisted core of parallel fibers. The helical wrap of the edge fibers around the core is initially equal to Z_1 and, in the S-twist zone, it is reduced to –a before increasing to Z_2.

To obtain effective wrapping, the width of the fiber ribbon entering the front drafting rollers is made to be as wide as possible without adversely affecting drafting. This is because air currents moving with the front drafting rollers can then suitably position the fibers at the ribbon edge for wrapping the core fibers.

When the boundary air layer moving with the front drafting rollers reaches the nip line of the rollers, the airflow has to move sideways and outward from the middle

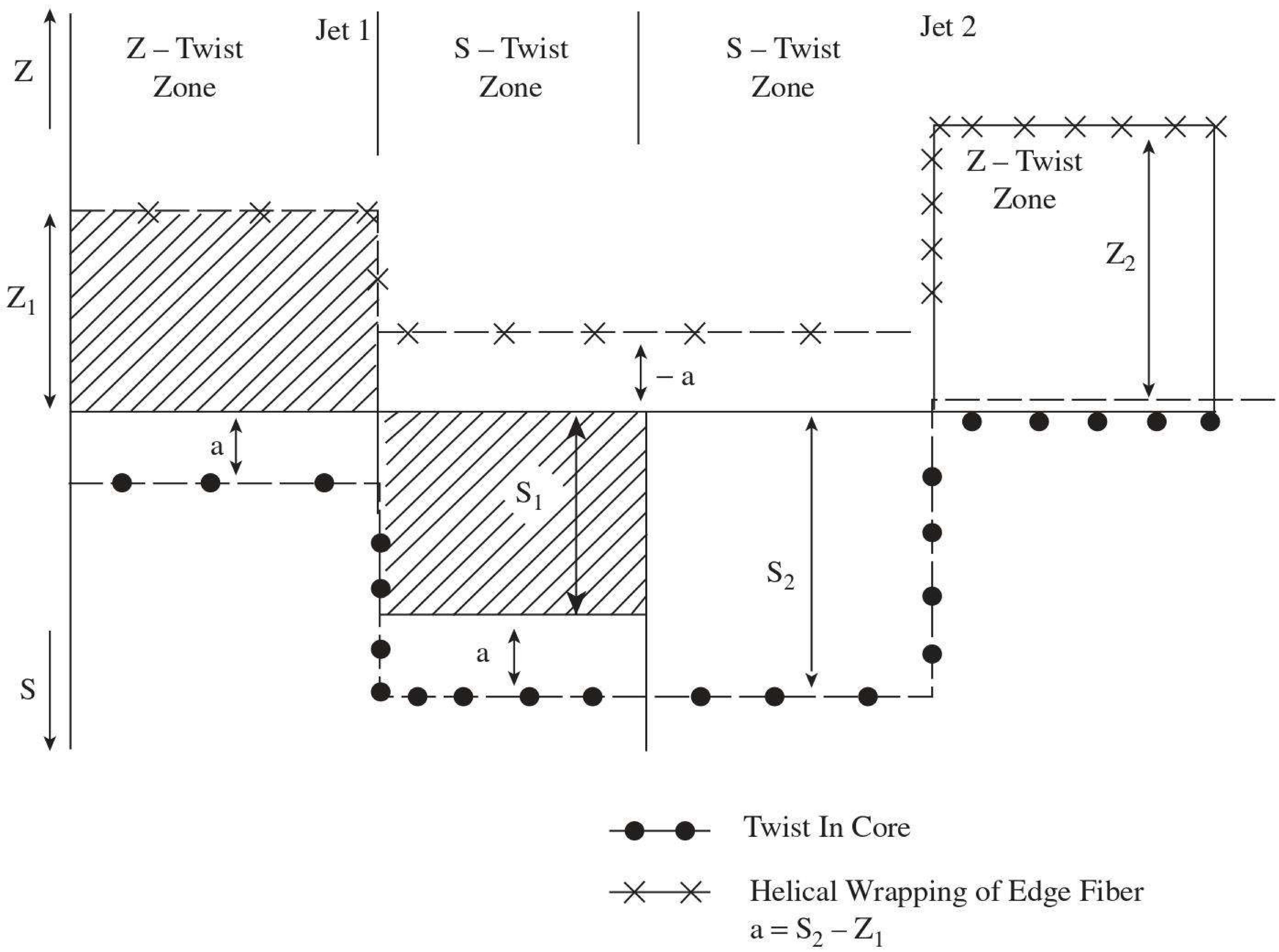


FIGURE 6.28 Illustration of twist distribution in thread line.

of the rollers. Compared with the more central part of the ribbon, fibers at the ribbon edge have insufficient neighboring fibers to support them against the sideways drag of the airflow. Therefore, they tend to move away from the bulk of fibers as they approach the nip line of the front drafting rollers. At the output side of the rollers, the airflow moves inward. Hence, the resulting velocity of the edge fibers is such that these fibers become inclined to the axis of the twisted core of fibers just before entering jet 1.

Figure 6.26 depicts how the edge fibers under the twisting actions of jet 1 forms the wrap-spun structure. For ease of explanation, the twisting and wrapping of the fiber ribbon is shown along a straight line in the figure, but its actual path is indicated by the dotted line, which denotes the spinning balloon. "F" is the width of fiber ribbon during drafting, which is separated by the airflow into "C" core and "W" edge fibers.

6.1.4.1.3 Single- and Twin-Jet Systems: Murata Vortex, Murata Twin Spinner, Suessen Plyfil

As a comparison with the above-described wrapping mechanism with tandem jets, it is useful to consider the effectiveness of wrapping with only one jet. In this situation, the Z–twisting action of the jet is not nullified, and the core is therefore Z–twisted. The edge fibers will, as described above, wrap the core with a Z–directional helix. Being that the core twisting is now in the same direction as the wrapping action, some edge fiber may become caught and twisted into the core, thereby reducing the number of them available to wrap the core. Because of the inclination of the approach of the free edge fibers to the axis of the core fibers, the angle of the wrap helix will be greater than the core twist angle. Since the S–twisting action of the single jet is equal in magnitude to its Z–twisting action, the core twist is removed as the forming yarn leaves the jet, but the angle of wrap is only reduced. Clearly, then, a single-jet system will not give as high a degree of wrapping as a tandem jet system unless a greater number of wrapper fibers can be generated.

One approach to increasing the number of edge fibers is to increase the length of the spinning triangle so that the twist insertion point is farther from the nip line of the front rollers. This results in edge fibers having to travel farther toward the twist insertion point at the apex of the spinning triangle. The effect of doing this can be demonstrated in conventional ring spinning by partially restricting the twist flow toward the nip line of the front drafting rollers. The result is an increase in edge fibers escaping twist insertion and becoming fly.

Figure 6.29 is a diagram of the single-jet design of the Murata Vortex system, which is a single air-jet spinning system. Compared with the tandem jet system, it incorporates a modified jet inlet. Little technical information is available on the working principle. Much independent research has yet to be done to gain a detailed understanding of the wrapping mechanism of the Vortex system. However, it is possible that a partial blocking of the twist flow may occur above the jet nozzles to enable the formation of an extended spinning triangle and thereby increase the generation of edge fibers.

The lower degree of wrapping that may be obtained from a single jet has the advantage of producing softly wrapped yarns. Two softly wrapped yarns can be subsequently plied to give a twofold wrap-spun yarn as a replacement for conventional plied yarns. The Murata Twin Spinner and the Suessen Plyfil are commercial twin-air-jet systems used for producing twofold wrap-spun yarns. The spun yarns from two single jets placed in parallel are wound simultaneously (in parallel) onto

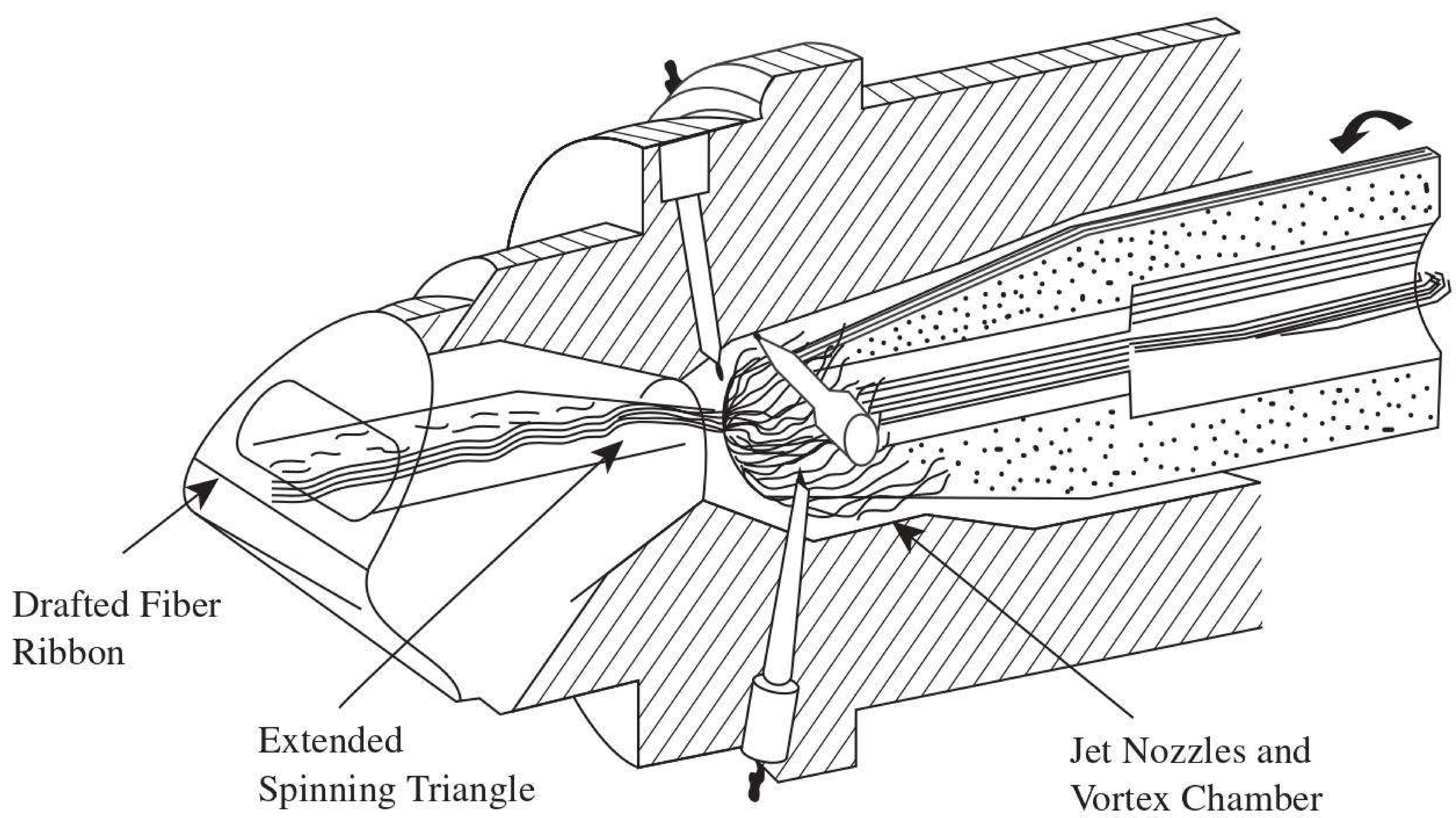


FIGURE 6.29 Murata Vortex single-jet design. (*Source:* US Patent: 5,528,895.)

one bobbin so as to form an assembly-wound package. The two yarns are subsequently unwound as one thread and plied, producing a twofold, air-jet wrap-spun yarn.

6.1.4.2 Filament Wrapping

Two commercial techniques are used for wrapping a filament around a core of staple fibers to produce a yarn. One uses the Repco system, replacing, at each spinning position, one of the alternately twisted strands with an alternately twisted filament (or filaments). The filament and strand subsequently ply together. Since the filament is finer than the strand, the effect is for the filament to wrap the strand in an alternating Z and S helix. This is called Selfil,[21] but it is not a widely practiced process.

By far the more common technique of filament wrapping is called hollow-spindle wrap spinning.[29] The basic principle of the process is illustrated in Figure 6.30. The essential features of the system are a roller drafting unit, a hollow spindle on which is mounted a pirn of filament, a pair of delivery rollers, and a package build unit. The spindle has an integral false-twister located at the bottom of the spindle, as shown in the diagram. This is a simple pin-type false-twister. There are other hollow-spindle systems with the false-twister located at the spindle top.

The drafted fiber ribbon issuing from the drafting system passes down the center of the hollow spindle and is threaded up to be false-twisted by the twisting device. The twist, which propagates to the nip of the front drafting rollers, prevents any uncontrolled drafting of the length of the twisted ribbon within the hollow spindle. The filament is also made to pass down the hollow spindle and around the pin twister. However, since the pirn rotates with the spindle, the filament is not false-twisted.

The effect of threading the filament around the pin twister is to cause the filament to wrap the drafted fiber ribbon as the ribbon is untwisted below the pin twister and thereby form the wrap-spun yarn. As the figure illustrates, the wrapping occurs below the false-twister, where filament and ribbon are held together between the twister and the delivery rollers. As the ribbon is untwisted, the rotation of the pin false-twister plies the ribbon and filament together, and, since the filament is the finer of the two counts, it wraps the untwisted fiber ribbon.

6.1.5 Twistless Spinning Systems

Definition: This is a system for yarn formation involving either continuous felting or the permanent or temporary adhesive bonding of fibers together to form a continuous length.

6.1.5.1 Continuous Felting: Periloc Process

The felting of linear fiber assemblies is fiber specific in that it concerns wool and wool blends. The underlying mechanism for wool felting is well reported[30,33] and is primarily the result of the differential frictional effect caused by the scale structure of wool fibers. Under the influence of mechanical force, wool will move unidirectionally, and the resistance to movement against the wool scale results in fiber entanglement, which is a useful means of consolidating an assembly of fibers into

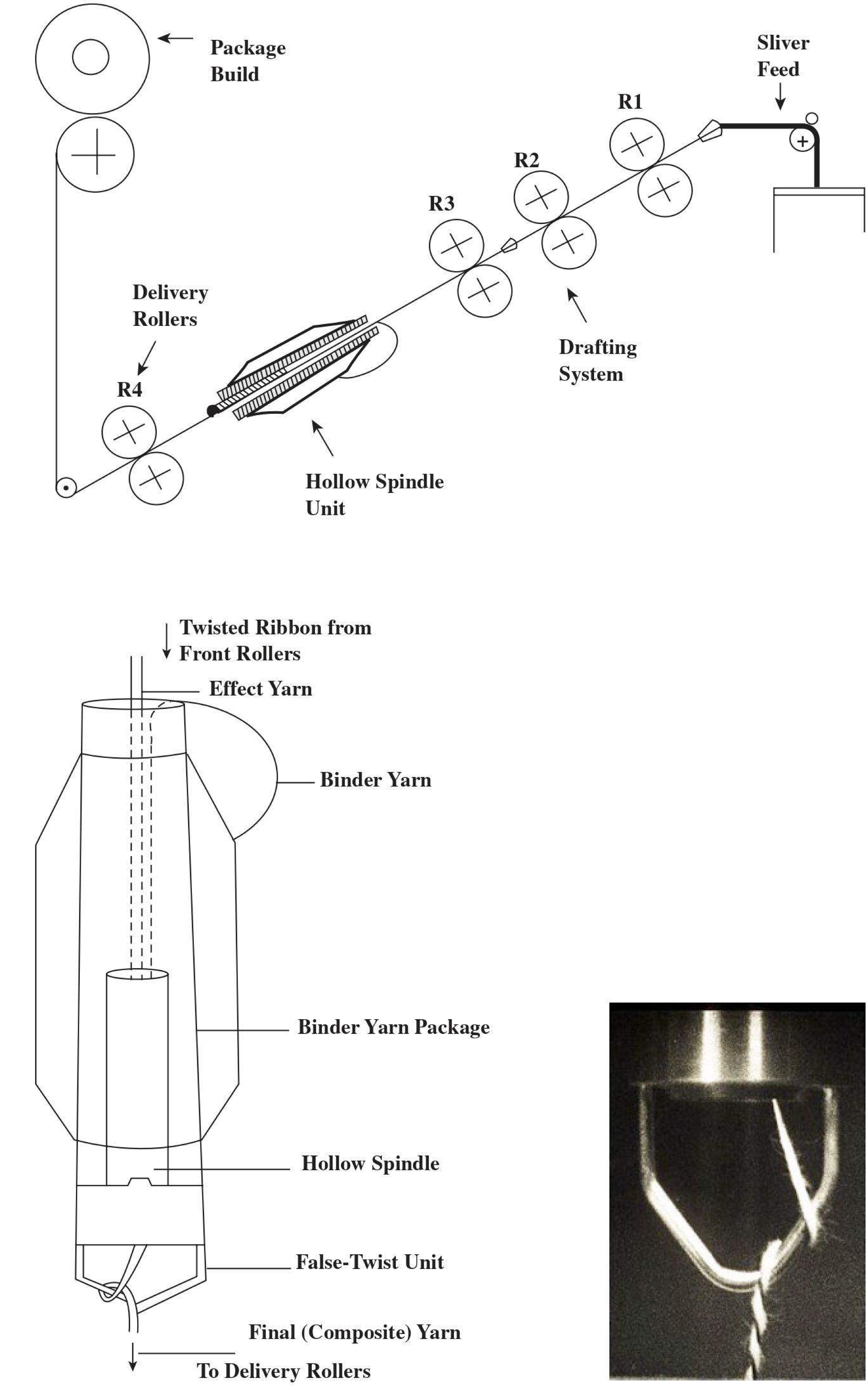


FIGURE 6.30 Hollow-spindle wrap spinning system.

the form of a yarn. Felting readily occurs when wool fibers are mechanically agitated in a suitable liquid medium and, besides the fiber properties, is dependent the on structure of the fiber assembly and the degree to which the liquid medium reduces the wool fiber modulus and acts as a lubricant. The felting of yarns has been carried out for many years,[34] as felted yarns are particularly desirable in the carpet field, where they are found to give reduced fiber shedding and to greatly improve tuft definition. Two continuous processes have been developed whereby not only can yarns be felted, but sliver and rovings can be converted into felted yarns.

Figure 6.31 shows a diagram of the Periloc process. The sliver or roving is fed without tension into a flexible tube along with hot water. The tube is mechanically agitated by a set of rollers mounted to a rotating circular plate; the rollers also rotate on their axes to enhance the mechanical treatment. The agitation consolidates the sliver into twistless felted yarn, which subsequently is passed through a line dryer. An alternative technique to the Periloc process is referred to as *rub-felting,*[35] which is analogous to the rubbing apron mechanism of a woolen card.

6.1.5.2 Adhesive Bonding: Bobtex Process

Although restricted to a limited market area within the technical textiles sector, the Bobtex process is nevertheless interesting as a concept because of its simplicity.[36,38] Figure 6.32 shows the system to consist of (A) a polymer extruder; (B) guides for a sliver feed to (C) two opening rollers; (D) a rotating, fiber-condensing drum, which is perforated around its peripheral surface and at which a suction is applied; (E) a false-twister and (F) a yarn wind-up; and (G) a package-build unit.

An untwisted filament yarn is passed through the extruder and across the surface of the fiber-condensing drum, then through the false-twister and onto the yarn package. A thermoplastic resin is extruded onto the filament yarn surface before the filament yarn reaches the fiber-condensing drum. On reaching the drum, separated fibers from the sliver feed are sucked onto the surface of the drum, and twist running up the filament yarn embeds the fiber into the molten resin on the filament yarn surface. As the resin cools, the fibers remain locked into the resin. The figure shows a cross section of the spun yarn, and the filaments can be seen locked into the yarn core.

The lack of any movement of the core filaments gives the yarn a high bending rigidity and restricts its use to high-strength technical applications. Glass, polypropylene, nylon, and polyester are the main filaments used, with a polypropylene resin binder. The filament usually constitutes 30 to 40% of the mass of the composite yarn, with the resin accounting for 10 to 20%, and the staple fibers having a proportion of 30 to 60%.

6.1.6 Core Spinning

Definition: This is a process by which fibers are twisted around an existing yarn, either filament or staple-spun yarn, to produce a sheath-core structure in which the already formed yarn is the core.

Core yarns are usually two-component structures, one forming the yarn core and the other the covering. Generally, a continuous filament yarn is used for the

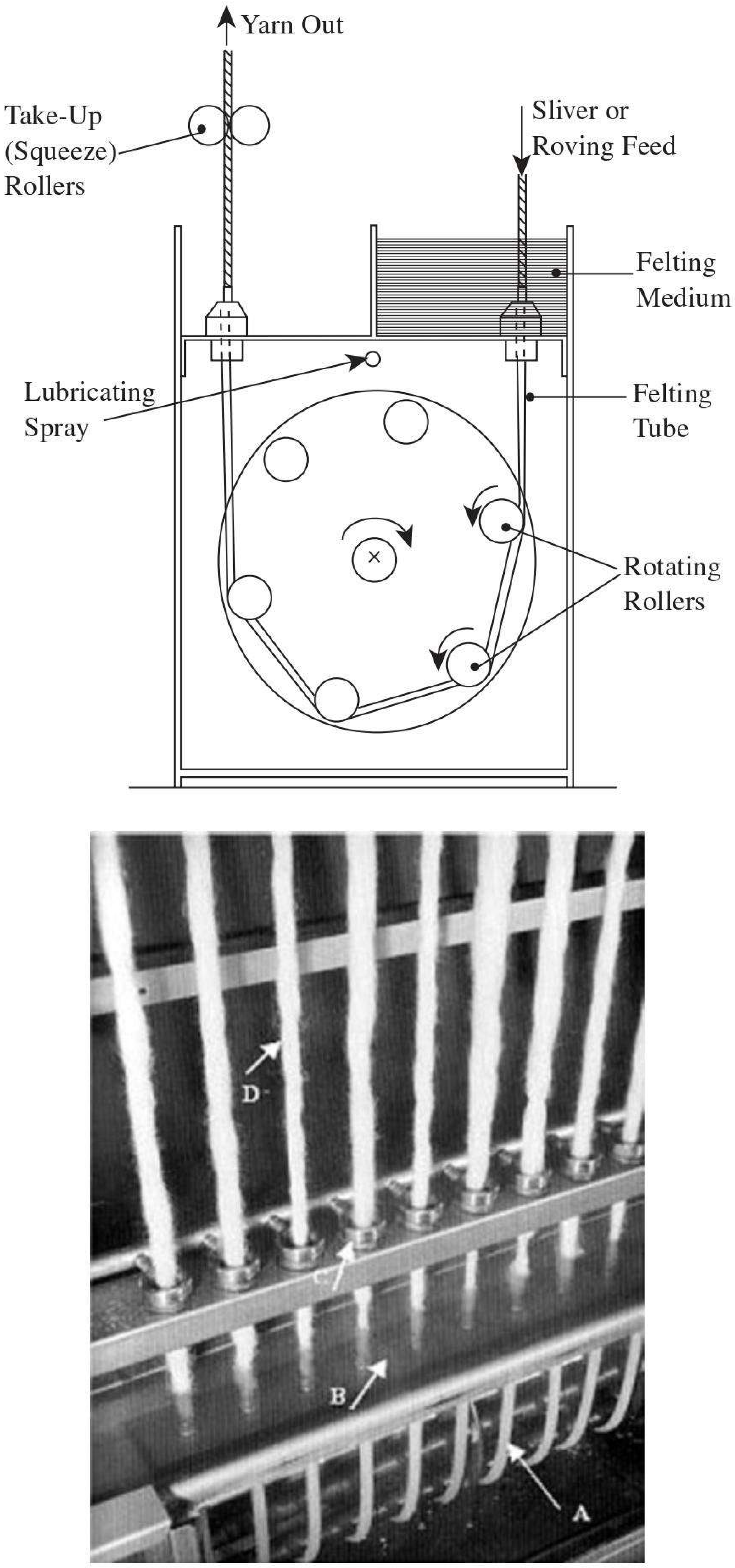


FIGURE 6.31 Periloc yarn felting system. (A) Felting tubes, (B) felting liquid medium, (C) false-twister, and (D) sliver. (Courtesy of Anon., *Wool Sci. Rev.,* 3(3), 1949.)

core and staple fibers as the sheath covering. Core yarns are usually used to enhance functional properties of fabrics, such as strength, durability, and, in the case of an elasticated core, “stretch-comfort.”

As Figure 6.33 illustrates, the ring-spinning method can be easily adapted for production of core yarns.[39,47] The filament is introduced into the center of the drafted

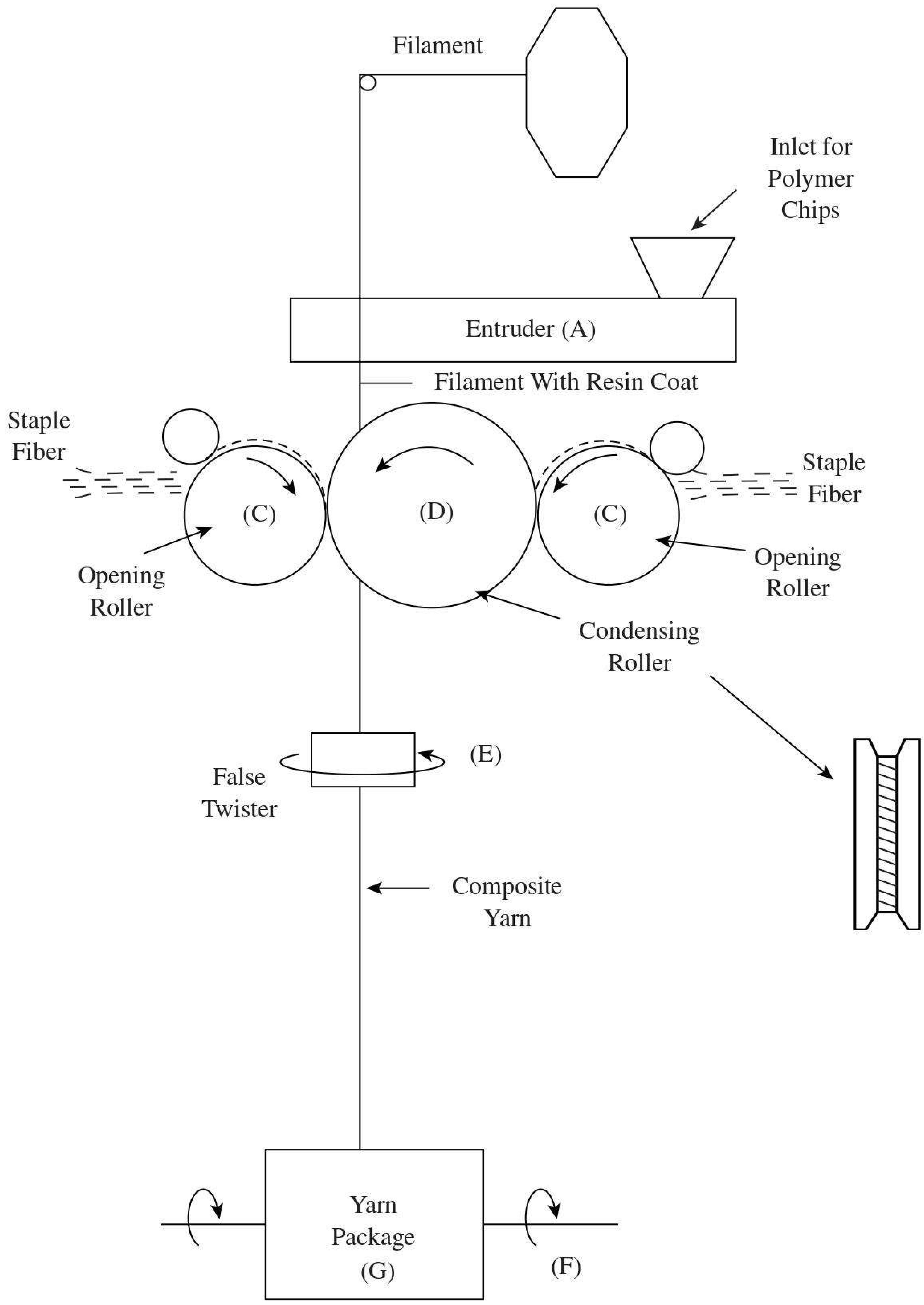
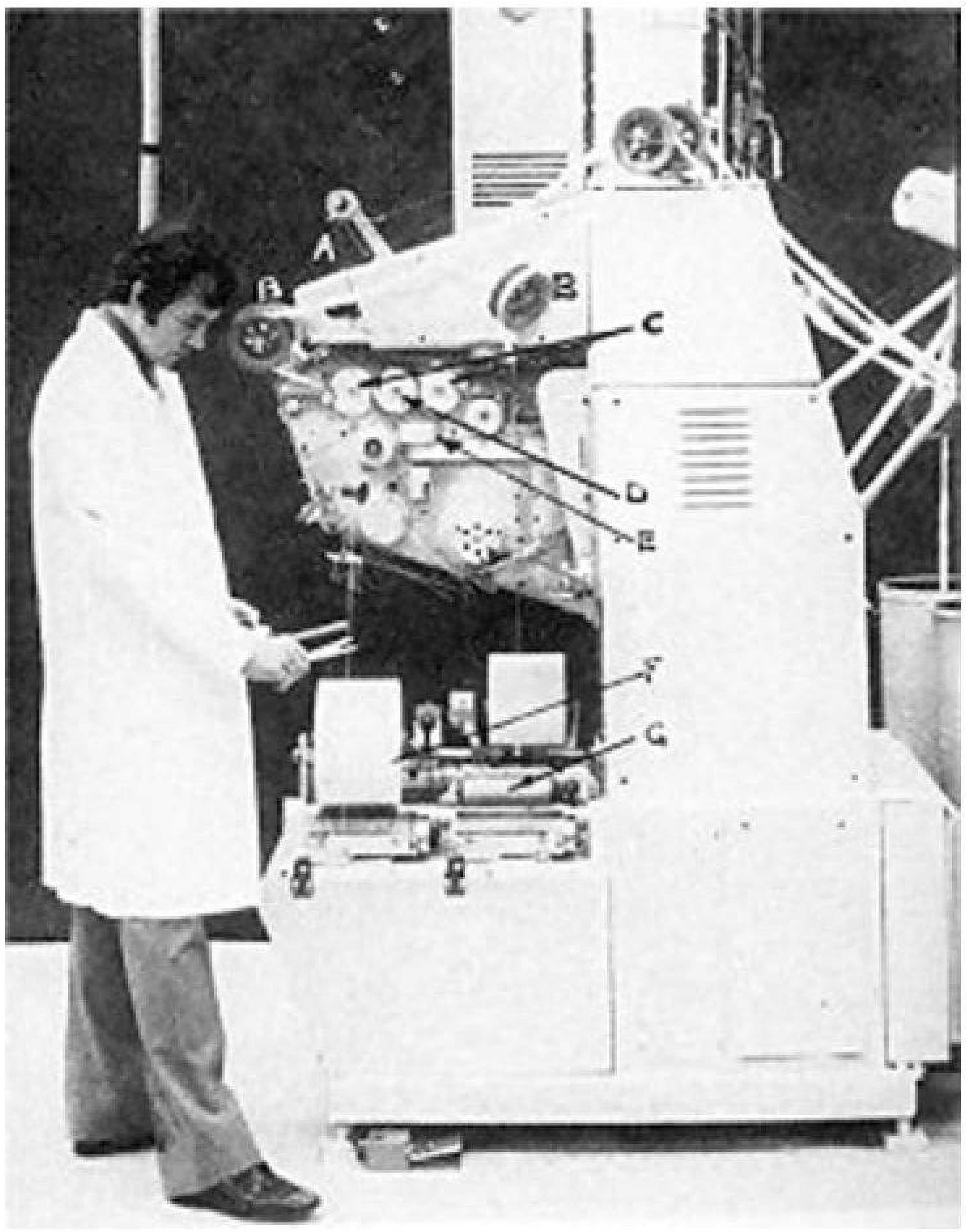


FIGURE 6.32 The Bobtex composite yarn system *(continues).*

fiber ribbon, at the nip of the front drafting rollers. It is usually pre-tensioned to an extension of around 5% for flat continuous filament yarns, about 30% for textured yarns, and up to 400% for an elastomeric core. If insufficiently tensioned, the filament will either periodically appear at the yarn surface, referred to as *grin through,* or become wrapped around the fiber ribbon as the ribbon is being twisted. The amount of twist, and the ratio of sheath to core employed, will depend on end use and particularly on preventing the sheath covering sliding along the core.

The unconventional processes that can be adapted readily for the spinning of core yarns are Dref friction spinning, Repco, air-jet, and hollow-spindle wrap spinning.



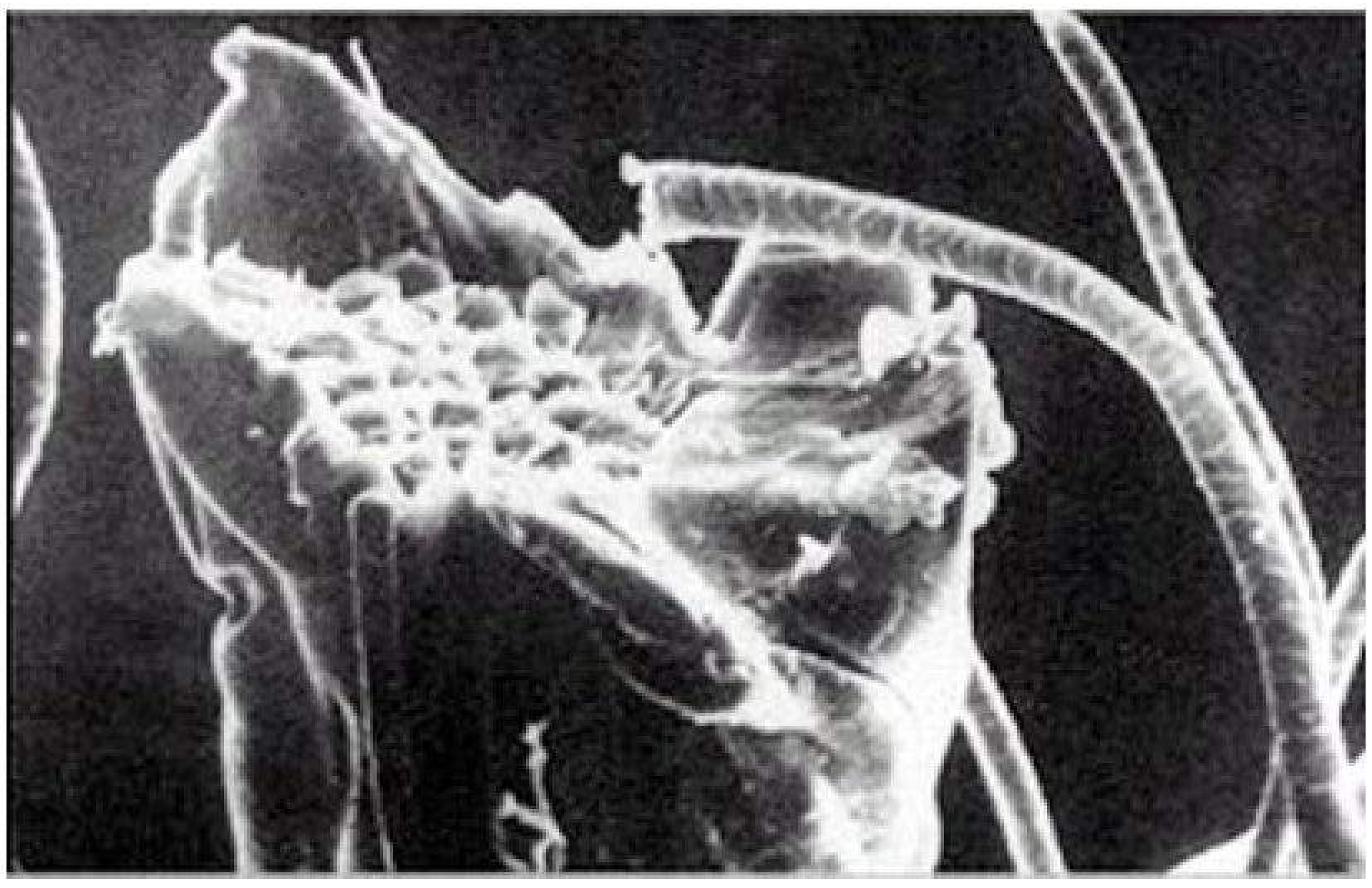


FIGURE 6.32 *(continued)*

6.1.7 Doubling Principles

Definition: This is the process of combining two or more yarns by twisting them together.

Before describing the structure-property relation of single yarns, it is desirable that a short reference be made to the operation known as *doubling, plying,* or *twisting.*

The basic objective of doubling is to attain a particular physical characteristic that cannot be obtained with a singles yarn of similar count to the plied yarn. Doubling is also used for the production of designed effects in yarns, but this involves a specialist type of doubling to produce what are called *fancy yarns,* which is the subject of Chapter 9.

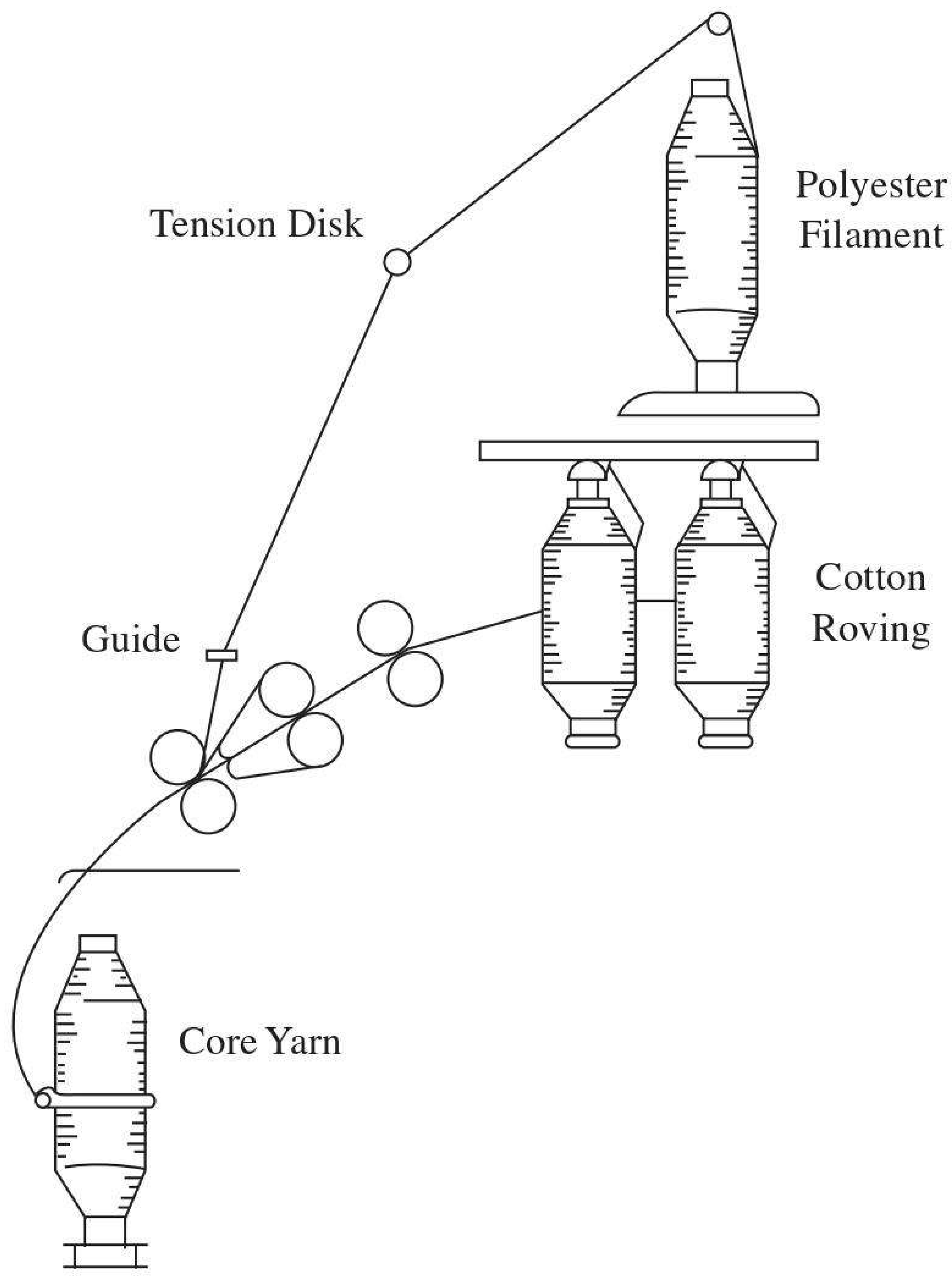


FIGURE 6.33 Conventional ring spinning of core yarns.

With regard to the physical characteristics of a yarn, these are altered by changing the direction and the amount of twist. An important parameter, therefore, is the *folded twist to singles twist ratio* (F/S ratio). We have seen in Chapter 1 that, with singles yarns, an essential feature is that fibers are assembled around the yarn axis, in most cases through the use of twist. In doubling, two or more singles yarns are assembled together and then twisted around each other, making a new yarn of a quite different character. With respect to this latter point, both the direction of the ply twist and the level of twist are of importance.

The ply twist direction is usually opposite to that of the singles yarn (i.e., *twist against twist*) but, for special applications, the same direction (*twist-on-twist*) may be required. In most cases, the singles twist will be in the Z direction, so plying with S-on-Z is a common practice. With Z-on-Z, the fibers in singles yarns will eventually come to lie at a steeper twist angle, and both the single and the folded yarn will be compacted to a smaller diameter than if the conventional S-on-Z step were to be followed. Generally, Z-on-Z plied yarns are usually assessed as hard to the touch and as having a strong tendency to form snarls* because they are twist lively.

Plying with the S-on-Z twist produces a doubled or plied yarn in which the fibers in the constituent singles appear to lie approximately parallel to the plied yarn axis. This gives the plied yarn a more smooth and lustrous appearance than a singles yarn or a Z-on-Z folded yarn. The S ply twist, instead of augmenting the Z singles

* *Snarly yarn* has a strong tendency to twist around itself if held in a untensioned state.

twist, balances it, and a suitable F/S ratio (usually 2/3) can be used to make the plied yarn twist stable.

One of the most desirable features of plied yarns is their very low irregularity as compared with a singles yarn of the same count. This is brought about by thick places in one singles component tending, on average, to offset thin places in the other.

Regarding yarn strength, it is universally agreed that a plied yarn will be stronger than a singles of the same fiber type and yarn count. This is because, with a plied yarn, there are initially fewer fiber lengths projecting as hairs from the singles and, when plied, many of the hairs are bound into the plied structure. More importantly, thin places are weak places and, as noted earlier, the two singles compensate for each other's irregularity. What is not necessarily the case is that the strength of a plied yarn is twice that of its constituent singles, and this is because the singles do not fully compensate for their differences in irregularity.

Plied yarns are generally considerably more expensive than singles of the same count, not only because at least one extra process is required, but also because the two singles, being finer than a yarn of the resultant count, are more costly to produce.

For certain special purposes, a third twisting operation may be needed, involving a combination of two or more plied yarns. The process is then known as *cabling*. An example is with some sewing threads in which the structure is required to have the maximum strength combined with the minimum irregularity, liveliness, and stretch.

There are three basic doubling methods: up-twisting, down-twisting, and two-for-one twisting, the latter two being widely used for staple yarns and illustrated in Figure 6.34. A more modern development is three-for-one twisting, which is essentially the combination of two-for-one and up-twisting.

6.1.7.1 Down Twisting

As shown in Figure 6.34, the yarns are withdrawn from the supply packages (A) by the feed rollers (B) and wound on the double-flanged bobbin (D) by the traveler (C) running on the ring (R). Twist is inserted by the rotation of the take-up package. Two bobbins of twisted singles yarn are therefore down twisted with S-on-Z, and the plied yarn wound onto a final bobbin.

It is important that the tensions in all the singles yarns are very similar during twisting. Otherwise, if yarns are not relaxed prior to doubling, their tendency to snarl will lead to faults in plied yarn. In addition, if two singles are not at the same tension, then, instead of plying, the lower-tension component will spiral around the higher-tension component.

6.1.7.2 Two-for-One Twisting

As also shown in Figure 6.34, the yarns are withdrawn from a stationary supply (A), which can either be an assembly-wound package or two separate packages, and passed through the center of the package(s). They are then ballooned around the supply package(s) by a rapidly rotating spindle (E) and wound up onto the take-up package (K). The yarns are ply twisted once between the package (A) and the spindle

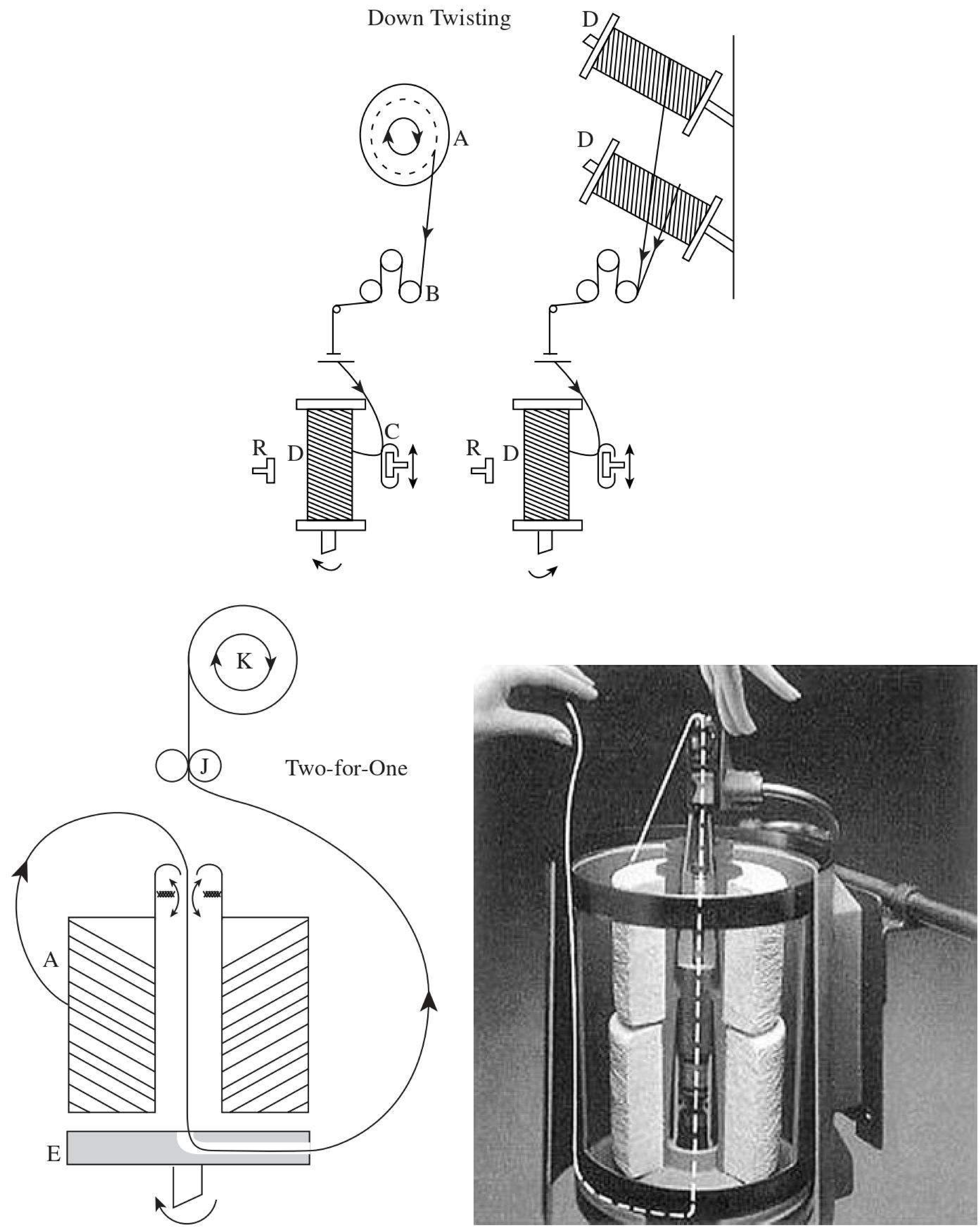


FIGURE 6.34 Doubling processes. (Courtesy of Savio Ltd.)

(E), and a further turn is inserted between (E) and the take-up rollers (J) so that two turns of twist are inserted for every turn of the spindle (E).

6.1.8 Economic Considerations

In discussing the economic aspects of spinning systems, it must be borne in mind that, for many and various reasons, yarn production costs can differ significantly from country to country and, at times, political issues can alter what may often be considered advantageous circumstances. It is therefore appropriate to discuss here only the technically based factors, which are significant when making investment decisions for spinning plants.[48] From this viewpoint, comparisons made between spinning processes principally include the following:

- Investment cost, relating to capital investment for machinery, buildings, depreciation and the interest on loans.
- Conversion cost, which involves the production rates of machinery, the efficiency of the process machines in handing the raw material, waste generated, direct labor, and power consumption. Fixed costs, such as insurance, indirect labor, maintenance, and so on, may or may not be included.
- Raw material cost. The quality factor of the raw material is at times a debatable point. Raw material cost usually accounts for around 50% or more of the production cost, and the debate is whether certain spinning systems enable cheaper material to be used. The other side of this idea of the use of cheaper material is what may be seen as another indeterminable, *product value.* To circumvent such sometimes indefinable parameters, the assumption may be made that the same raw materials would be processed except where there are established technical reasons why a particular spinning system cannot spin certain materials.

From the above points, comparisons may be made according to four key factors: labor, space, power, and capital.

It was stated at the beginning of Section 6.1 that ring spinning was the dominant spinning process, and this is in spite of its much lower production speed, as shown in Figure 6.2. Ring spinning is therefore generally taken as a comparator for both process economics and product quality.

It is useful to have a general view of the cost structure of a typical ring-spinning production, and Table 6.3 gives the data for the production of 30 tex ring-spun 100% carded cotton yarns with respect to the above four cost factors. These figures illustrate what is well known — that roving production, spinning, and winding account for over 80% of the conversion cost. Much has been done in the way of automation and machine integration. Examples include automatic doffing of ring bobbins at the ring spinning machine and, where appropriate, linking the spinning machine with the winding machine,[49,56] plus auto-doffing at the roving frame with automatic transport of the roving bobbins to the ring frame. However, the ring spinning process is unlikely to overcome the inherent disadvantage of low production speed. This is because of the limitation of twisting and winding occurring through one action — the circulation of the traveler around the ring.

There is little publicly available data that allows us to present a comparison of the various systems described in the preceding subsections. However, being the most widely adopted of the alternative spinning systems, rotor spinning is often used to illustrate how high-production systems compare with ring spinning, even though many of the systems are restricted to the production of coarser yarn counts.[57,63] Figure 6.35 gives a comparison for the two systems based on the four key factors.

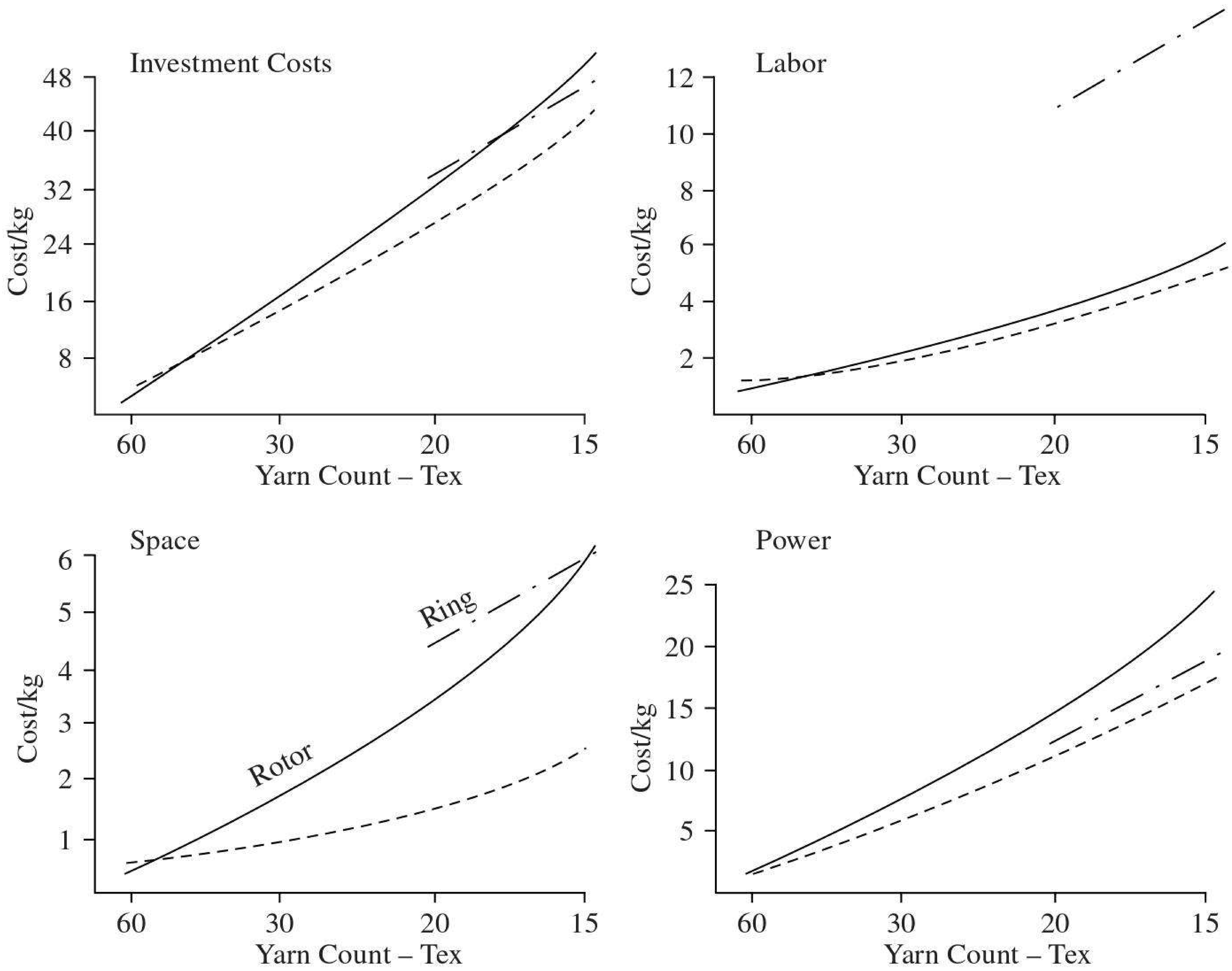


FIGURE 6.35 Comparison of key factors, ring and rotor.

TABLE 6.3
Production Cost Structure

Stages	Labor (%)	Space (%)	Power (%)	Capital (%)	Total (%)
BR	2	8	4	5	4
C	1	7	8	8	6
D	1	3	1	1	1
D	1	3	1	1	1
RP	19	15	8	10	13
RS	23	46	62	51	44
W	53	19	16	24	31
Total	100	100	100	100	100

BR = opening and cleaning, C = carding, D = drawing, RP = roving production, RS = ring spinning, W = winding

It can be seen that, in all cases except for power consumption, rotor spinning has significant cost advantages. This is because there are fewer process stages, since sliver is fed to the rotor machine, and the automation of rotor machines[64,66] includes doffing, yarn-end piecing, and cleaning. Importantly, rotor packages do not need rewinding. It is, however, important to note that all the advantages shown for the four key factors are mainly in the count range of around 20 tex and coarser.

At the finer end of the count range shown, ring spinning is not far removed from the rotor costs (except for labor) and, projecting to finer counts, the indication is that the difference in cost becomes negligible and eventually in favor of ring spinning. This is because the finer the yarn count, the more difficult it is to produce satisfactory rotor yarns with low twist. As explained earlier, there are a number of changes that can be made to rotor parameters to improve twist insertion and thereby increase production speed for fine counts — in particular, smaller rotor diameters and faster rotor speeds. However, similar to many of the other alternative systems to ring spinning, the yarn structure and related properties often become the all-important factor. Table 6.4 gives as an example the range of reported end uses of the yarns for most of the systems described above. It is evident that the ring-spun yarn's product value is one reason for its continued importance. The structure-property relation of ring-spun yarns is a an important factor in the yarn's acceptance for a wide range of end uses, and the following section deals with the topic of yarn structure and properties.

TABLE 6.4
Product Applications

End products of yarns produced by different spinning systems							
End use	Rotor	Open-end Dref 2	Dref 3	Wrap spinning air-Jet fasciated	Hollow spindle	Ring spinning	Repco
Shirting				X		X	
Bedding				X		X	
Outerwear	X			X	X	X	
Sportswear	X		X			X	
Toweling					X	X	
Domestic Textiles	X	X	X		X	X	
Blankets	X	X				X	
Knitted Goods					X	X	X
Stretch Garments						X	X
Decorative Fabrics	X					X	
Carpeting		X			X	X	X
Industrial Textiles	X	X				X	

Courtesy of Krause, H. W., Staple-fibre spinning systems, *J. Text. Inst.,* 3, 185–195, 1985.

6.2 YARN STRUCTURE AND PROPERTIES

The primary purpose of a staple yarn structure is to provide the means of utilizing the properties of fibers of discrete lengths (in particular, elastic properties) sufficient for the yarn to sustain spinning and subsequent manufacturing processes, and for the ultimate textile fabric to have the visual and tactile aesthetics and elastic properties required for specific end uses.

Yarns encounter differing kinds and levels of deformation during spinning, subsequent processing, conversion into fabrics, and in fabric end uses. For example, yarns may pass over guide rollers, tensioning devices, and other machine elements during spinning and post-spinning operations; they are also subjected to complex deformation forces in winding, sizing,* weaving, knitting, sewing, and intermediate processes.

In daily use, yarns, in the form of knitted and woven fabrics, are subjected to deformation resulting from tension, compression, and bending. Garments are required to give the consumer tactile and thermal comfort. For tactile comfort, the fabric must have a pleasant handle or feel against the skin. The accommodation of body movement is by fabric slippage over the skin as well as by fabric stretching and folding or buckling. Thermal comfort requires a warm, dry microclimate next to the skin obtained through trapped layers of air for insulation. The fabric is required to maintain body heat with minimal restriction to perspiration vapor flow during sedentary body states and good moisture transfer by wicking for active states. Thus, although a first requirement for comfort is a low scratchiness[68] (exhibited by fibers of low bending rigidity and friction), with regard to fabric, the yarn structure-property relation is as important as the fabric structure-property relation to the overall performance of the end product.

With respect to yarn structure and properties, we will consider only single yarns, since most fabrics are made from single yarns; particularly yarns produced by the more commercially used spinning systems, namely ring, rotor, air-jet, hollow-spindle, and Dref friction spinning.

6.2.1 Yarn Structure

In Chapter 1, the simple helix model was described as a simple means of representing a yarn in which twist is used to bind fibers that are assembled with their lengths straight and parallel prior to twist insertion. We noted that, because the model did not include the discontinuities in the helices representing the twisted fibers, it is a more suitable representation of continuous filament yarns than of staple yarns, which are made from fibers of discrete lengths. The helix model, however, has been used over many years to gain an understanding of the importance of structural parameters of staple yarns. From knowing the model's limitations, key features of staple-yarn structures have been identified and subsequently used to devise more sophisticated models in the attempt to theoretically derive predictive equations for yarn properties in relation to fiber properties. These newer models do not, however, give any further insight into what has already been established from theoretical studies of the simple helix model and from experimental observations of real yarn structures. In our consideration of staple yarn structures, we shall therefore use the helix model as a reference for comparative observations with real yarn structures and, where appro-

* Sizing is a process in which short-staple yarns to be used as warps in weaving are impregnated with a gelatinous substance, such a starch, to improve their abrasion resistance and strength and to reduce friction.

priate, refer to the predictive models. As the simple helix model relates best to a continuous-filament yarn structure than to a staple-yarn structure, it will be useful at times to refer to the filament yarn structure for comparative purposes.

6.2.1.1 Surface Characteristics and Geometry

Figures 1.3 (Chapter 1) and 6.36 (below) depict the surface structures of a continuous filament yarn and of ring-, rotor-, friction-, and air-jet spun yarns. Although the yarns shown are not of the same count or fiber type, the figure serves the purpose of comparing the typical structural features of the different yarns. It can be seen that, whereas the filament yarn has no filaments projecting from it surface, the staple yarns, because of the discontinuities of the fiber helices, have fiber ends and loops jutting out from the body of the yarn to give the yarns a hairiness profile. The fibers forming the hairs have part of their lengths caught within the body of the yarn and part extending from the yarn surface. We shall consider later the difference in hairiness between the various yarn structures.

Looking closely at the conventional ring spun-yarn structure, we can see that the fibers, which form the body of the yarn, lie parallel along the helix of twist. With the rotor yarn structure, the vast majority of fibers appear to lie almost parallel to each other with the same helix angle of twist. Around these are wrapper fibers with varying angles of wrap; some show almost a 90° wrapping angle. Rotor yarns are basically two-zone structures comprising a core of fibers that are aligned with the helix of the inserted twist and form the bulk of the yarn, then an outer zone of wrapper fibers, which occurs irregularly along the core length. A detailed study of the surface structure of rotor yarns[69] shows that the variation of surface appearance along the yarn length may be classified as indicated in Figure 6.37 and Table 6.5.

From the description of the spinning process, the Dref-3 yarn (not shown) is also a two-zone structure, whereas the Dref-2 (shown) is a layered structure. Both friction-spun yarn structures have a uniform surface appearance of fibers lying along the helix angle of twist. This, however, is not case with air-jet spun yarns. These are two-zone structures, where the central core of fibers has no twist and is wrapped by an outer zone of fibers, which, similar to rotor yarns, occurs irregularly along the core length. Figure 6.38 and Table 6.6 give a simple classification of the surface appearance of air-jet yarns.[70,71] Although these structural classes are distributed at random relatively to each other, depending on the process conditions and on fiber properties, their distribution along the yarn length can follow a pattern.[72]

Hollow-spindle, wrap-spun yarns (HS yarns) are basically two-component yarns comprising a twistless core component of parallel staple fibers, of any length, and a filament component, which normally constitutes 2 to 5% of the yarn mass as a wrap binder on the outside (see Figure 6.36). Because of the arrangement of the core fibers, HS-yarns are also referred to as *parallel yarns.* The filament essentially effects the necessary cohesion of the staple fiber core by exerting radial pressures along its helix of wrap and thereby increasing the frictional contact between the core fibers. The number of filament wraps per unit length in basic HS yarns is approximately the same as the level of twist in a similar count conventional ring-spun yarn. During processing, HS yarns appear lean and smooth. This is the result

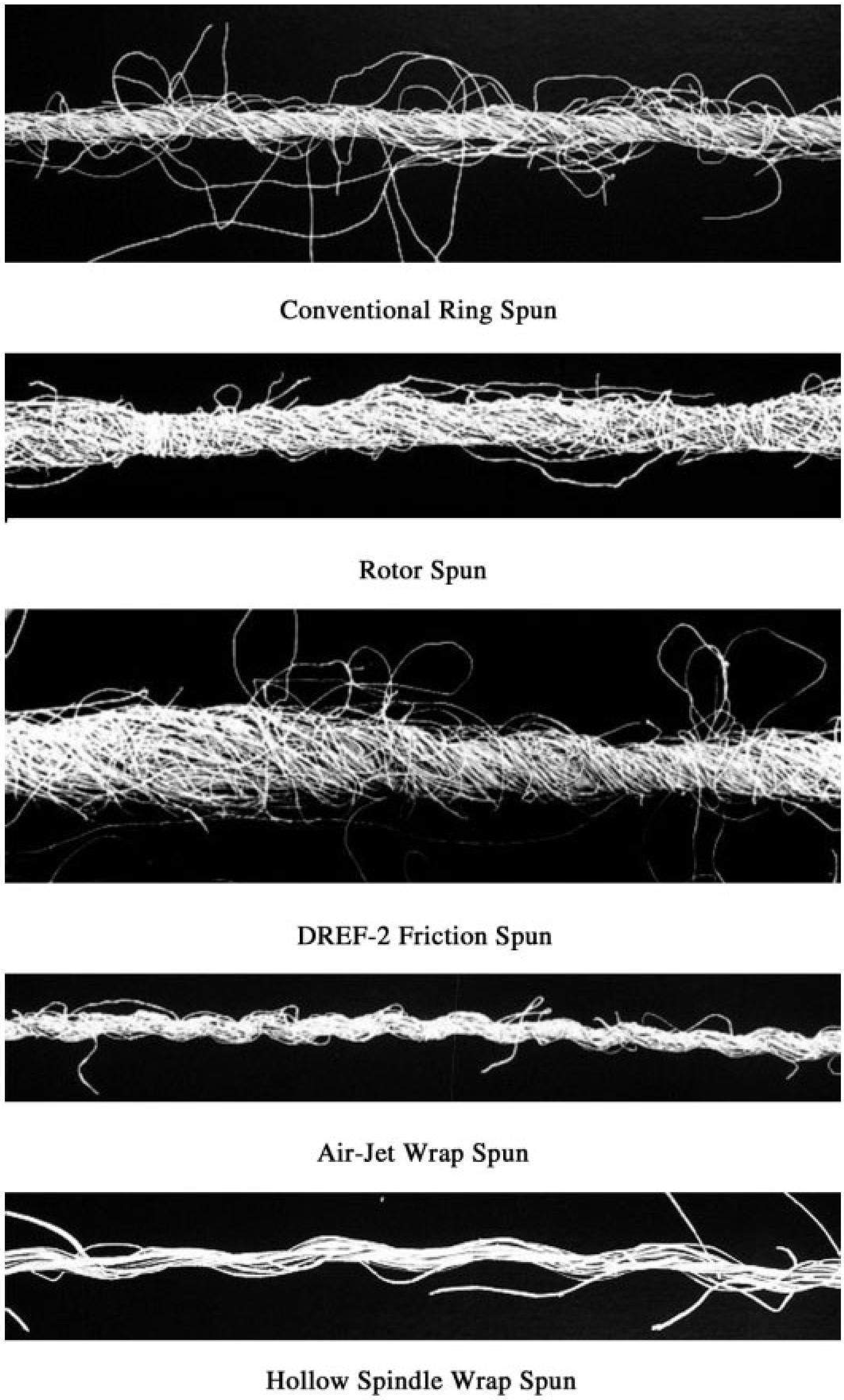


FIGURE 6.36 Spun yarn structures.

of the constrictive effect of the wrapping filament under tension, and it accounts for the low hairiness of the yarns. When not under tension, the contraction of the filament gives the yarn its bulky, crimped appearance.

6.2.1.2 Fiber Migration and Helix Model of Yarn Structures

From the above descriptions, it is evident that the simple helix model does not fully explain how fibers of discrete lengths can be held together to form a yarn. Such a

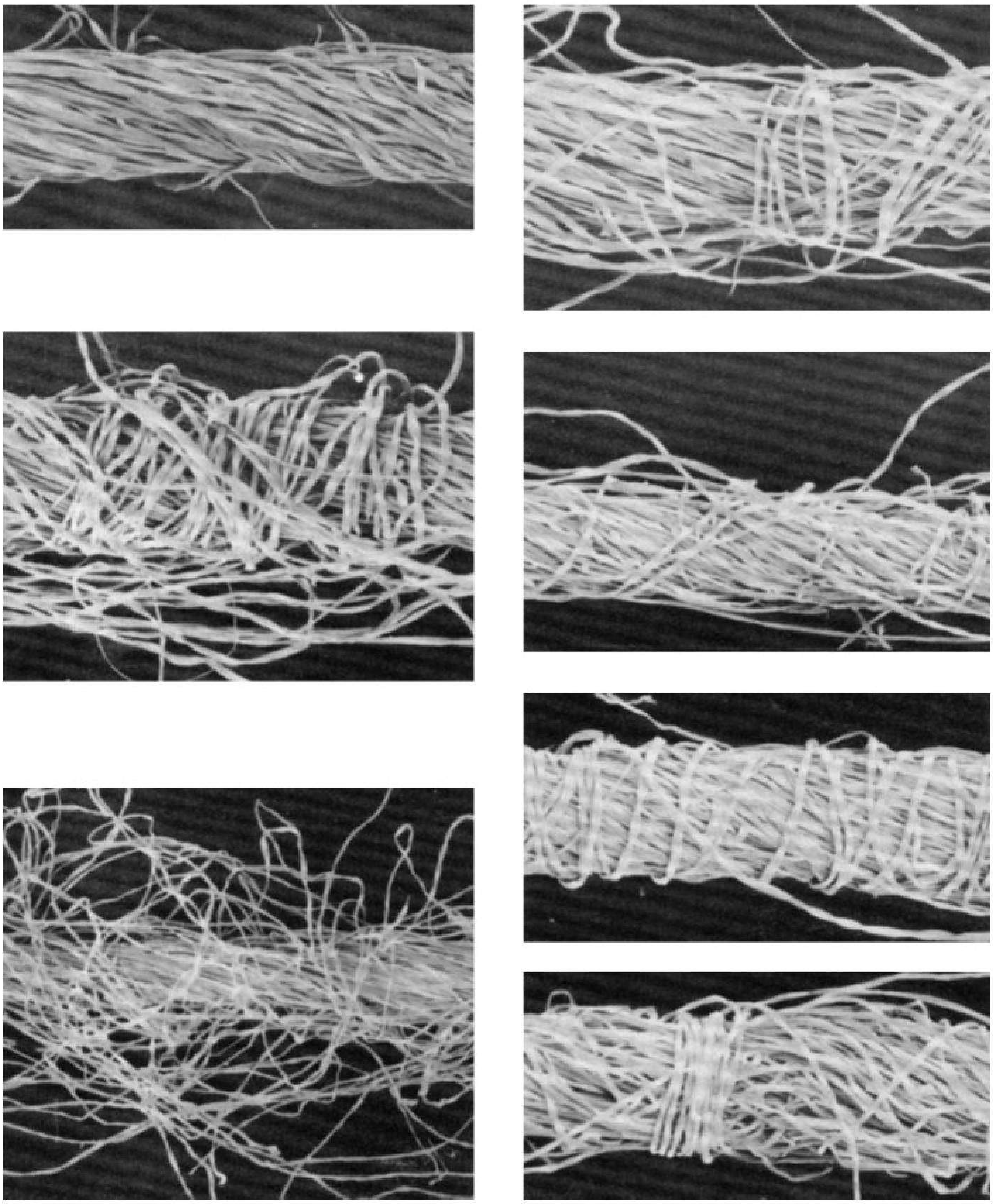


FIGURE 6.37 Observed surface structure along rotor-spun yarns. (Courtesy of Lawrence, C. A. and Finikopulos, E., Factors effecting changes in the structure and properties of open-end rotor yarns, *Indian J. Fibre and Text. Res.*, 17(12), 201–208, 1992.)

simple structure formed from staple fibers would be incapable of withstanding tensile loads and surface abrasion. Furthermore, a staple-yarn structure based on the simple helix could not be made by known spinning methods. This is because, with each turn of twist, the paths followed by fibers in the yarn vary in length according to their distance from the axis. To achieve this, each fiber would have to be delivered for twisting at a rate appropriate to the position it would occupy in the yarn, and this is not practicable.[73]

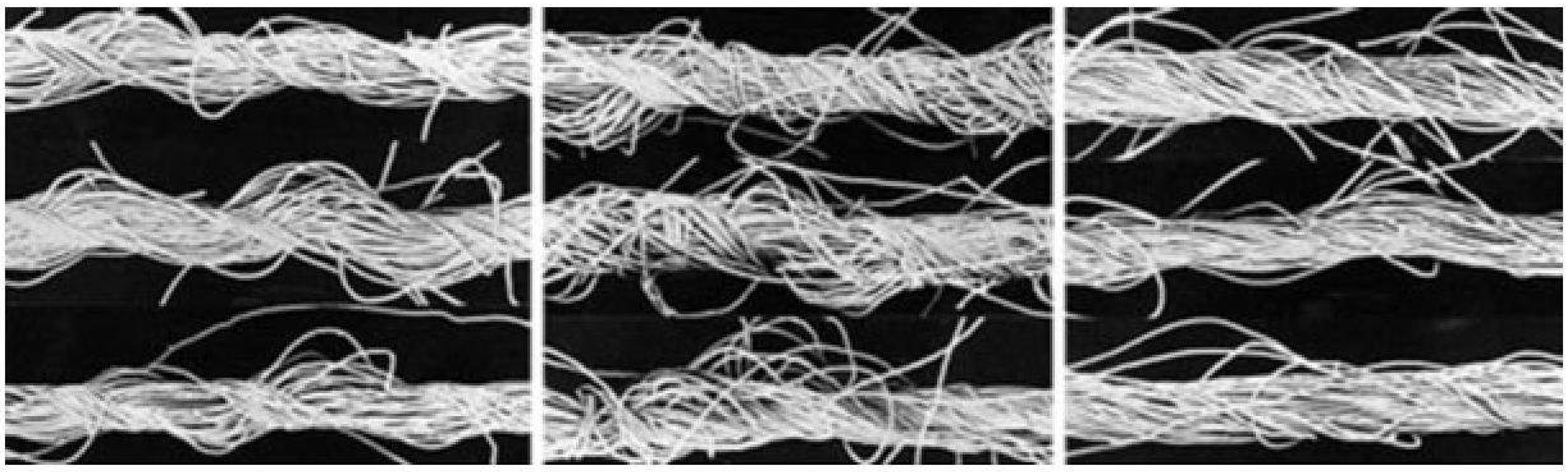


FIGURE 6.38 Air-jet spun yarn surface structure.

TABLE 6.5
Classification of Rotor–Spun Yarn Surface Structure

Class of surface structure	Description
Class I – Ordered	There are no wrapper fibers; has the appearance of uniformly twisted core fibers.
Class II – Loosely wrapped	Loose wrapping of fibers around the core. Wrapping angles differ from the twist angle of core fibers.
Class III – Hairy	Surface fibers are loosely attached to the yarn and appear entangled.
Class IV – Multiple wraps	Part of the wrapping fibers bind the core with a high wrap angle, and part at a lower angle having direction opposite to that of the core twist.
Class V – Opposingly wrapped	Wrapper fibers have a wrap helix in opposite direction to the core twist.
Class VI – Tightly wrapped	These sections of yarn appear uniformly wrapped and have few protruding fiber ends or loops. The angle of wrap is approximately 90°.
Class VII – Belts	Fibers are wrapped very tightly around the core at 90° in a narrow length on the order of 1 mm.

TABLE 6.6
Classification of Air-Jet Spun Yarn Surface Structure

Class of surface structure	Description
Class I – Ribbon wrapped	A thin ribbon of fibers uniformly wrapped around the twistless core; the angle of wrap ranges from 40° to 45°.
Class II – Randomly wrapped	Fibers wrapping the twistless core at varying angles; although most wrappers have the same helix direction, some are in the opposing direction. The Class II substructure may be further divided into four groups.[71]
Class III – Unwrapped	Sections of yarn with no apparent wrapper fibers, in which the core appears twisted or twistless.

The idea that staple yarns have self-locking structures is attributed to Peirce[74] and Morton.[73] Essentially, a self-locking structure is achieved by fiber lengths meandering from the outer to the inner regions of a yarn, throughout the yarn length, as they are twisted to lie along the helix angle. In this way, fibers become interlaced to give the spun yarn cohesion. This action is called *fiber migration.* Migration also occurs in twisted filament yarns.[75]

Definition: Fiber migration is the cyclic change in the distance of elements of a fiber or filament (along its length) from the axis of a yarn, which occurs during production of the yarn.[76]

The simple helix model may be modified to depict the cyclic path migration of the fibers moving from one cylindrical layer to another (see Figure 6.39). Hearle[75] used the variable $(r/R)^2$ as a relative measure of the radial positions of points along the length of a fiber within the yarn, with respect to the yarn axis (z). A plot of $(r/R)^2$ against the corresponding distances along z gives what is termed the *migration envelope,* and the degree of migration may be quantified by the parameters given in Table 6.7.

TABLE 6.7
Fiber Migration Parameters

Migration parameter	Migration equation
Mean fiber position	$Y_m = \frac{1}{Z_n}\int Y\,dz$ $= \sum \frac{Y}{n}$ where n is the number of measured positions over a yarn length Z_n
Root mean squared (rms) deviation	$D = \left[\frac{1}{Z_n}\int (Y - Y_m)^2 dz\right]^{\frac{1}{2}}$ $= \left[\frac{\sum (Y - Y_m)^2}{n}\right]^{\frac{1}{2}}$
Mean migration intensity (the rate of migration given by the slope of the migration envelope)	$I = \left[\frac{1}{Z_n}\int \left(\frac{dY}{dz}\right)^2 dz\right]^{\frac{1}{2}}$
Equivalent migration frequency	

Grishanov[77] reports a more rigorous and elaborate approach for mathematical modeling of fiber migration in a staple yarn. This method employs the Markov process to model the path of individual fibers through the yarn. It thereby incorporates the main features of a yarn structure, such as irregularities in the number of

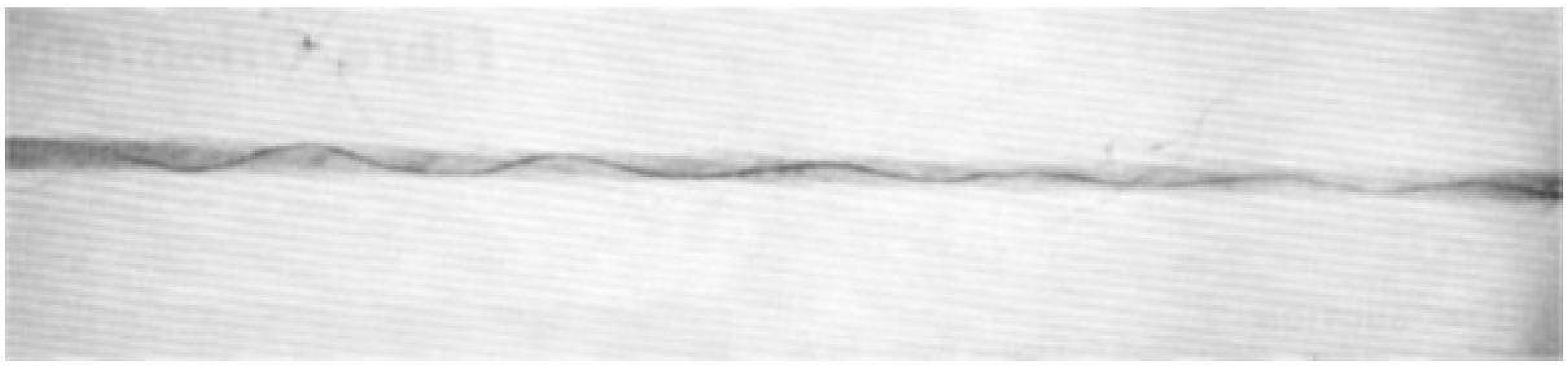


FIGURE 6.39 Tracer fiber showing migration path in conventional ring-spun yarn structure.

fibers in the cross section, variation in yarn diameter, and hairiness. The migration is developed as a probability matrix, called a *transition matrix,* of fiber lengths moving between radial distances. The migration characteristics of mean fiber position, root-mean-square deviation, and mean migration intensity are expressed in terms of the transition matrix. The transition matrix is then used to establish a finite element representation of the yarn structure.

It the earlier descriptions of the basic principles of the spinning processes, the details of the formation of the different yarn structures were not considered. It is, therefore, appropriate now to describe how the above yarn structures are formed, taking into account fiber migration.

6.2.2 Formation of Spun Yarn Structures

6.2.2.1 Conventional Ring-Spun Yarns

In ring spinning, the spinning triangle is the yarn formation zone. It is here that the individual fibers or groups of fibers are twisted and consolidated to form the ring-spun yarn structure. During the formation of the conventional ring-spun yarn structure, fibers in the spinning triangle will be in one of the following four situations:[77]

1. The leading end of a fiber is caught in the convergence point (i.e., twist insertion point), but its trailing end is free.
2. The leading end is free while the trailing length is still under the control of the front drafting rollers and subsequently becomes caught among other fibers being twisted at the convergence point.
3. Both leading and trailing ends are free.
4. The leading end is caught in the convergence point while its trailing length is still under the control of the front drafting rollers.

In the first situation, the trailing end of the fiber will project from the surface to become a hair. Case 2 results in the leading end projecting as a hair. For 3, the fiber may wrap around the yarn as a wild hair or, more likely, escape to become fly and eventually be collected as waste. With case 4, the fiber gets bound into the yarn structure through the mechanism of migration and twist. The vast majority of the fibers are in this situation, and they are therefore the ones that give the yarn its cohesion and mechanical properties. Accordingly, we will now consider the mechanism of fiber migration.

6.2.2.1.1 Mechanism of Fiber Migration[73]

At the spinning triangle, the fibers in the edge zones follow a longer path than those closer to the center line of the triangle, coincident with the yarn axis. Assuming the length issuing from the front rollers to be the same for all fibers, then the spinning tension and twisting action will induce the highest tensions in the edge fibers. The fiber tensions become progressively lower to reach a minimum at the center line of the triangle. The fibers at the edge zones therefore have the largest of the tension components directed sideways toward the central line of the triangle. Consequently, the edge fiber lengths issuing from the front rollers will move to toward the central line of the triangle, i.e., the regions that will become the inner zones (or inner cylindrical layers) of the yarn, displacing sideways the lower tensioned fibers in their path. The latter may become buckled. As the edge fibers move toward the center, their path lengths momentarily decrease, and their tensions also decrease. Those fibers that are displaced outward toward the edge of the triangle will increase in tension and start to move back to the axis. Some fibers may block the movement of others inward or outward from the axis. The result is that a given fiber length, as it is issuing from the front rollers, traverses to and from its initial position in a region near the apex of the spinning triangle and thereby intermingles with other fiber lengths doing the same thing. The intermingling occurs just before the point of twist insertion. Thus, the relative positions of the fibers at that point become locked into the forming yarn structure.

Hearle describes the type of twisting that occurs to the drafting ribbon of fibers at the point of convergence as a wrapped form.[75] This is where the twisting torque tends to fold the ribbon width around the central line of the triangle. The relative position of fibers in the spinning triangle is therefore also important to the formation of yarn hairs. For example, if Z twist is being inserted, then, in the spinning triangle, the right-hand-edge fibers will fold over toward the left at the twist insertion point. It is likely to be during folding that fiber migration occurs so that, when twisted into the yarn structure, fibers have a helical path with an alternately increasing and decreasing radius due to the migration.

Because of the yarn thread angle from the front rollers to the lappet guide, the bottom rollers obstruct the left-hand-edge fibers of the spinning triangle from similarly folding under toward the right. The result is that migration of these fibers is restricted, and most of their lengths are present in the outer zones. The left-hand-edge fiber would then tend to form surface hairs. By including around 0.1% of a colored fiber in the raw stock, the migration paths of fibers in a spun yarn can be observed. The yarn is immersed into a liquid of a suitable refractive index to make the uncolored fibers almost invisible, and the dyed fibers are visible through a microscope (see Figure 6.39). This is procedure is commonly called a *tracer fiber technique*.[75]

With fairly simple image analysis, the cyclical variation of the fibers can be characterized by the migration parameters. Table 6.8 gives migration parameters for a conventional ring-spun yarn produced from viscose rayon fibers.

As can be seen, the degree of migration increases with twist. Hearle[75] has shown theoretically that, for ideal migration, where a fiber migrates regularly and uniformly through the yarn thereby giving a uniform packing density of the fibers, $Y_m = 0.5$, and $D = 0.29$. However, it can be see from the figures in Table 6.8 that, even at high twist levels, ideal migration is not achieved.

TABLE 6.8
Migration Characteristics for a Conventional Ring–Spun Yarn

Migration parameters	Yarn twist multiplier ($tex^{1/2}/cm$)		
	210	300	600
Y_m (CV%)	0.33 (39)	0.36 (32)	0.38 (22)
D (CV%)	0.17 (28)	0.16 (20)	0.21 (12)
I (CV%)	0.12 (32)	0.17 (24)	0.49 (22)
Equivalent migration frequency [per cm] (CV%)	0.10 (25)	0.16 (23)	0.34 (19)

Courtesy of Hearle, J. W. S., Grosberg, P., and Backer, S., *Structural Mechanics of Fibres, Yarns, and Fabrics*, Vol. 1, Wiley Interscience, Chap. 3, 1969, p. 148.

It is assumed that, in the helix model, ideal migration occurs to give a uniform packing density throughout the yarn. Consequently, the total length of fibers in each cylindrical zone must be proportional to the volume of each zone and therefore should increase linearly with zone radius. Figure 6.40 shows the zonal distribution of fiber lengths. The dotted line represents the situation for ideal migration, and the solid line shows that, in real yarns, this is not achieved — but that the packing density decreases sharply near the surface, which is characteristic of most yarns.

The fiber migration frequency varies with twist (see Table 6.8), and this shows that the migration is not a random process. If it were simply a random criss-crossing of fibers as they emerge from the front rollers, then the frequency of reversal (the fiber migration frequency) would be independent of the twist level. Since increased twist will increase tension, then the change in frequency with twist supports the mechanism for migration

Once the yarn is formed, the interfiber friction will tend to hold the fibers in their positions, but applied stresses may cause fiber lengths to shift position. An example of this is pilling. Pilling is where small balls of entangled fibers, called

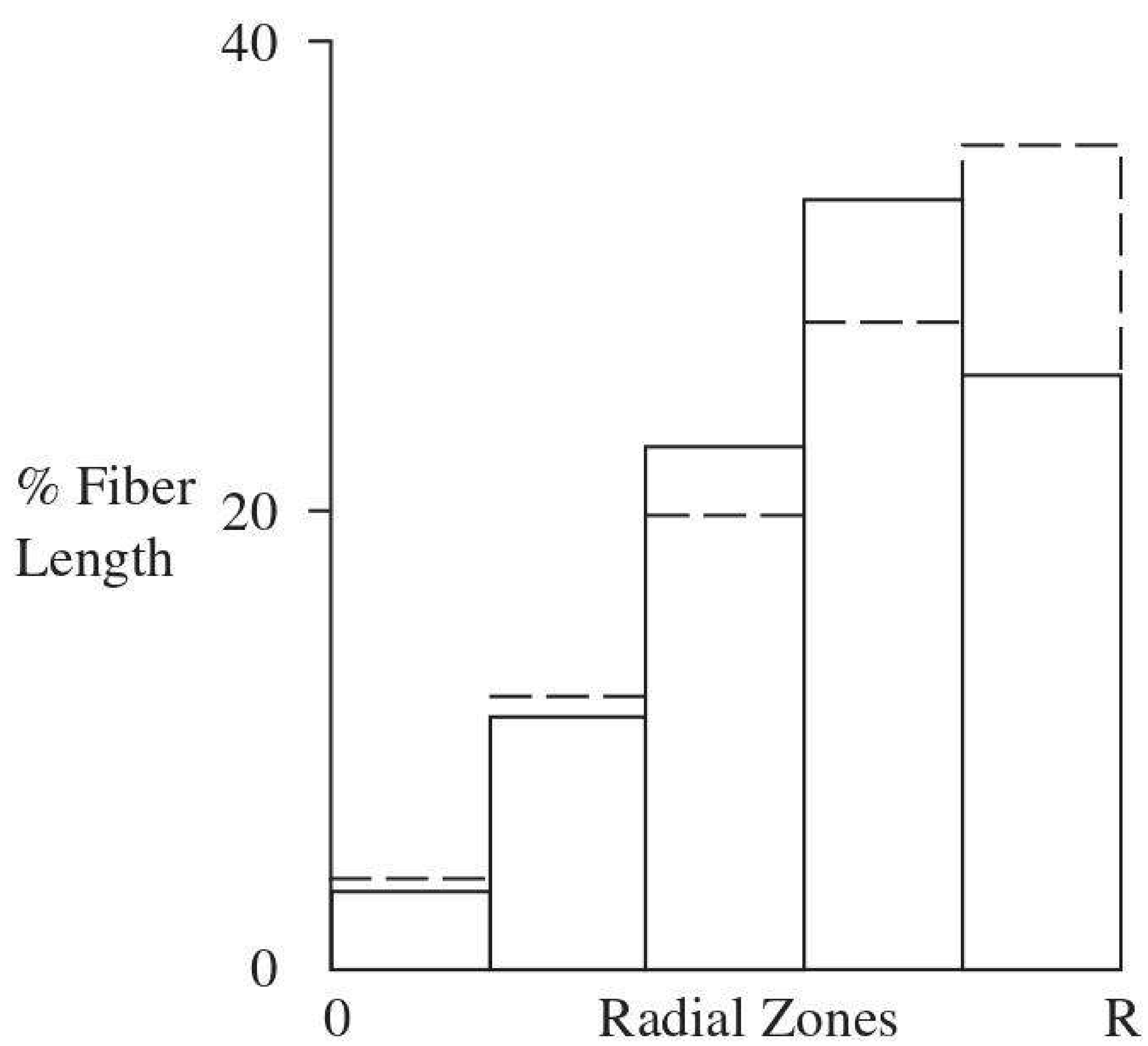


FIGURE 6.40 Mean zonal distributions. (Courtesy of Morton, W. E., The arrangement of fibres in single yarns, *Text. Res. J.*, 4, 325–331, 1956.)

pills, cling to the fabric surface of a garment, giving the garment an unsightly appearance. The pills are formed during wash and wear as stresses, rubbing actions, and reduced interfiber friction cause some fibers to migrate and protrude from the surface of the constituent yarns of the fabric. These fibers entangle and form pills, which become a problem if fibers are too strong for the pills to easily break away.

6.2.2.2 Compact Ring-Spun Yarns

We saw in Section 6.1.1.4 that, with appropriately applied suction, the width of the spinning triangle can be considerably reduced. This means that the leading ends of virtually all fibers will be caught at the twist insertion point and, although some fibers may fall into situation 1, described above (Section 6.2.2.1), the vast majority will be *in situ*ation 4 and thereby have their lengths integrated into the yarn. The yarn structure is therefore considerably less hairy than conventional ring-spun yarns, as can be seen from Figure 6.41. It may be reasoned that, with a very small spinning triangle, only a low level of fiber migration may take place. However, as we shall see later, this is not a disadvantage to yarn tensile properties.

6.2.2.3 Formation of Rotor Yarn Structure

Section 6.2.1 briefly explained that the rotor yarn is formed by individual or small groups of fibers accumulating within the rotor groove, around the inner rotor circumference, to form a ribbon of fibers that is progressively peeled from the groove and simultaneously twisted to produce the yarn. To gain a fuller understanding of how the rotor yarn structure is made, we need to consider in greater detail the buildup of fibers in the rotor groove to form the ribbon of fibers, referred to as *cyclic aggregation,* and the insertion of twist into this ribbon.

6.2.2.3.1 Cyclic Aggregation

At the start-up of spinning, when the tail end of a seed yarn enters the rotor and becomes attached to the ribbon of fibers in the groove, the count of the ribbon is

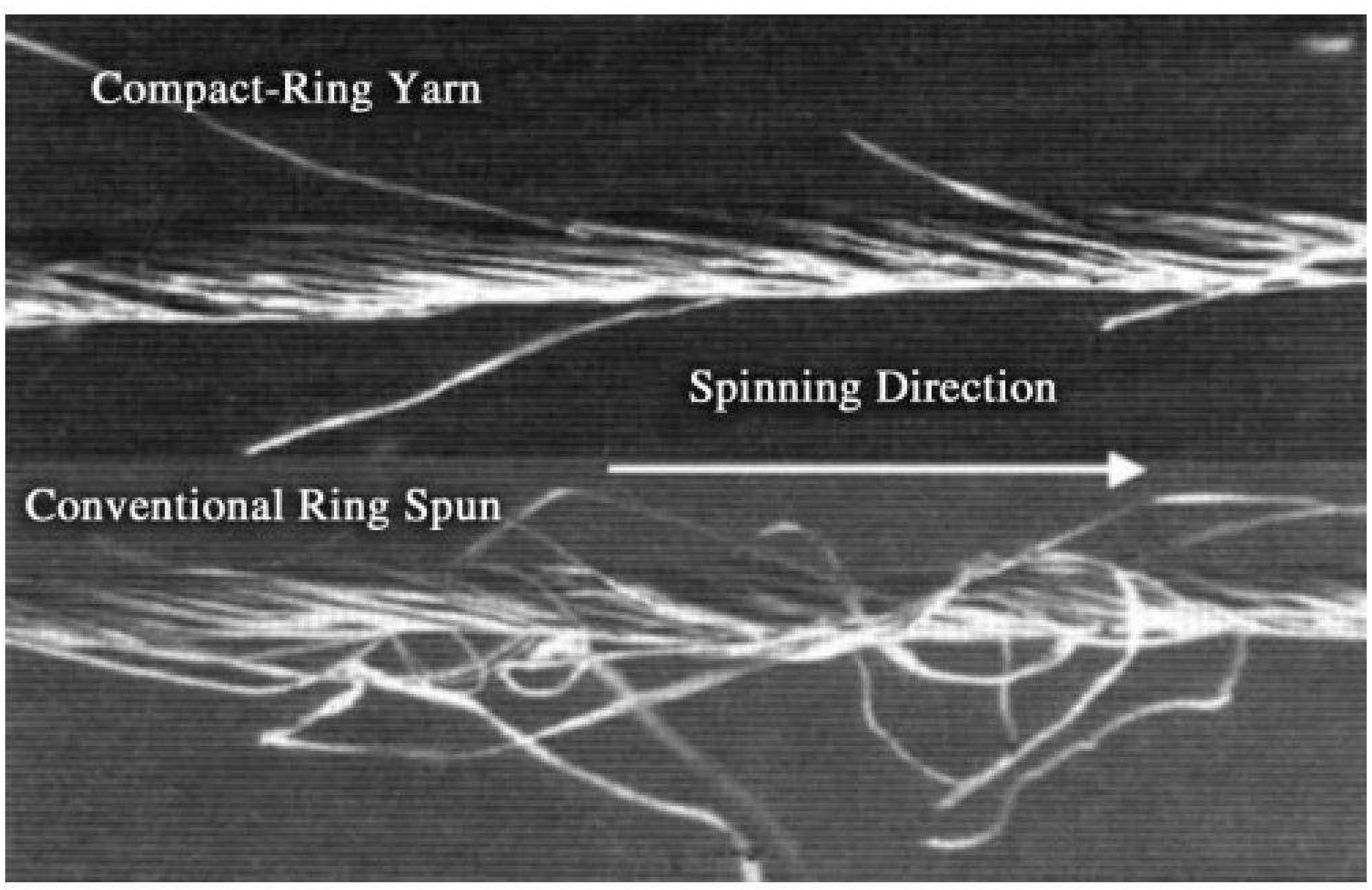


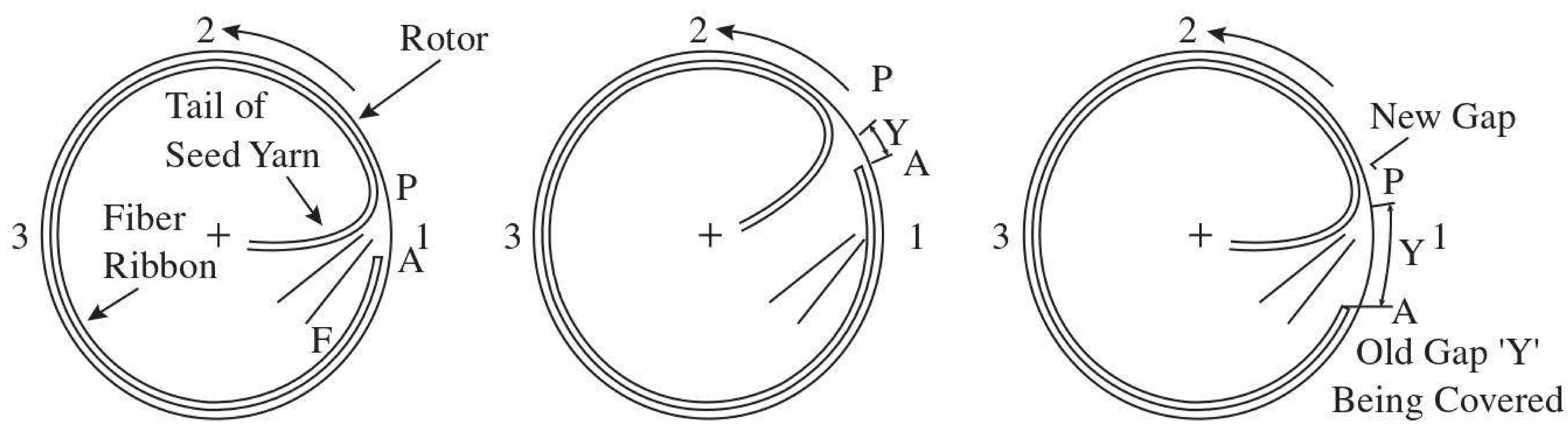
FIGURE 6.41 Conventional ring-spun yarn and compact ring-spun yarn structures. (Courtesy of Rieter Machine Works Ltd.)

not necessarily the required count for the yarn. The required yarn count is obtained when this initial deposited fiber ribbon is removed, i.e., after a yarn length equal to the circumference of the rotor is produced. Let us begin by considering the removal of this first ribbon layer. For the sake of simplicity, we will ignore the effects of twist contraction and assume that, at the moment the tail end of the seed yarn contacts the initial deposited fiber ribbon, the peel-off point, P, coincides with the point at which fibers are entering the rotor groove. Section 6.1.2.1 explained that fibers leave the exit of the transport channel, are deposited on the rotor wall, and slide down the rotor wall into the rotor groove. The point of entry into the rotor groove is likely to be only a short distance from the transport channel exit. We shall therefore take the channel exit as the point of coincidence. Let A be a mark on the rotor at that point. Figure 6.42 then depicts a plan view of inside the rotor the instant the tail end of the seed yarn begins to peel the fiber ribbon from the rotor groove and insert twist into it. A smooth doffing tube navel is being used, so the peel-off point and the twist insertion point are the same, as shown in Figure 6.43.

Consider now the first rotation of the rotor. The numbers 1, 2, 3, and 4 are reference points external around the rotor circumference and are separated sequentially by 1/4 rotor circumference spacing. The rotor rotates in the counterclockwise direction and, as A and P move away from 1 toward 2, a gap, Y, will appear between P and A. This is because the ribbon is being peeled from the groove. The peeling speed is approximately equal to the yarn delivery speed, V_d. As Equation 6.15 indicates, this makes N_P greater than N_R. The mark A also indicates the tail end of the fiber ribbon. With the rotor moving in the counterclockwise direction, fibers leaving the transport channel are entering the rotor groove and forming, in the counterclockwise direction, a new fiber layer on top of the existing fiber ribbon.

If t minutes is the time taken for A to reach reference point 2, then the gap length is $Y = t\,V_d$, and a new layer of fibers of about 1/4 the rotor circumference would have been deposited onto the ribbon in the counterclockwise direction. As P and A move on to 3 and then to 4, Y increases, and the length of the new layer being deposited would have increased first to 1/2 and then to 3/4 of the rotor circumference.

Consider the First Rotation of the Rotor



A plan view inside the rotor the instant the seed yarn makes contact with the fibers accumulated.

NB fiber deposit is in the reverse direction to the rotor rotation.

FIGURE 6.42 Peeling and twisting of fiber ribbon during rotor rotation.

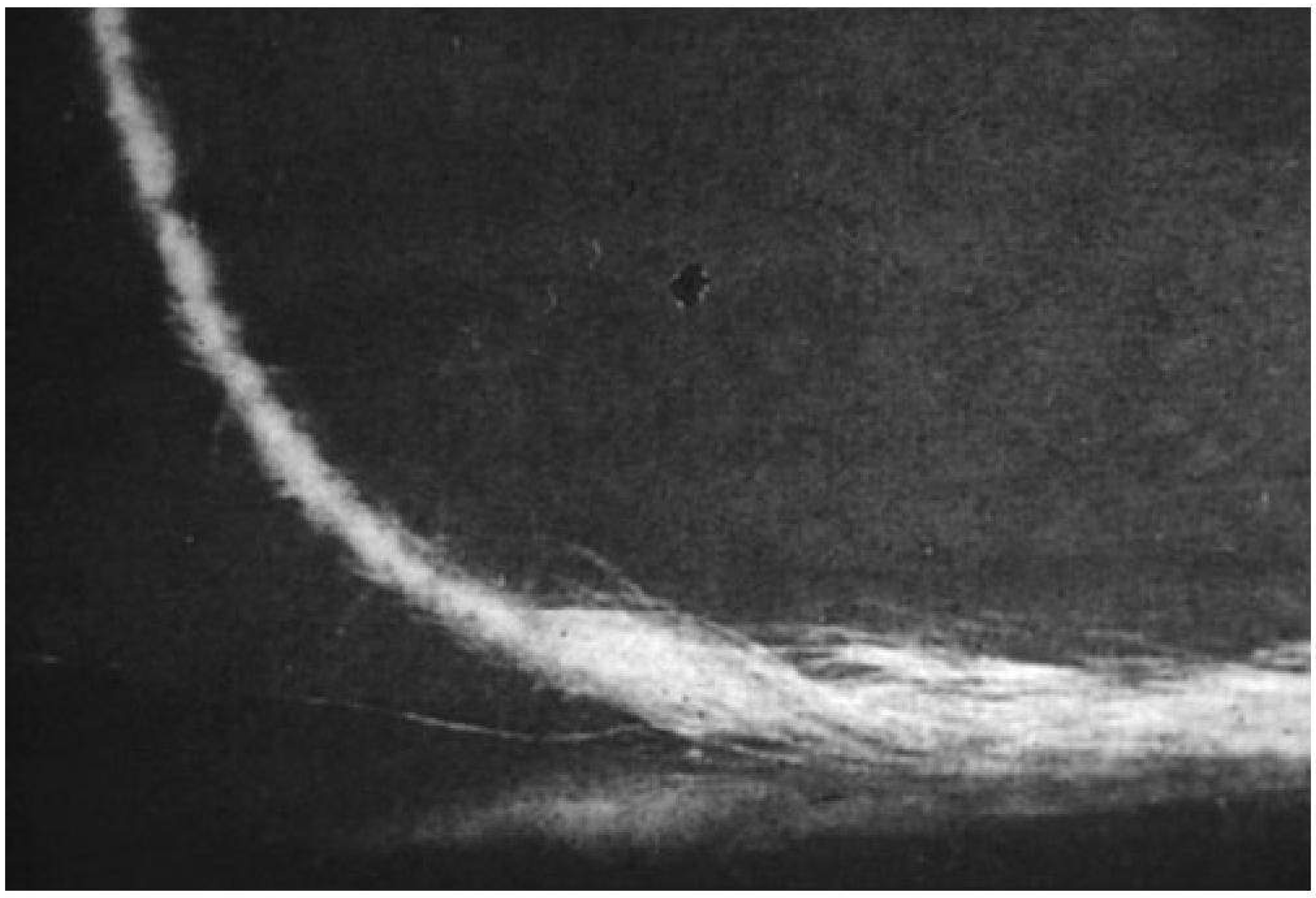


FIGURE 6.43 Twist insertion with smooth doffing tube navel.

With P and A moving on from 4 to 1, Y becomes a maximum value, Y_{max}, when P reaches 1. Since Y_{max} is obtained with one revolution of P,

$$Y_{max} = \frac{V_d}{N_P} \tag{6.21}$$

The new layer being deposited in the counterclockwise direction meets the peel-off point when P reaches 1. The depositing fibers go across the peel-off point and then subsequently into the gap Y_{max}. The ribbon (along with the newly deposited layer) continues to be peeled from the groove and twisted into the yarn. Thus, a new gap begins at the crossover of the newly depositing fiber layer at P. When A reaches 1, this newly depositing layer will have covered Y_{max}, and a second layer will have started. This means a new tail end of the fiber ribbon would have formed a distance Y_{max} from the first tail end at A. During the second rotor rotation, the deposition continues as in the first rotor rotation and the new gap increases to Y_{max}. However, this time, when A reaches 1, a new tail end would have formed a distance 2 Y_{max} from A, and a third fiber layer will have started. The process is cyclical, and the fiber layers aggregate with each rotor rotation, hence the term *cyclic aggregation.*

After a time, $t_r = \pi D_R/V_d$ minutes, the original fiber ribbon plus the fiber layers deposited on top of it would be peeled from the rotor groove. The peel-off point, P, the exit of the transport channel, and the mark A on the rotor will once again coincide. The gap behind the peel-off point will be Y_{max}; there will be $N_L = t_r\, Np$ $(= \pi D_R/Y_{max})$ number of fiber layers accumulated at A, and if there are X_F fibers of T_f fineness (dtex) in each layer, then the product $N_L X_F T_f \times 10^{-1}$ should equal the yarn count being spun. The thickness of the newly formed fiber ribbon will taper linearly around the rotor circumference from the peel-off point to the tail end. As the ribbon continues to be peeled from the groove, the accumulation of the depositing fiber layer will always result in there being the correct number of layers at P to produce the required yarn count.

From Equation 6.21, it can be shown that, for commonly used twist factors, Y_{max}, on average, is of the order of 1 mm. This means that, when the depositing layer crosses over P, individual or groups of fibers will bridge the gap behind the peel-off point. For the gap to be maintained, the twist torque must be sufficient to bind these fibers onto the surface of the forming yarn. Since the main body or core of the yarn is already formed from the fiber ribbon, these bridging fibers wrap around the yarn body and become the wrapper fibers depicted in Figures 6.44 and 6.45. In Section 6.1.2.1, it was explained that, to overcome the resistance by frictional barriers in the spinning thread line to twist flow to rotor groove, the doffing tube navel can be designed to give a false-twist effect. This results in the peripheral twist extent or tying-in zone in the rotor groove and the separation of the peel-off point and the twist insertion point. The ribbon is therefore now partially twisted prior to being peeled from the rotor groove. Although this reduces spinning end breaks and the level of twist required to spin, the disadvantage is that, when the depositing layer now crosses the tying-in zone and the peel-off point, more fibers will be incorporated onto the forming yarn as wrapper fibers.

Figure 6.44 shows a bridging fiber that has landed with the leading length caught in the tying–in zone while its trailing length lies across the gap Y_{max} and into the tail

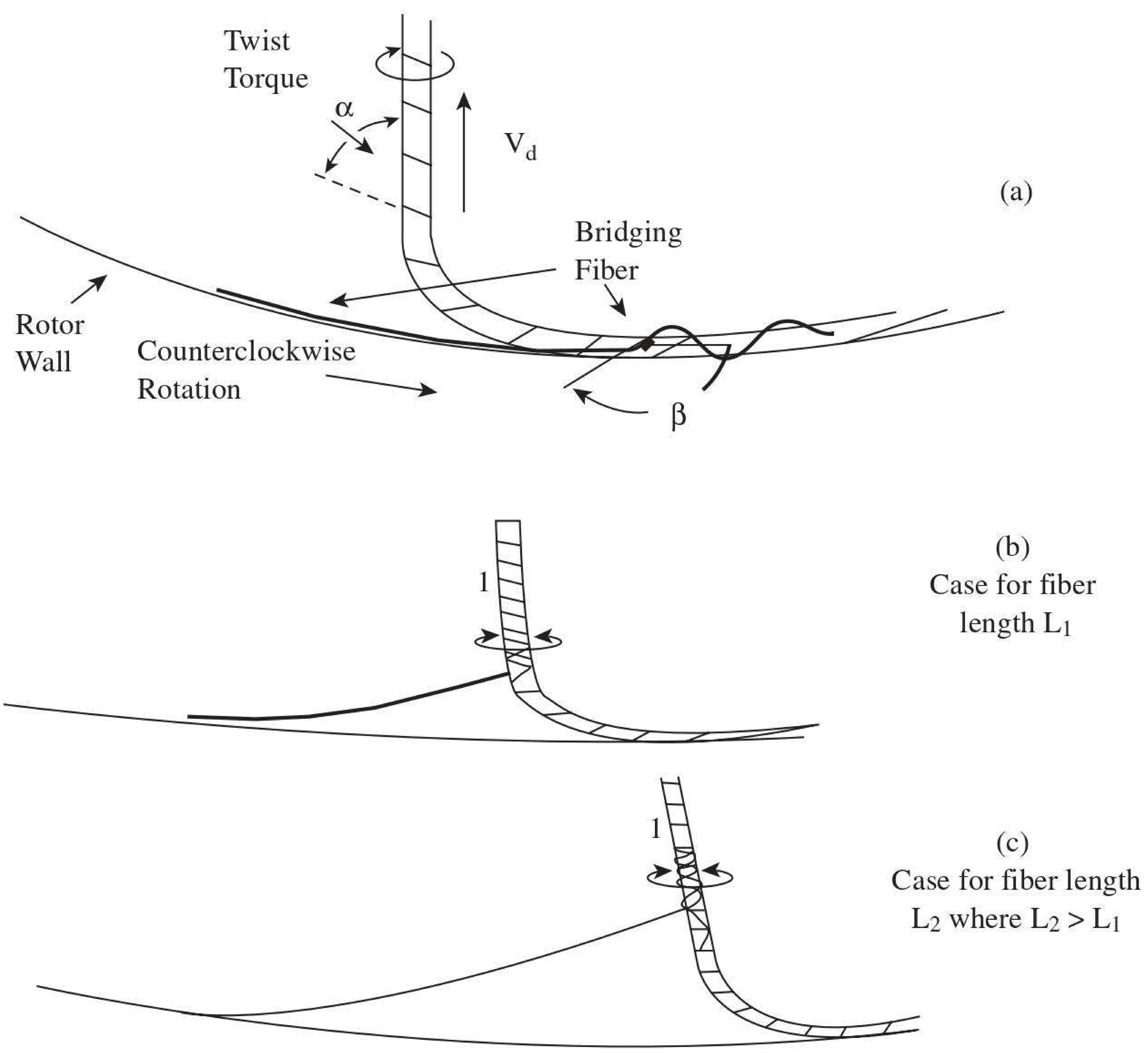


FIGURE 6.44 Wrapper fiber formation. (Courtesy of Nield, R., *Open-End Spinning,* monograph No. 1, *The Textile Institute*, Manchester, UK, 1975.)

FIGURE 6.45 Wrapper fiber formation.

end of the fiber ribbon (not shown). The twisting torque is in the direction for inserting S-twist into the fiber ribbon; the surface fibers of the body of the yarn subsequently having a twist angle α (see Figure 6.44a.) As a fiber slides down the rotor wall and into the rotor groove to become a bridging fiber, its leading end will be caught by the twist insertion point, become partially embedded in the forming yarn, and rotate in the twist direction. This causes the length landing on the peripheral twist extent to become wrapped in the Z-twist direction around the yarn. When this short, twisted length is peeled from the rotor groove, the bridging fiber length becomes folded, and its trailing length is lifted from the gap and the tail end of the fiber ribbon to form a catenary (Figure 6.44b and c). The twist torque wraps the trailing length around the yarn initially at almost 90° to the yarn axis, giving a "belt-wrap" appearance, and then the remaining length is wrapped in the S-twist direction; the angle of S-wrap varies as the yarn moves toward the doffing tube. Fibers of differing lengths will have different caternary suspensions and therefore differing S-wrap angles. Figure 6.45 shows the fiber caternary suspensions during rotor spinning of cotton fibers.

When the yarn length reaches the doffing tube, the reverse twisting (i.e., the Z-twisting) of the false twist removes S-twist not only from the yarn core but also from what was the trailing length of the wrapper fiber. However, what was the leading length of the wrapper fiber receives further Z-twist and binds tighter onto the yarn. Figure 6.46 depicts the Z-wrap, belt-wrap, and S-wrap of wrapper fibers in cotton and viscose rotor-spun yarns. The tracer fibers in (a) and (d) show the Z and S wrap directions, (b) and (c) show the belt wraps, and a fold can be seen in (e).

Microscopic studies[78,79] have shown that the frequency of occurrence of belts along the yarn follows a Poissonian type distribution. This suggests that wrappers

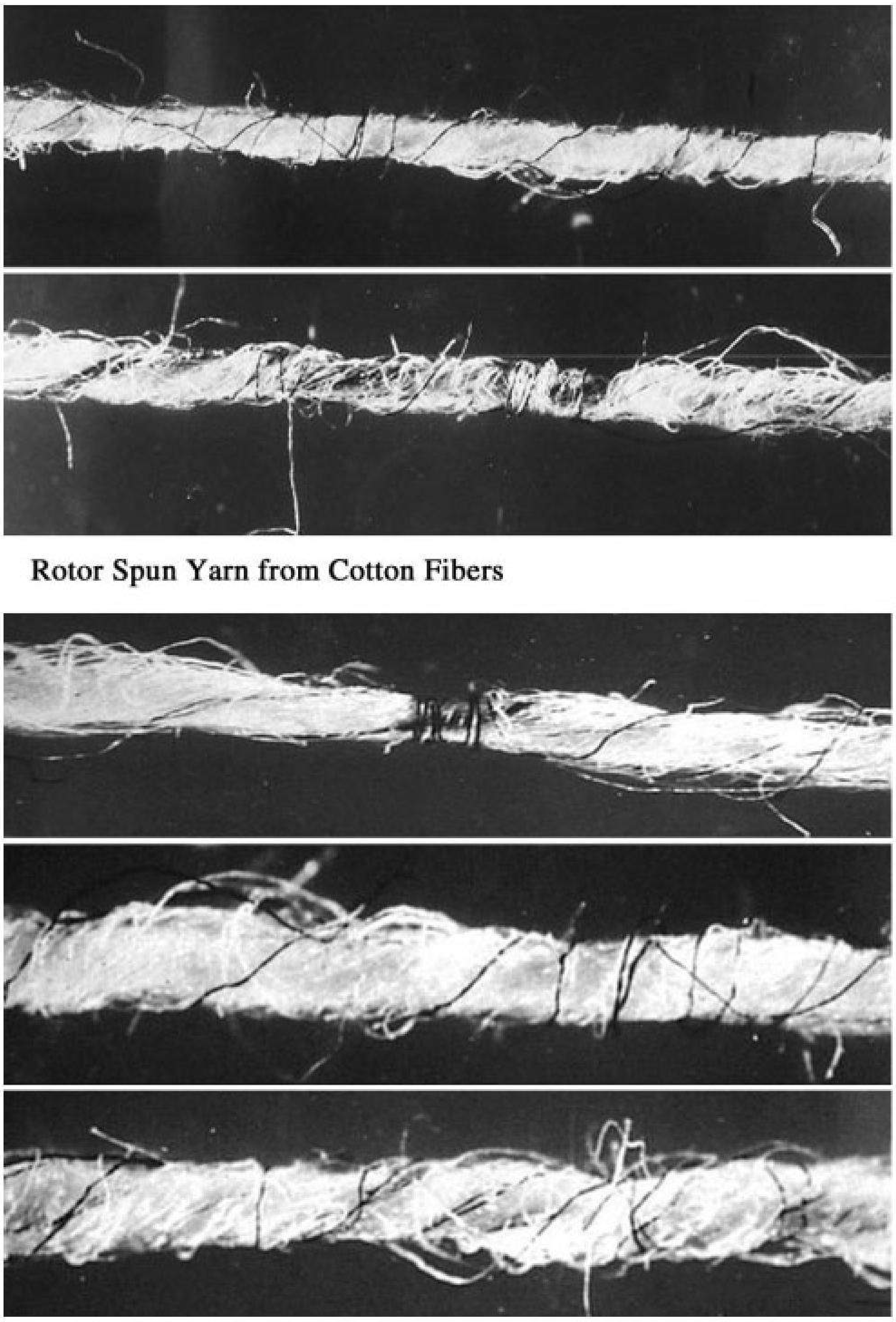


FIGURE 6.46 Wrapper fiber configurations.

may be considered as "defects" in the rotor yarn structure. The belt wraps in particular are known to register as neps in Uster irregularity yarn testers.[80]

Figure 6.47 shows the front and back of a denim fabric in which the warp yarns were Indigo dyed. What appear as blue neps in the back of the fabric are wrapper fibers on the warp yarns; similarly, the white neps in the front of the fabric are wrapper fibers on the weft yarn. The neppiness is very low, and the fabric was considered of acceptable quality.

Several factors will influence the degree of wrapping, the frequency of belts, and the Z- and S-wrap angles of the wrapper fibers.[80,82] The strongest influence is the level of false twist generated by the doffing tube navel. The higher the level of false twist, the longer the tying-in zone. This reduces the end breaks and gives spinning stability, but it increases the number of wrapper fibers and the level of Z-wraps. Increased frictional drag by the rotor and ribbon tail on the trailing length

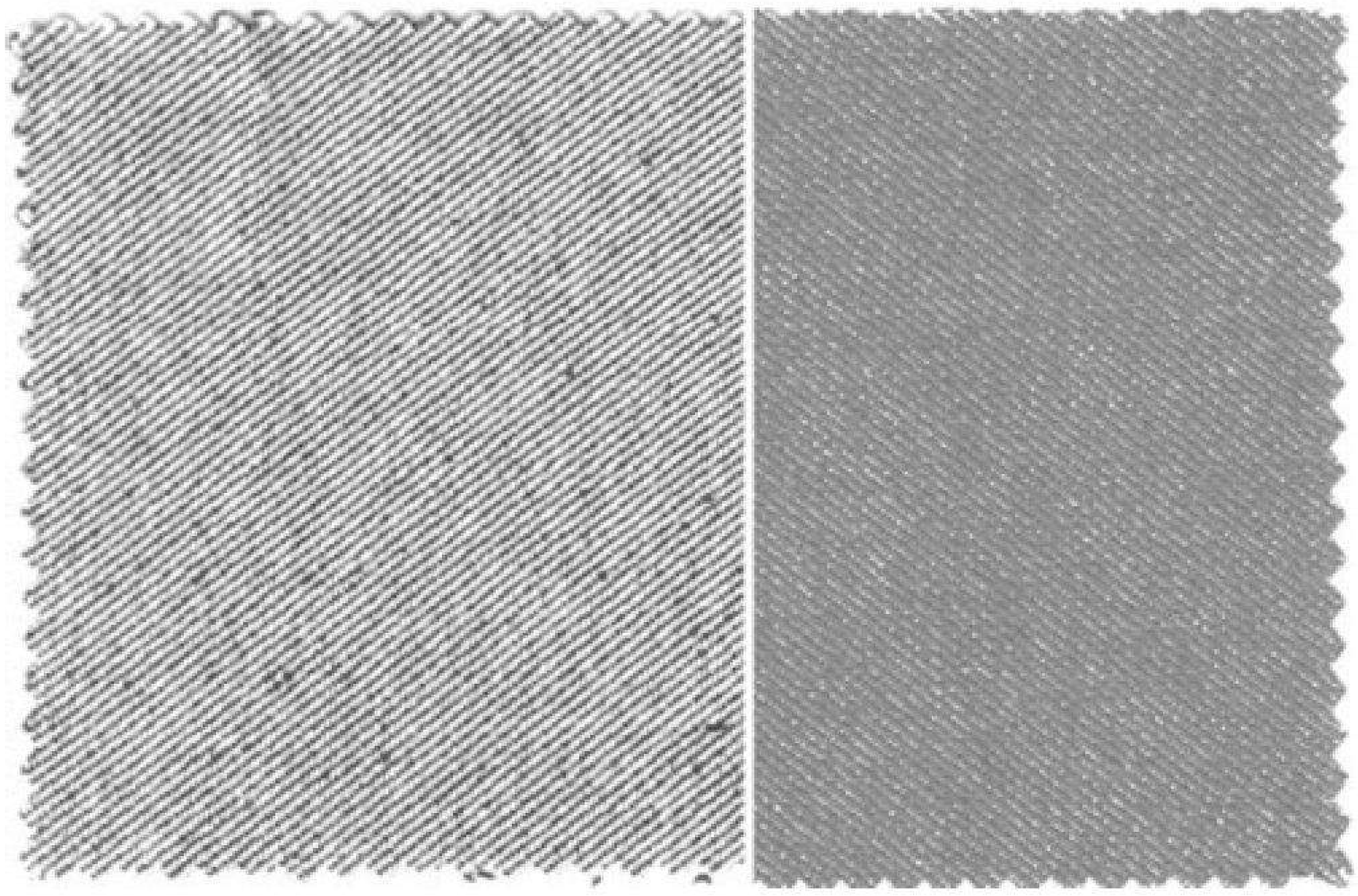


FIGURE 6.47 (See color insert.) Denim fabric woven from rotor-spun yarns.

of the bridging fiber will increase the level of S-wraps; longer fibers also increase S-wraps. With respect to the five classes of rotor surface structure shown in Figure 6.37, it can be seen from Figure 6.48 that the yarn consists largely of classes I, II, and III. It is also evident that steel doffing tubes with groove navels result in more wrapper fibers and surface hairs (classes II and III)

Ideally, in rotor spinning, the individual fibers are subjected to continuous acceleration on being removed from the opening roller by the air suction, transported by the airflow to the rotor, and then sliding down the rotor wall into the rotor groove. The ideal case means that the fibers are straightened during transport to the rotor groove and lie together in a parallel state to form the ribbon of fibers. It should be noted that, when the ribbon of fibers is peeled from the groove, the fibers are being removed from their trailing ends. In reality, there will be some fibers that are straight within the ribbon, but the vast majority are not. Several studies[83,85] have looked at how fiber straightening can be achieved, particularly with regard to the spinning of fine-count rotor yarns. The removal of fibers from the opening roller, their transit in the airflow, and landing on the rotor groove have still to be fully optimized for the highest percentage of fibers in the fiber ribbon to be straight. Thus, although these fibers conform to the twist helix of the yarn, their configurations within the rotor yarn is very different from fibers within ring-spun yarn structures; the fibers in rotor yarns are largely hooked and buckled and of a lower fiber extent than in ring-spun yarns. In ring spinning, a flat ribbon of fibers issues from the front drafting rollers to be twisted; in contrast, the fiber ribbon in the rotor groove is compacted by centrifugal force and consequently twisting is akin to a twisted cylindrical form rather than a twisted ribbon or a wrapped ribbon form.[75] The differences in tension between fibers at the point of twist insertion are small, and therefore the level of fiber migration is low.

With low fiber migration and hooked and buckled fiber configurations, the meaningfulness of migration parameters for rotor yarns becomes questionable, since these parameters do not show a distinction between complex fiber shapes being twisted into

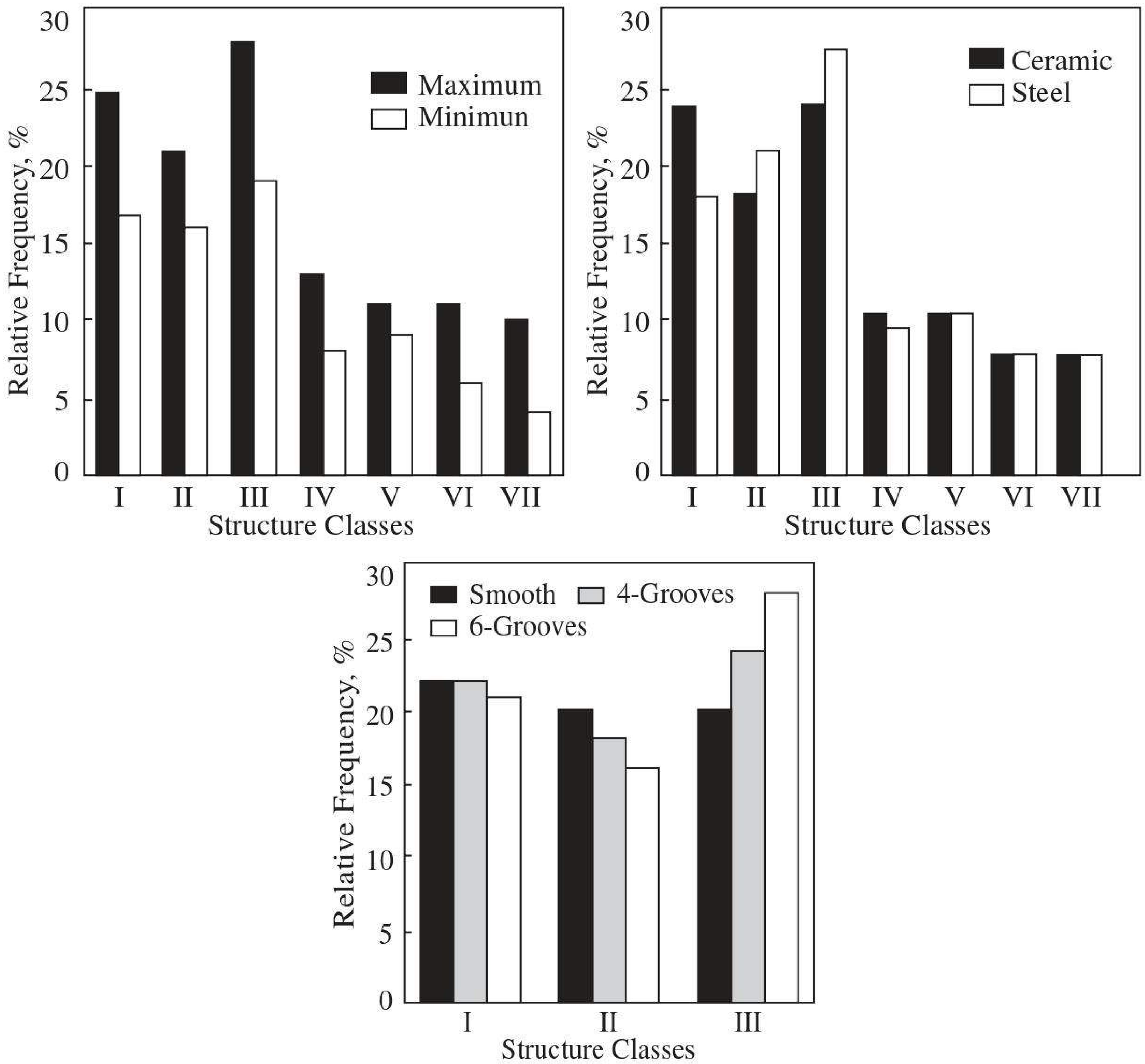


FIGURE 6.48 Distribution of rotor yarn surface structures. (Courtesy of Lawrence, C. A. and Finikopulos, E., Factors effecting changes in the structure and properties of open-end rotor yarns, *Indian J. Fibre and Text. Res.*, 17(12), 201–208, 1992.)

a yarn structure and the meandering and interlacing of fiber lengths resulting from tension differences. Kasparek's theory of spun-in fiber in yarns[86] gives an alternative approach for studying the integration of fiber lengths within a yarn structure.

6.2.2.3.2 Theory of Spun-in Fibers in Yarns

Figure 6.49 gives a diagram of a fiber within a yarn structure. The probability, P, of the fiber being incorporated into the yarn, i.e., spun into the yarn structure, depends on the ratio of the sum of the elemental lengths Δl_i to actual fiber length L_F, so

$$P = \frac{\Sigma \Delta l_i}{L_F} \tag{6.22}$$

Thus, if $\Sigma\Delta l_i = L_F$, $P = 1$, and the full length of the fiber will be spun in. If $\Sigma\Delta l_i = 0$, $P = 0$, and the fiber resides on the yarn surface, e.g., totally as a wrapper fiber or hair. If part of the fiber length is spun in and the rest protrudes from the yarn or forms a wrapper, then $\Sigma\Delta l_i < L_F$, and $1 > P > 0$.

Instead of taking tracer fiber measurements along the meandering and complex fiber configuration to determine L_F, it is more convenient to use the projected

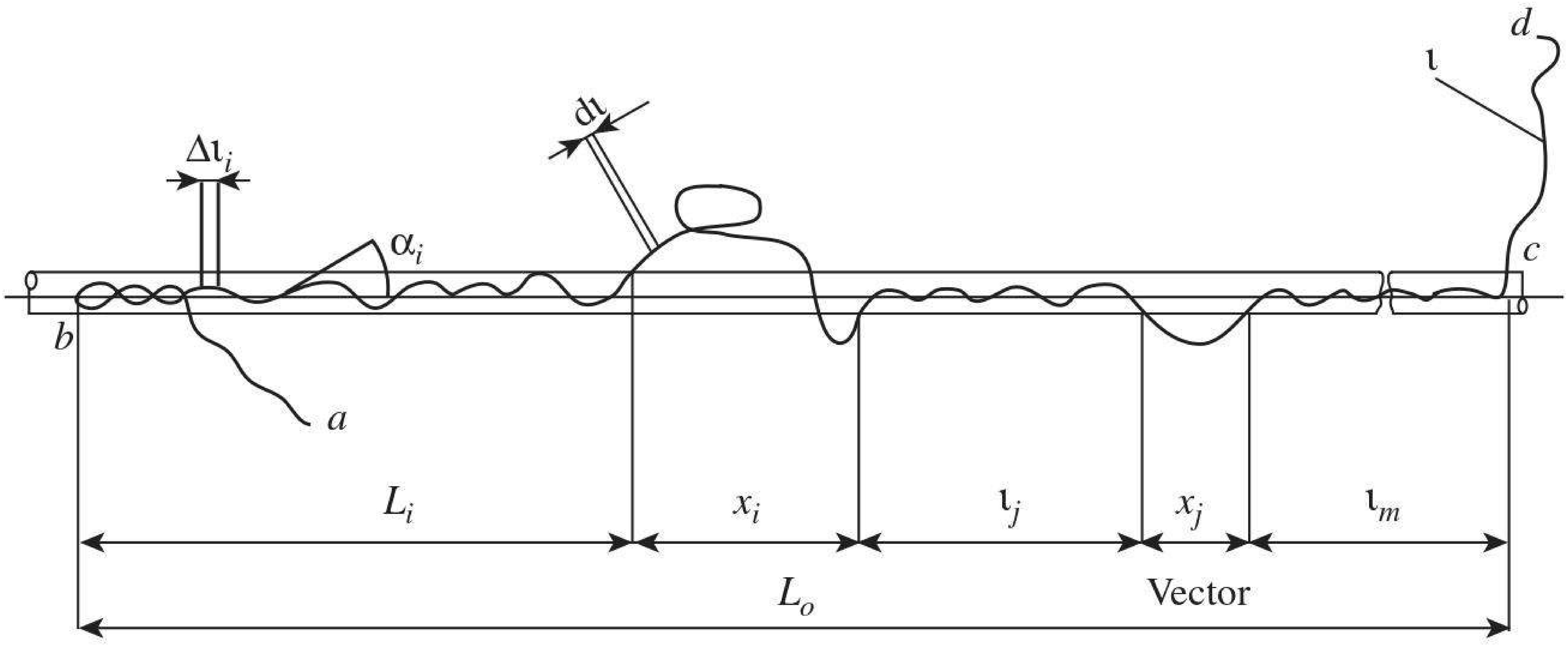


FIGURE 6.49 Elemental lengths of a spun-in fiber. (Courtesy of Rohlena, V., *Open-End Spinning*, Chap. 7, Elsevier Science, New York, 1975.)

elemental length and fiber extent, L, and refer to the probability ratio as the spun-in coefficient, $K_{Fi.}$ For the yarn length L_i in the diagram

$$L_i = \Sigma \Delta l_i \cos \alpha_\mathrm{i} \tag{6.23}$$

where α = the angle between the elemental length and the yarn axis, as shown

This can be repeated for L_j, L_m, and so forth., so

$$K_{Fi} = \frac{\Sigma L_n}{L} \tag{6.24}$$

where $n = i, j, m$, etc.

$$= \frac{L_O - \Sigma\ x_n}{L} \tag{6.25}$$

where $\Sigma\ x_n$ = the fiber lengths projecting out of the yarn body

Kasparek has classified typical fiber configurations observed for differing ring yarn and rotor yarn structures into the nine classes with associated K_{Fi} values depicted in Figure 6.50.

It follows from the above that the mean spinning-in coefficient of a yarn is

$$K_F = \Sigma\ K_{Fi}\left(\frac{N_i}{N}\right) \quad \text{for } i = 1 \text{ to } N$$

where N_i/N is the relative frequency of the nine classes among N observations of tracer fiber configurations.

Table 6.9 gives K_F values for conventional ring-spun and rotor-spun yarns, and it can be seen that the mean spun-in lengths for the former are significantly greater.

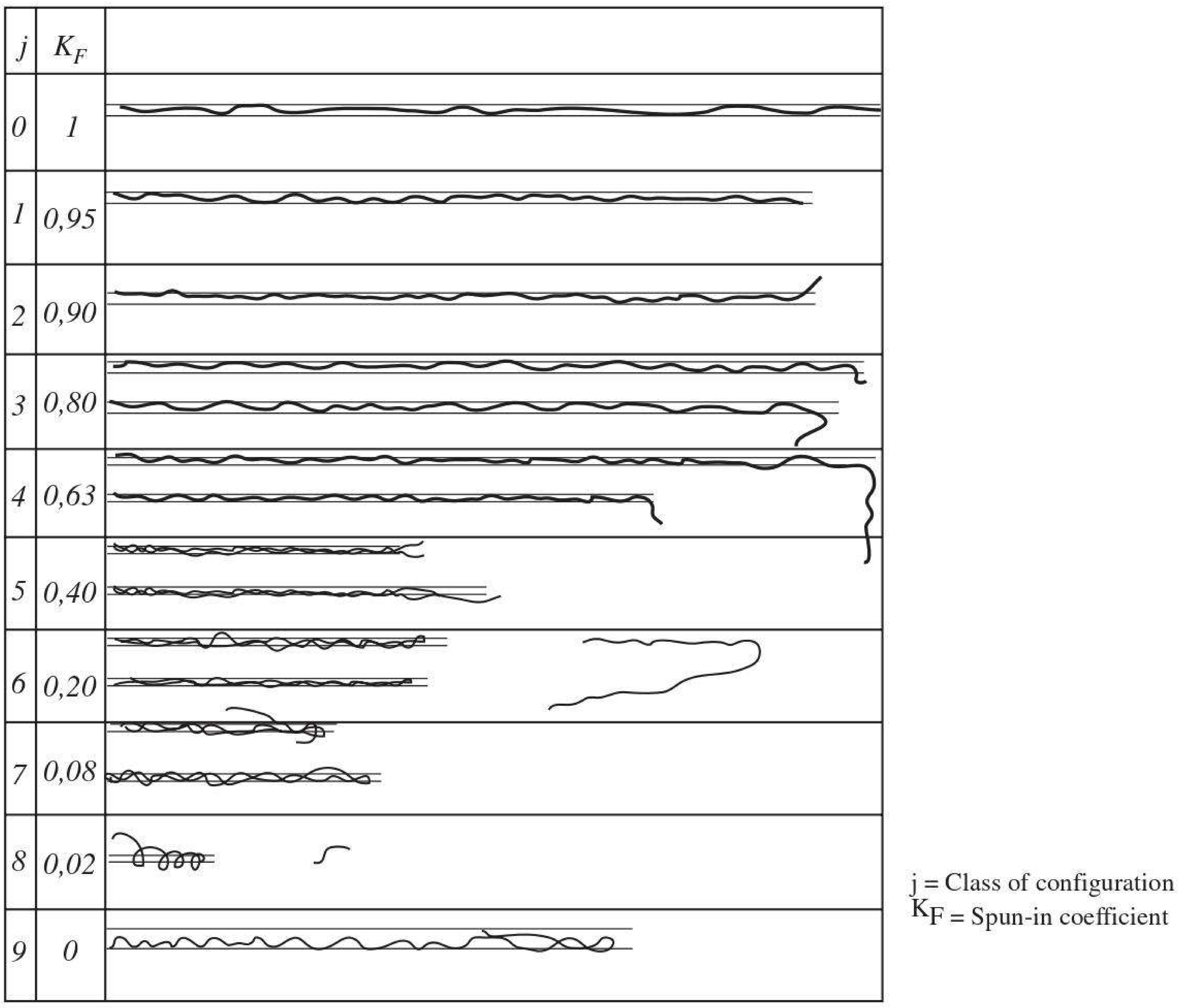


FIGURE 6.50 Classification of fiber configuration in yarns and K_{Fi} values. (Courtesy of Rohlena, V., *Open-End Spinning*, Chap. 7, Elsevier Science, New York, 1975.)

TABLE 6.9
K_F Values for Conventional Ring-Spun and Rotor-Spun Yarns

Yarn structure	Mean spun-in coefficient, K_F	Standard error (%)	Coefficient of variation (%)
Combed ring-spun (conventional)	0.757	1.78	29.44
Combed ring-spun (conventional)	0.760	1.62	26.34
Carded ring-spun (conventional)	0.659	2.11	35.20
Carded ring-spun (conventional)	0.686	1.97	32.01
Carded ring-spun (conventional)	0.661	2.29	36.95
Rotor-spun	0.512	2.58	42.82
Rotor-spun	0.504	2.66	43.41
Rotor-spun	0.482	2.71	45.89

Courtesy of Rohlena, V., *Open-End Spinning*, Chap. 7, Elsevier Science, New York, 1975.

Several other researchers[87] have used the mean fiber extent coefficient K_p (= L_O/L = the arithmetic mean of observed fiber extents/mean fiber length) as a shorter means to quantify the fiber length utilization of yarn structure. This approach does not take account of elemental lengths on, or projecting from, the yarn surface. However, such work has shown that machine settings (e.g., opening roller speed, rotor diameter, rotor speed, and air-suction) affect fiber length utilization (see Table 6.10) and that there is good correlation between fiber length utilization and yarn strength (see Figure 6.51). As K_p increases, yarn tenacity increases.

TABLE 6.10
Effect of Rotor Spinning Parameters on Mean Fiber Extent

ORS	MFE	RS	MFE	AS	MFE	RD	MFE
5000	23.07	30,000	20.78	8	18.21	46	20.78
6500	20.78	50,000	20.85	32	20.65	56	21.57
8500	17.18	70,000	19.70	57	21.30	–	–

ORS = opening roller speed (rpm), RS = rotor speed (rpm), AS = air suction (cm water gage pressure difference), RD = rotor diameter, MFE = mean fiber extent (mm).

Courtesy of Chandraray, S. and Dutta, B., Mean Fibre Extent of Rotor-Spun Yarn, *Indian J. Text. Res.,* 12(6), 133–138, 1987.

6.2.2.4 Formation of Friction-Spun Yarn Structures

As Figure 6.52 illustrates, the friction drums are longer than the width of the fiber feed. The yarn formation therefore occurs along two parts of the friction drums,[88] first in zone 1, the fiber supply zone, and second in zone 2, where the forming yarn

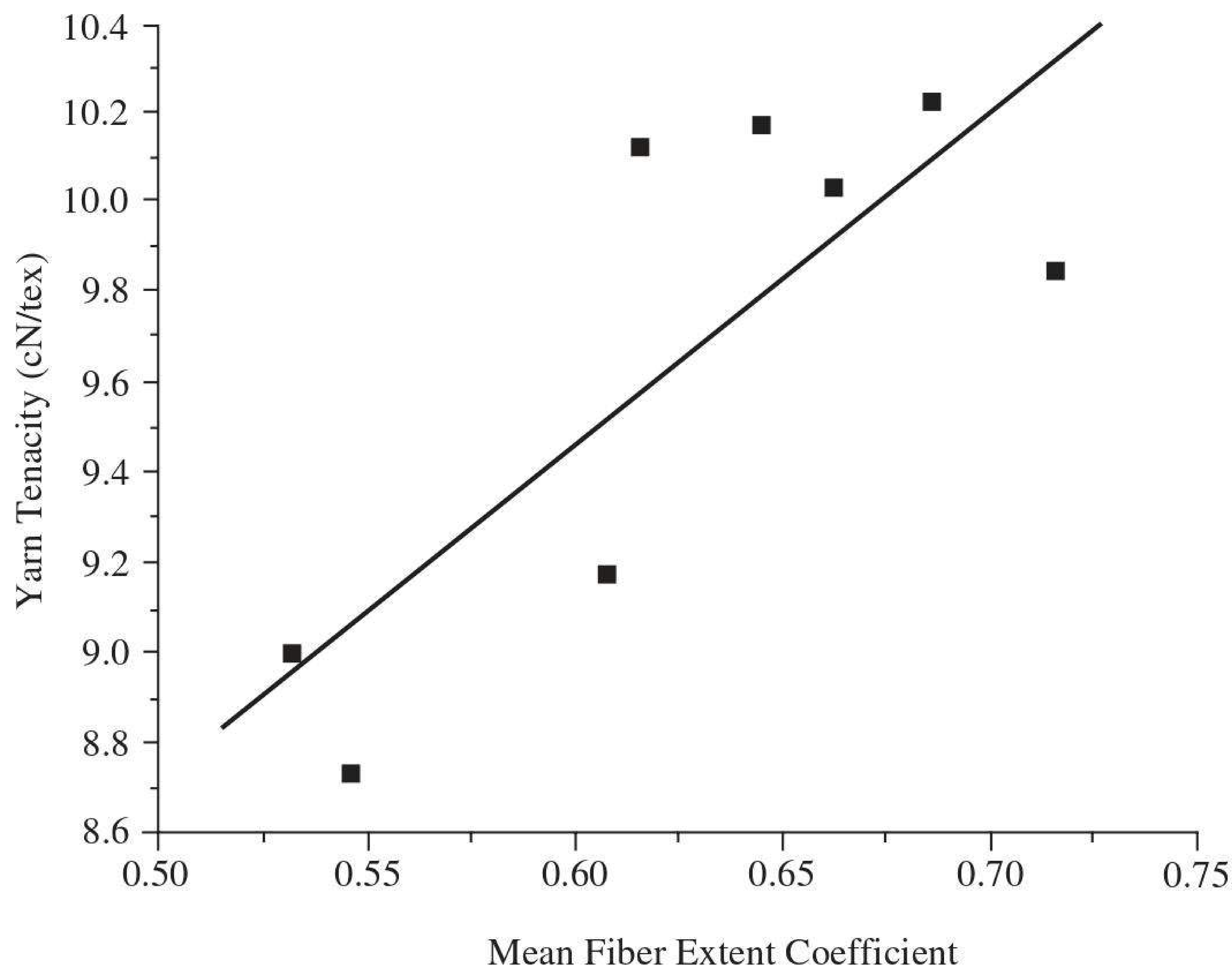
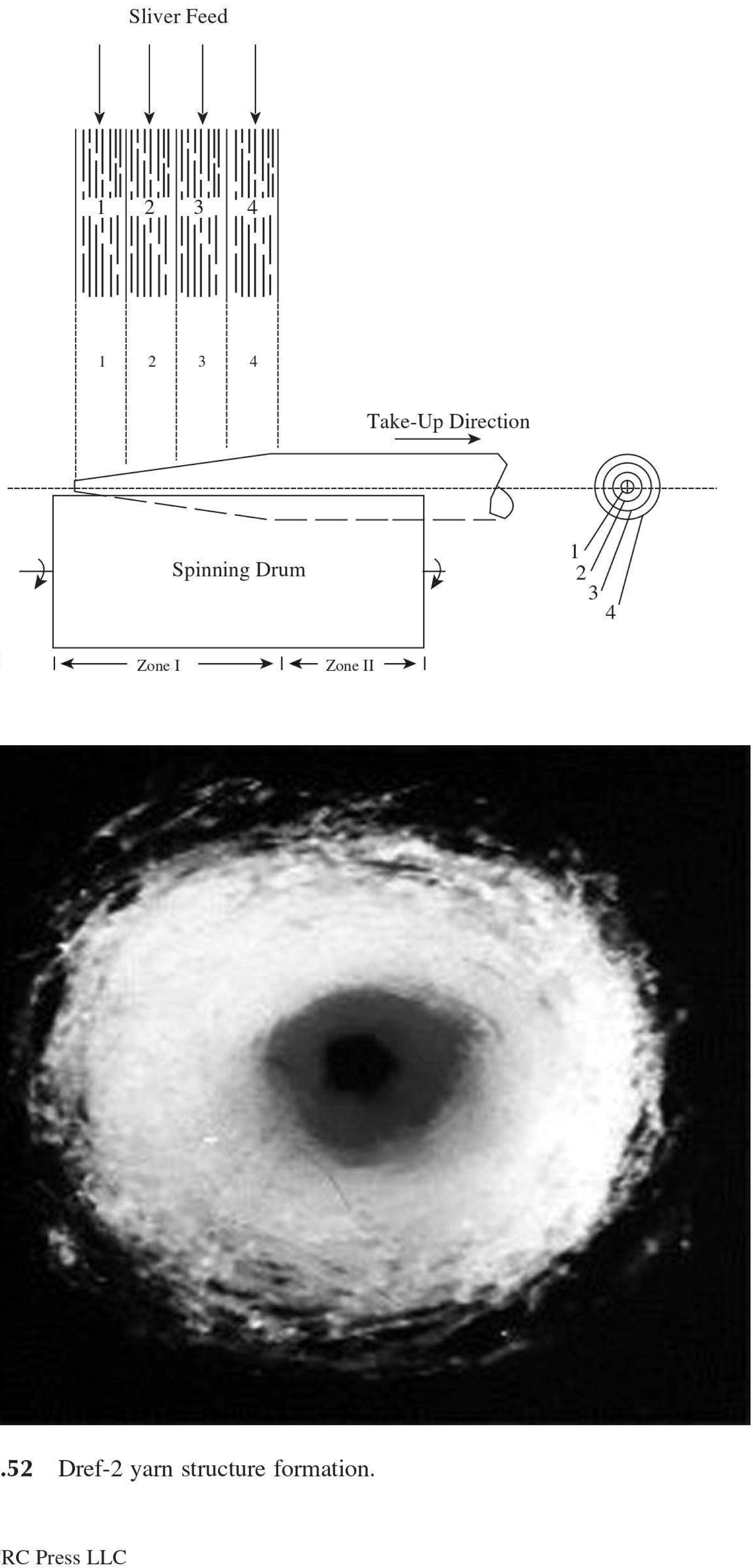


FIGURE 6.51 Effect of mean fiber extent coefficient on rotor-spun yarn tenacity. (Courtesy of Chandraray, S. and Dutta, B., Mean Fibre Extent of Rotor-Spun Yarn, *Indian J. Text. Res.,* 12(6), 133–138, 1987.)



(a)

(b)

FIGURE 6.52 Dref-2 yarn structure formation.

receives no more fibers. The fibers landing onto the friction drums in zone 1 form a conical yarn end or tail between the drums. Figure 6.53a shows the fibers traveling from the opening roller to the friction drums, and Figure 6.53b shows the fibers landing and being twisted to form the yarn. The fibers are individually twisted onto the conical yarn tail during their deposition. The formation of the Dref-2 yarn structure is therefore a buildup of fiber layers from the sliver feed.

As the forming yarn length moves in the direction of take-up, the separated fibers from each consecutive sliver are deposited onto the previous layer. Thereby, fibers present in a particular sliver become integrated into the corresponding concentric layer of the yarn; the fibers from the first sliver farthest from the delivery rollers forming the center region of the yarn. The yarn cross section shown in Figure 6.52 was obtained with sliver (1) composed of black colored fibers, sliver (2) of red colored fibers, and slivers (3) and (4) of white fibers. It is therefore possible to produce yarns with each concentric layer being composed of a different fiber type.

It is evident that any migration between layers is very small and that the yarn is much more compact in the region of the core. Since spinning tension is low, it is unlikely that this compaction is caused by any applied axial tension on the fibers (as is the case for ring spinning) and is therefore more likely to be the result of a higher twist level at the yarn core. In zone I, the twist level is low, and centrifugal forces cause the yarn tail to swell. The twist in zone II is much greater, and the yarn diameter decreases. As the yarn leaves the friction drum, the amount of twist in each radial position will depend on the length of time fibers in that position stayed within the two zones. This is because the twist gained is cumulative between the point where a fiber lands and the end of the friction drums. This means that fibers forming the yarn core are the most highly twisted.

In Dref-2 spinning, the individual fibers are blown off the opening roller and, during transport to the friction drums or rollers, they become buckled. On landing, and during twisting (see Figure 6.53), fibers have hooked, folded, entangled, and looped configurations. Figures 6.54 and 6.55 show the results of observed tracer fiber configurations in the second and fourth layers of a Dref-2, 270-tex yarn spun from 3.3-dtex, 50-mm acrylic fibers. It can be see that the fiber configurations fall within classes 4 through 9, the surface layer of the yarn having the greater amount of folded configurations and therefore a much lower K_F value. The folded configuration is sizeable within the second layer and, consequently, the K_F is much lower than for ring and rotor yarns, even though all the fiber length is within the yarn. Nevertheless, there is an indication of a trend that inner layers have the better fiber configuration and mean spun-in coefficient.

Table 6.11 shows that, similar to rotor spinning, machine settings influence fiber length utilization in Dref-2 yarns, and Figure 6.56 shows the relation between K_F and yarn tensile properties.

Dref-3 yarn structure is formed by a drafted ribbon of parallel fibers lying within the nip of the friction drums and being false-twisted, while simultaneously fibers from the opening roller are twisted onto the false-twisted ribbon. Core fibers in Dref-III yarn have, therefore, entrapped false twist.[88] The lower the core count, the higher is the entrapped twist. Under identical spinning conditions, the twist in the Dref-II yarn structure is greater than the sheath fiber twist in the Dref-III structure. It can

(a)

(b)

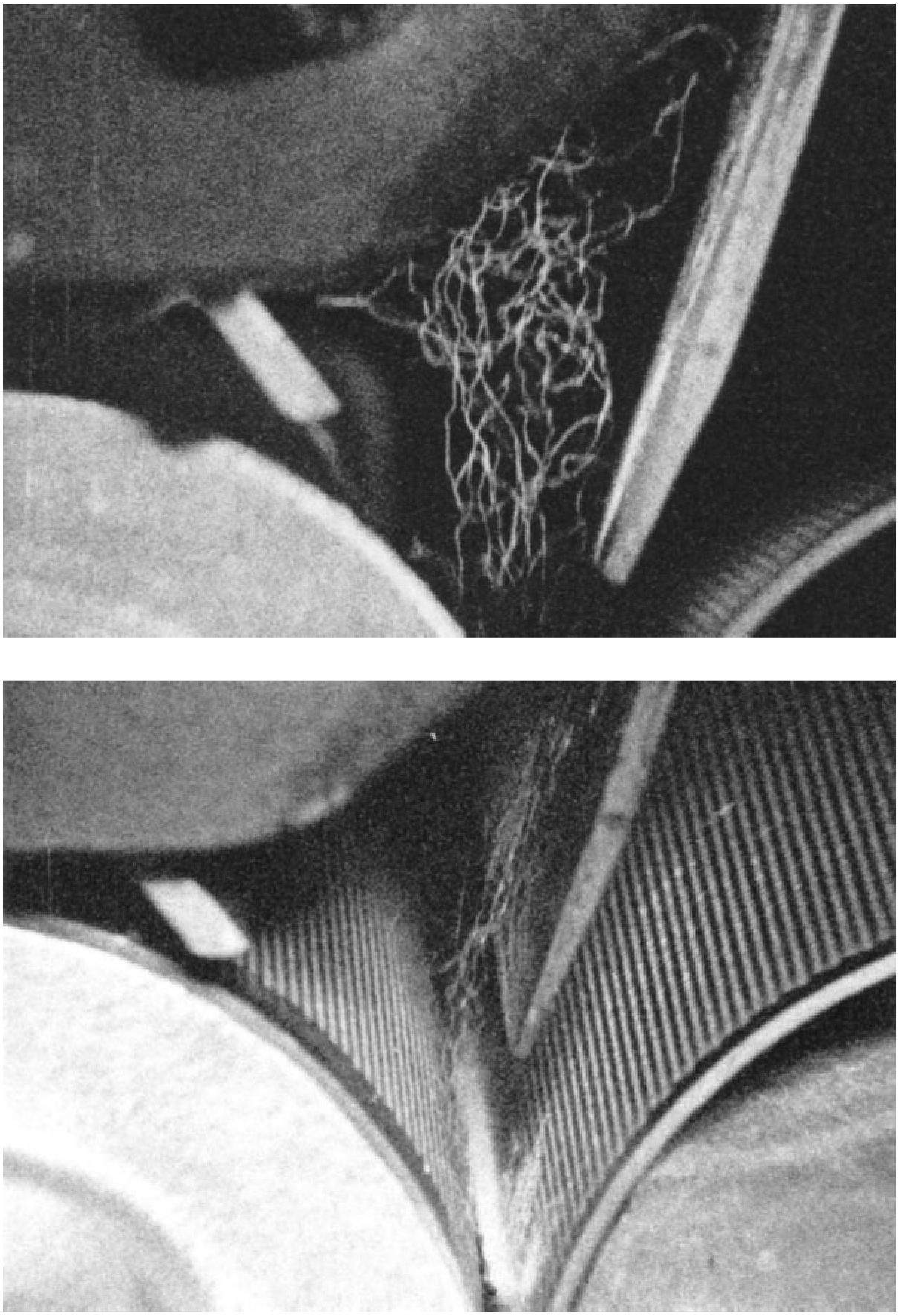


FIGURE 6.53 Transportation, deposition, and twisting of fiber in Dref-2 spinning.

be reasoned that the fiber configurations in the central region of the Dref-III yarn will be of classes 1, 2, and 3 (see Figure 6.50), whereas the sheath fibers will have similar configurations to those of Dref-2 yarns.

It is evident from the K_F values for the Dref-2 yarns, as compared with those for ring and rotor yarns, that significant improvement in fiber straightening is needed if finer yarn counts are to be produced by the open-end friction spinning technique. To improve fiber straightening, it is necessary for the fibers in flight to approach the

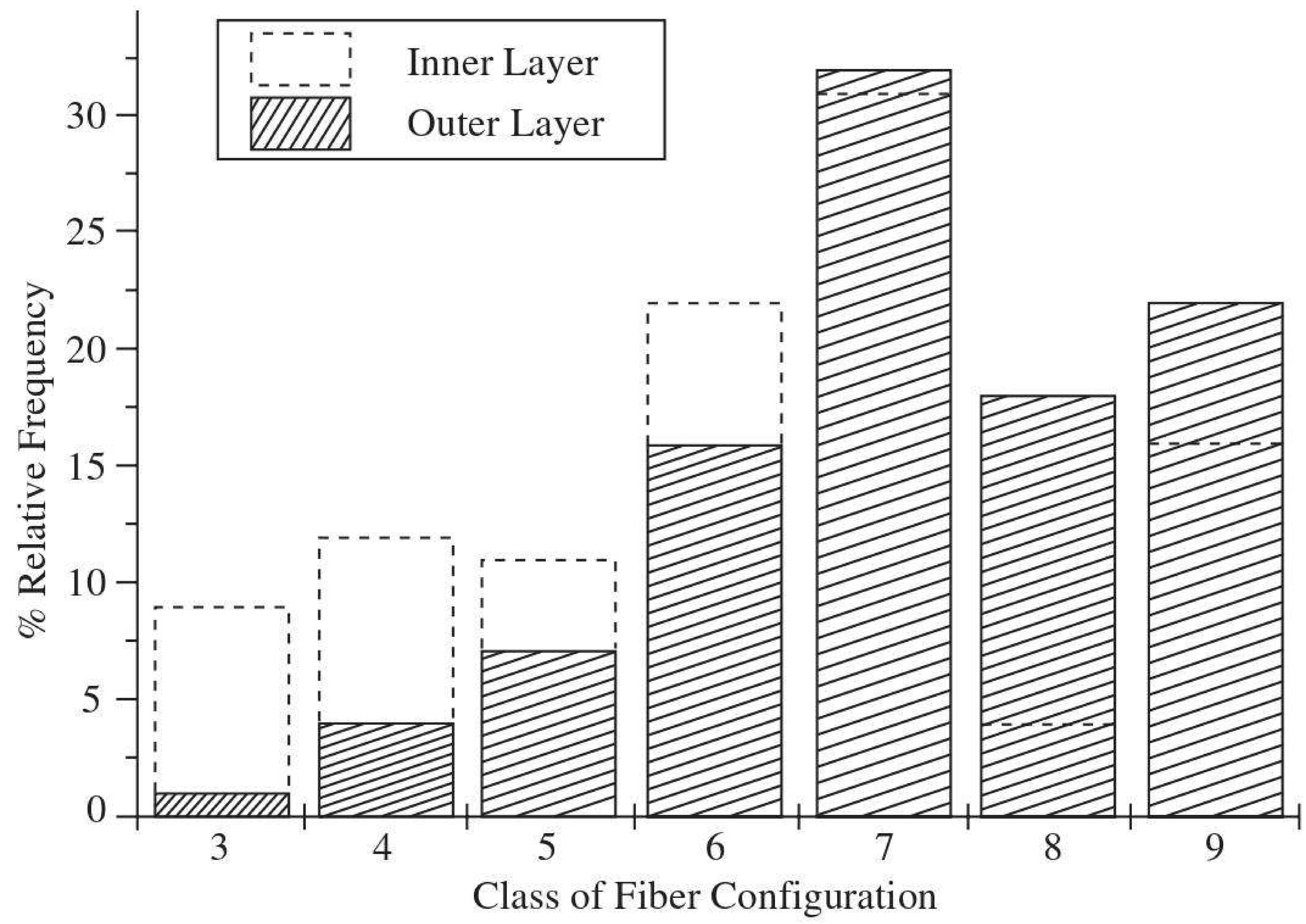


FIGURE 6.54 Relative frequency of fiber configurations in inner and outer layers of Dref-2 yarn.

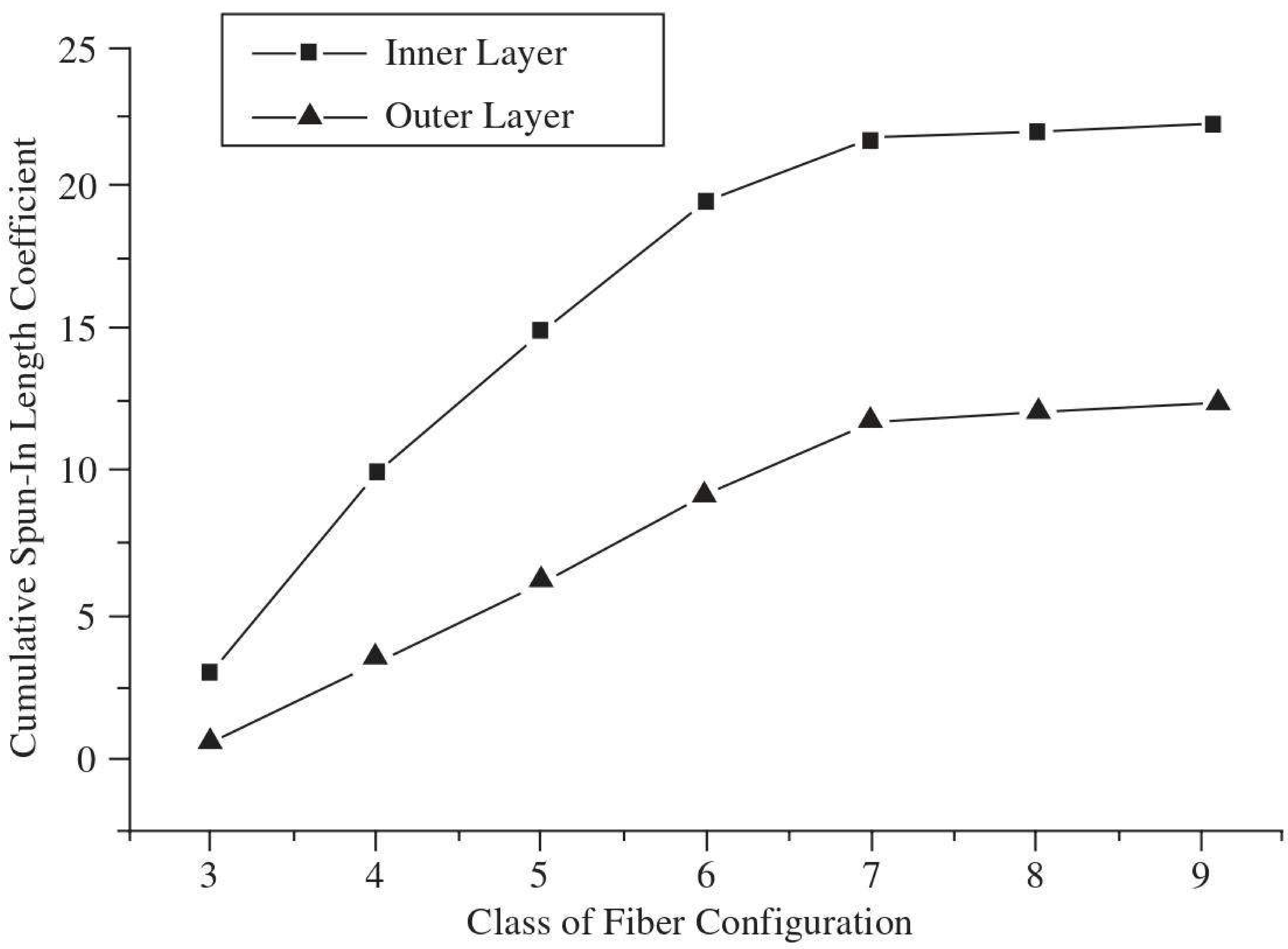


FIGURE 6.55 Spun-in length coefficient K_F for Dref-2 yarn.

forming yarn at a shallower angle than in the Dref-2 system (see Figure 6.58a). Suction rather than blowing is preferable for the transport of fibers, so that some degree of fiber straightening occurs prior to fibers being incorporated into the yarn structure. Much research[89,93] has been carried out into the development of open-end friction spinning for the production of finer count yarns that have a more ring-spun like structure. A comparison of Figure 6.36 and 6.57 shows that the finer yarn still has fiber loops rather than fiber ends projecting from its surface, but the general

TABLE 6.11
Effect of Spun-In Length Coefficient of Dref–2 Yarn Properties

ORS	K_F	FDS	K_F	AS	K_F	YD	K_F
3000	0.21/0.12	800	0.15/0.1	90	0.15/0.10	80	0.22/0.12
4000	0.10/0.05	3200	0.09/0.05	165	0.15/0.08	226	0.15/0.07

ORS = opening roller speed (rpm), FDS = friction drum speed (rpm), AS = air suction (mm H_20), YD = yarn delivery rate (m/min).

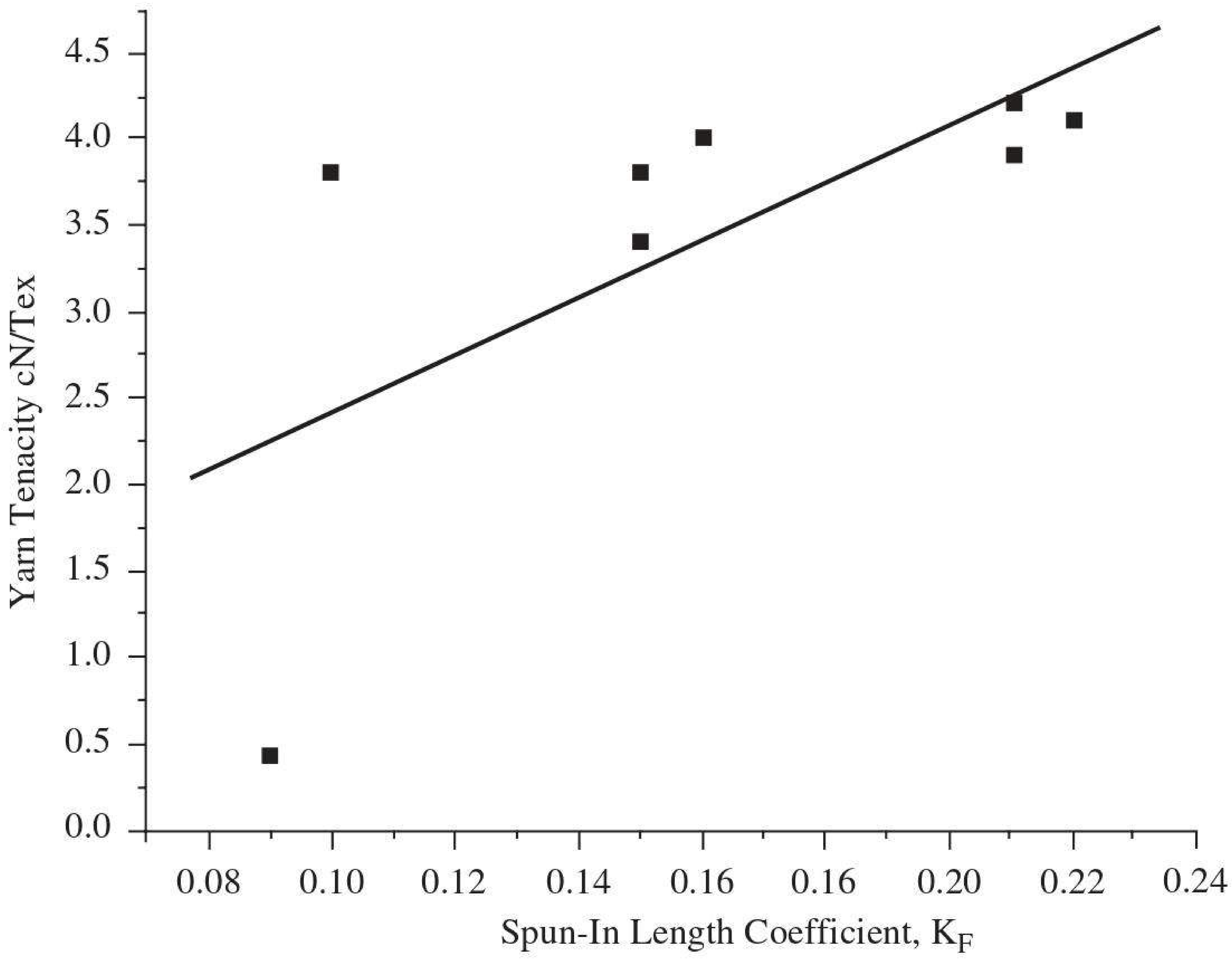


FIGURE 6.56 Effect of spun-in length on Dref-2 yarn strength.

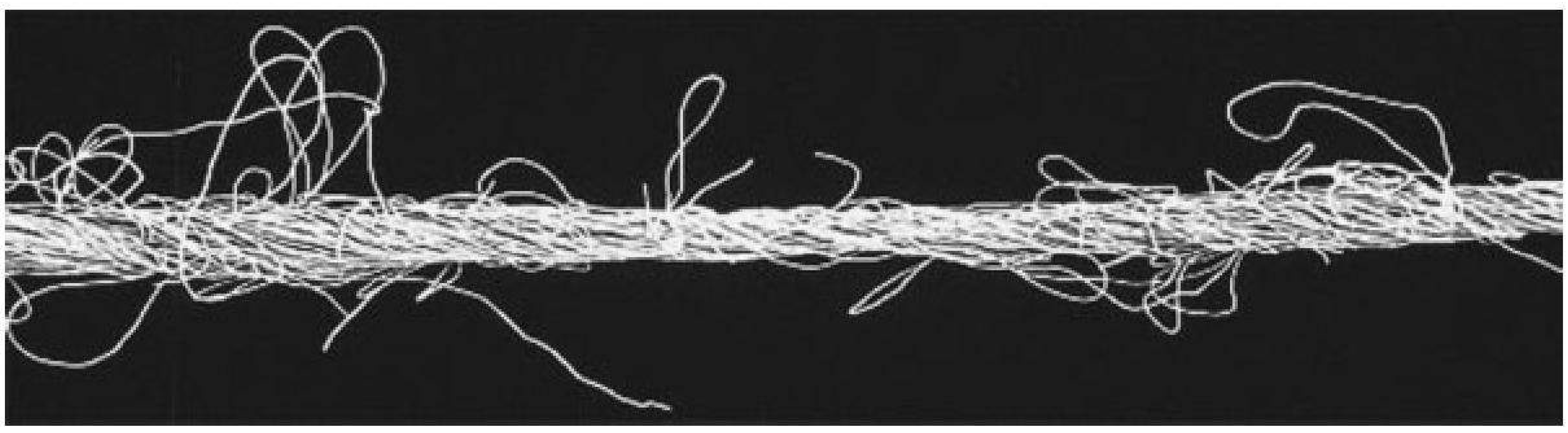


FIGURE 6.57 Structure of friction-spun yarn produced with inclined fiber channel.

structure is more akin to the conventional ring spun than to the Dref-2 yarn. Although the various prototype systems producing this type of friction-spun yarn have yet to reach, successfully, the commercial stage, the mechanism by which fibers are integrated into the yarn structure is fundamentally different from the Dref-2 system and is therefore of technical interest.

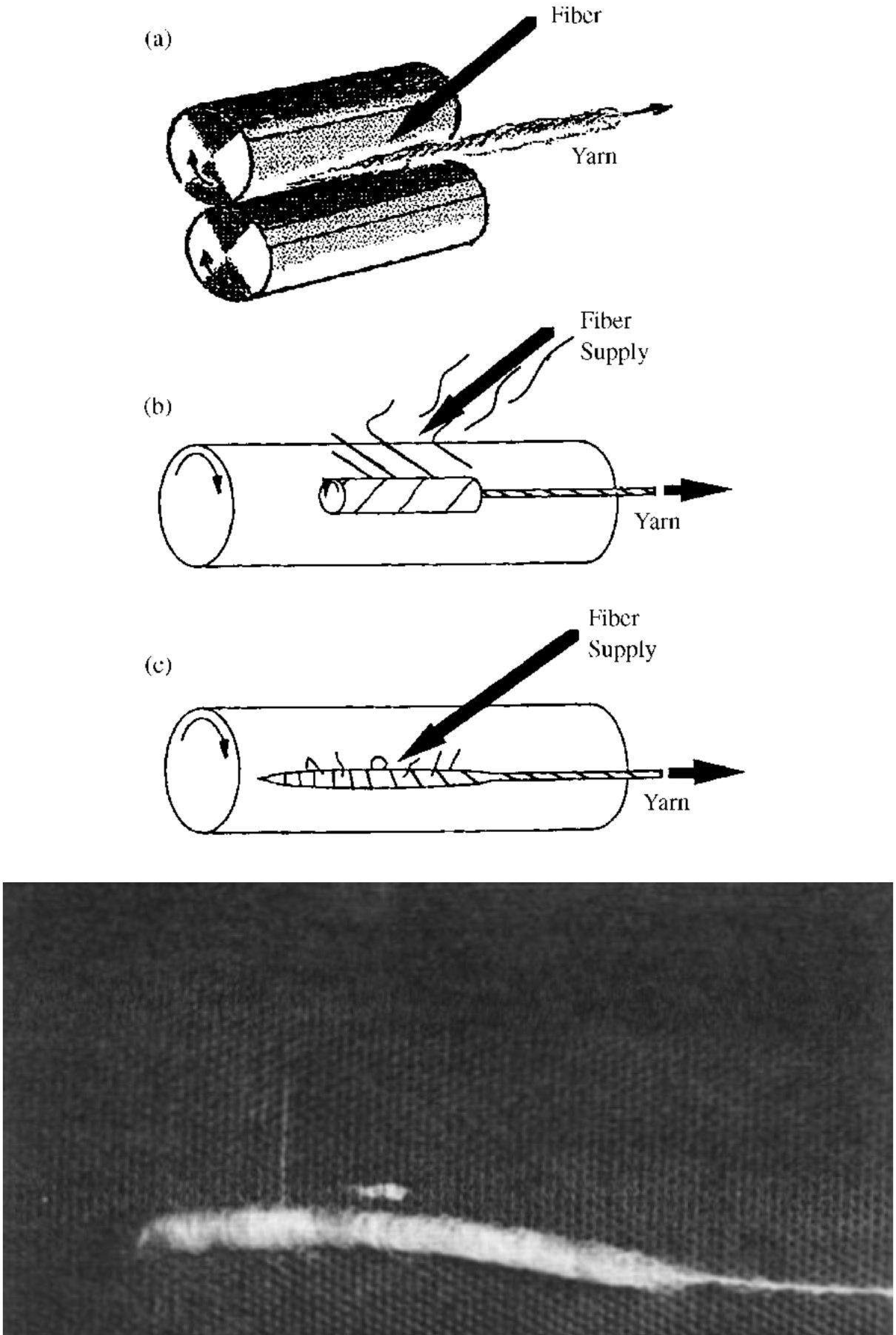


FIGURE 6.58 Yarn formation in fine-count OE friction spinning. (Courtesy of [top] Lord, P. R., and Rust, J. P., Fibre assembly in friction spinning, *J. Text. Inst.,* 4(82), 465–478, 1991, and [bottom] Stalder, H. and Soliman, H. A., A study of the yarn formation process during friction spinning, *Melliand* [Eng. ed.], 2, E44–46, 99–103, 1989.)

Stalder,[89,90] Lord,[91] and others[92–94] have established that, when fibers are delivered (usually from a single sliver feed) in an airflow down a channel inclined acutely to the yarn length between the friction drums, the fibers are deposited to form a sleeve, lofty in structure, around the conical end of the yarn (see Figure 6.58). The sleeve is usually squashed within the nip of the friction drums. Importantly, it is the fiber sleeve that rotates by frictional contact with the drum, and it does so without moving along the nip line of the drums. The yarn tail is formed within the sleeve, but it does not rotate;[89] the forming yarn length is only pulled away with the velocity of the delivery rollers.

The fibers are individually twisted onto the sleeve during their deposition. The fibers may be deposited, preferably, at the interface of the sleeve and the drum surface (Figure 6.58b) or directly onto the fiber sleeve (Figure 6.58c). The hypothesis is that the leading end of a fiber makes first contact with the friction drum surface, and the momentum of the trailing end causes the fiber length to fillip over its leading end as the fiber is being twisted into the rotating sleeve. This fillip-over action tends to give some degree of fiber straightening and results in the sleeve fibers having an S-twist helix. The preferred state of fiber deposition at the sleeve-drum interface is obtained by employing only one perforated drum with applied suction, the other drum (friction drum) being a solid surface, and by positioning the exit of the fiber transport channel close to the interface (see Figure 6.59).

Fiber ends projecting from the rotating sleeve provide the means of capturing the leading ends of the depositing fibers for the latter to be twisted onto the sleeve. Fibers may also be captured as illustrated in Figure 6.60. At (a), the fiber approaches and is pulled into the interface of the sleeve and the first drum surface. The sleeve rotates at a surface velocity $V_y < V_{R1}$. It is, however, likely that the torsion resistance of the sleeve is sufficiently small that slippage between itself and drum is negligible in comparison with the Dref-2 system.[53] At (b), the fiber contacts the second drum surface, or is entangled in the sleeve, and moves toward the second interface. In positions (c) and (d), the fiber becomes twisted onto the sleeve.

Figure 6.61 depicts how fibers forming the sleeve are subsequently twisted onto the conical tail of the yarn. The leading ends of fibers in the rotating sleeve become attached to the yarn tail (Figure 6.61a) and, as the yarn length is pulled away by the delivery rollers, the attached fibers are Z-twisted onto the tail (Figure 6.61b). The figure shows a fiber with S-helix angle γ being twisted with Z-helix angle β onto the yarn tail at a point where, locally, the diameter is indicated as "d" (Figure 6.61c). From the geometrical parameters given in the diagram, (Figure 6.61c and d) the following equation can be derived for the yarn twist:[89,90]

$$\frac{1 - (\pi D_R T_{AV}/Y)}{\sqrt{[1 + (2\pi d_G T_{AV}/3)^2]}} = \cos\gamma + (\sin\gamma/Y) \tag{6.26}$$

where D_R = fiber sleeve diameter
T_{AV} = average yarn twist
Y = ratio of drum surface speed to yarn speed
d_G = average yarn diameter

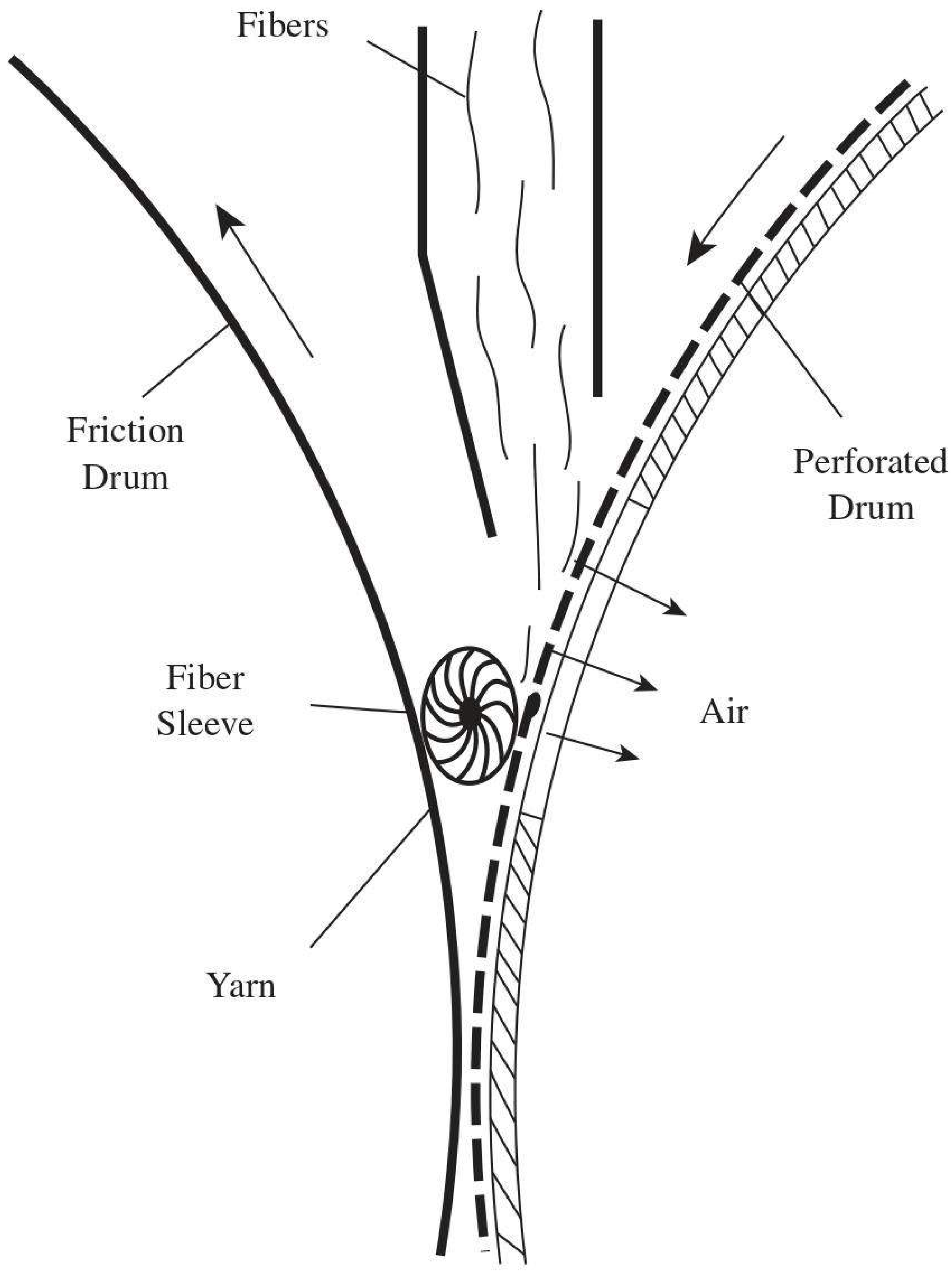


FIGURE 6.59 Fiber deposition at the sleeve-friction drum interface. (Courtesy of Krause, H. W., Soliman, H. A., and Stalder, H., The yarn formation in friction spinning, *Int.Text. Bull., Yarn Forming,* 4, 31–42, 1989.)

The yarn twist decreases with increasing diameter. Hence, because of the conical tail, fibers are twisted onto a variable diameter, "d" (see figure), which results in the twist in friction-spun yarns being higher at the center than the surface. For a given Y, coarser yarns will therefore have a lower average twist than finer yarns. As may be expected with regard to the ratio of drum to sleeve diameter, the yarn twist decreases with increasing sleeve diameter. If γ is too small an angle, then the pulling of yarn length by the delivery rollers may cause slippage between the fibers in the sleeve and the yarn tail.

6.2.2.5 Formation of Wrap-Spun Yarn Structures

6.2.2.5.1 Air-Jet Spun Yarns

The occurrence of the three subclasses of air-jet wrap-spun yarn structure shown in Figure 6.38 may be explained from further consideration[95] of the mechanism of edge fiber wrapping described in Section 6.1.4.1.2. As the drafted ribbon of fibers issues from the front drafting rollers, similar to conditions in ring spinning, the bulk of the fibers become twisted to form the bulk or core of the yarn, the twist angle being, say, α_K. Not all of the fibers will be caught by the twist triangle. The

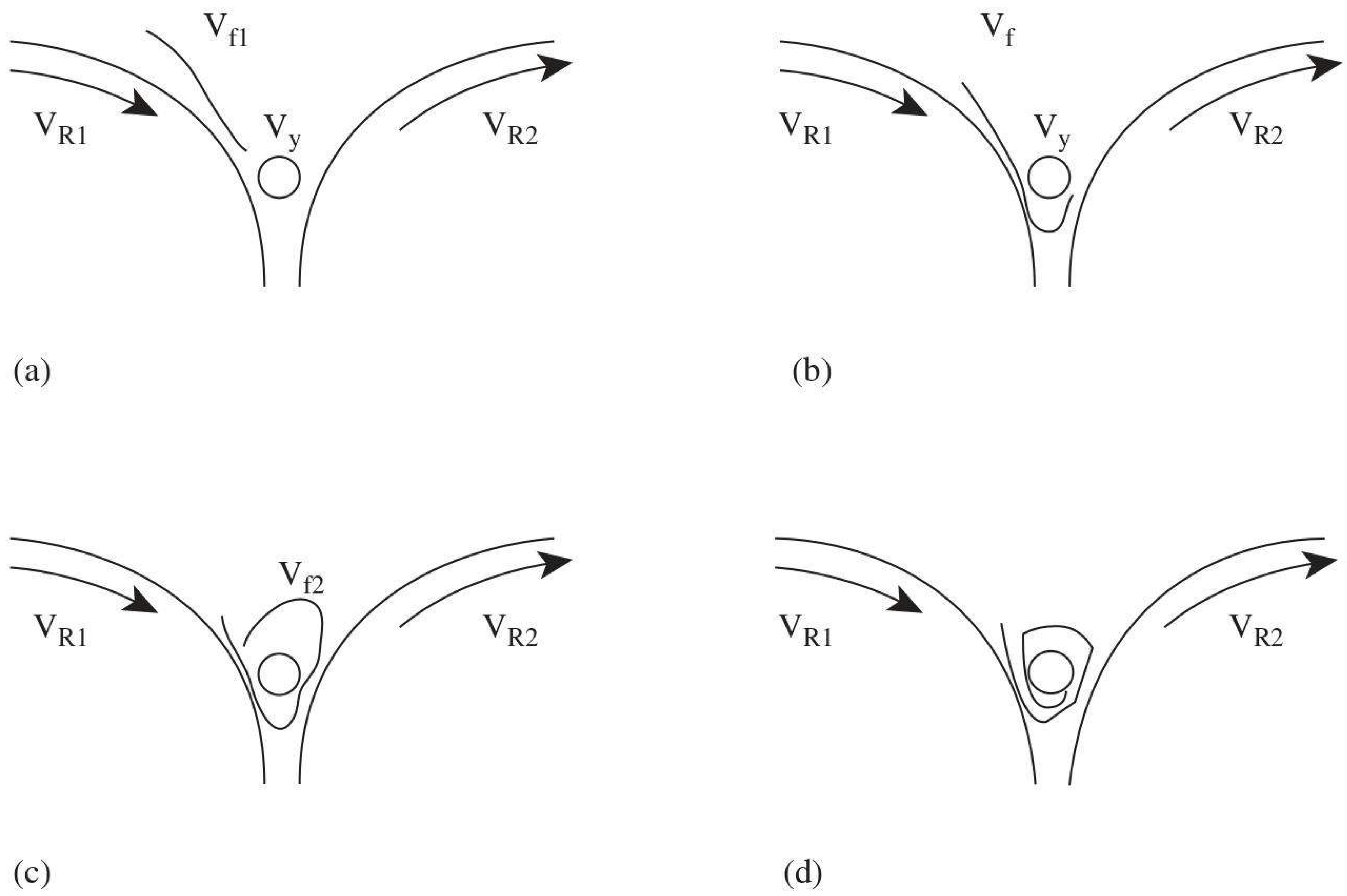


FIGURE 6.60 Fiber capture by rotating sleeve. (Courtesy of Lord, P. R. and Rust, J. P., Fibre assembly in friction spinning, *J. Text. Inst.,* 4(82), 465–478, 1991.)

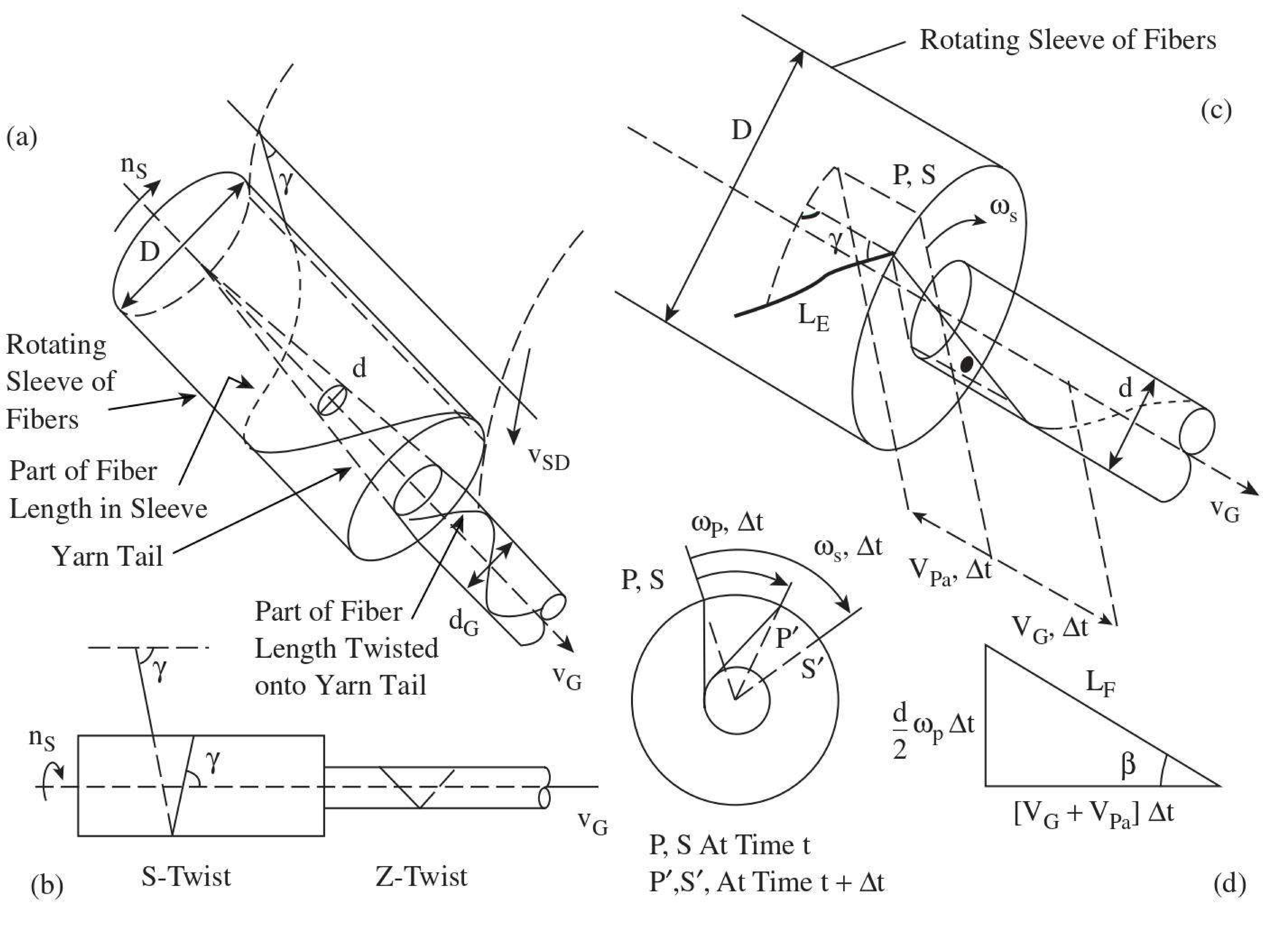


FIGURE 6.61 Twisting of fibers onto yarn tail. (Courtesy of Stalder, H. and Soliman, H. A., A study of the yarn formation process during friction spinning, *Melliand* [Eng. ed.], 2, E44–46, 99–103, 1989.)

free fibers, which are mainly edge fibers, subsequently come into contact with the rotating body of fibers and wrap around it; if the wrap angle of an edge fiber is α_R, then $\alpha_K > \alpha_R$.

The aim is to secure sufficient edge fibers for wrapping so as to obtain useful yarn strength.[96] To do so, the edge fibers must not get pulled into the twist insertion point but, instead, wrap the balloon length of the forming yarn core well below the twist insertion point. If the spinning conditions are such that the ballooning core has a large circularly polarized amplitude (see Chapter 8) and a high rotating speed, then the airflow generated by the balloon, near the front drafting rollers, will push edge fibers away from the twist insertion point while the suction of the first jet pulls the edge fibers into contact with the balloon below the twist insertion point. The amplitude and rotating speed of the balloon are governed by the jet-nozzle angles, jet pressures, ribbon width, production speed, and thread-line tension, i.e., overfeed ratio. The second-jet angle and applied pressure determine the twist level at the twist insertion point. A low level of twist assists in preventing edge fibers being twisted into the core. More edge fibers are formed with a wide ribbon issuing from the front rollers. Usually, only 6% of all fibers are used for wrapping.[97]

As Figure 6.62 illustrates, the class of substructure wrapper that a fiber eventually forms is governed by the size and direction of the wrap angle the edge fibers have

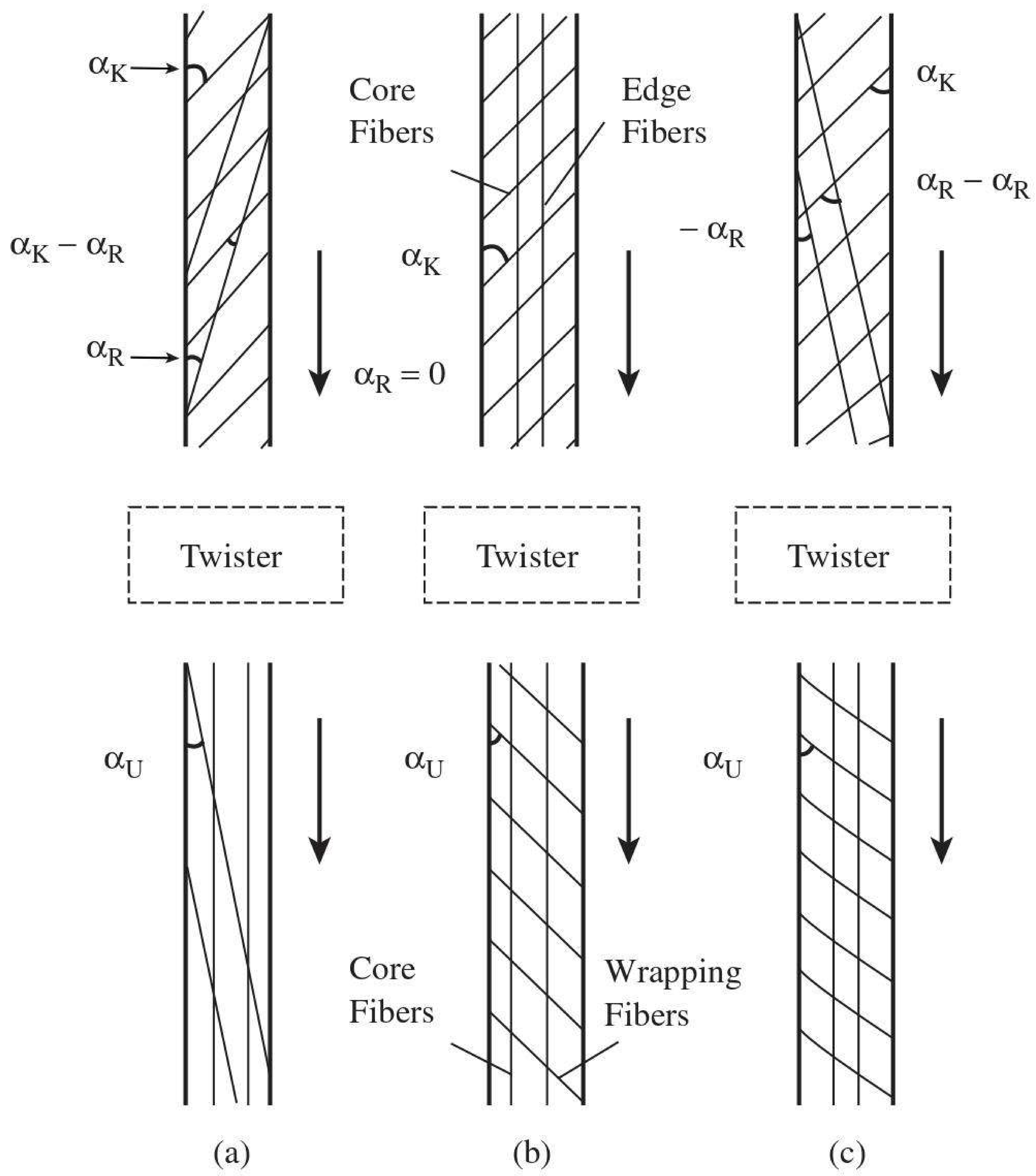


FIGURE 6.62 Edge fiber wrapping before and after air-jet twisting device.

when they are first wrapped onto the core fibers.[95] If α_R is in the same direction as α_K (say, Z) then the resulting substructure will be Class I (Figure 6.62a). The resulting wrap angle is α_U.

For the case where α_R corresponds to an S-wrap, a Class II type substructure will result (Figure 6.62c); when $\alpha_R = 0$, a Class III substructure is formed (Figure 6.62b). A Class I corkscrew formation occurs when $\alpha_K >> \alpha_R$. In such circumstances, the untwisting of the core gives a sizeable increase in length but also a sizeable contraction in the length of the wrapping helix, which buckles the core length.

The simple helix model may be modified to basically represent the air-jet structure. For Class I, only the wrapper fibers would collectively adopt the yarn helix angle $\alpha < 90$; the remaining fibers would from the twistless core of the yarn. Class II would have a twistless core of fibers similar to Class I, but each fiber in a group of wrapper fibers would have differing values of α_U. With Class III, the surface (i.e., wrapper) fibers would give the yarn a twisted appearance, $\alpha_U = -\alpha_K$. As each class length is much shorter than a fiber length, parts of a wrapper fiber length will be among the core fibers so that, when a load is applied to the yarn, tension is induced in the wrapper fibers and thereby radial pressure is applied to the core fibers. The resulting interfiber friction prevents slippage.

6.2.2.5.2 Hollow-Spindle Wrap-Spun Yarns

In the formation of hollow-spindle (HS) yarns, the manner of wrapping is an important factor, since wrapping coils must be distributed as uniformly as possible along the yarn. Wrapping takes place at the point where the filament makes contact with the staple fiber core and is done with or without the use of a false-twister. The simplest and most effective is with a false-twister. Based on the description of the process, given in Section 6.1.4.2, Figure 6.63 shows that the location of yarn formation may be divided into three zones. The tension during twisting is much lower than in ring spinning, and therefore fiber migration is negligible, and the formation of hairs is relatively low. Fiber lengths that do project from the core are subsequently bound onto the core by filament wrapper.

As shown, there are two ways by which wrapping can occur using the false-twist spindle technique, depending on the threading of the false-twister. With Case A, positive threading, wrapping occurs within the hollow spindle, giving a low level of S-wraps per unit length. But this increases to the preset value below the false-twister, where there is a much shorter yarn length between the false-twister and the delivery rollers. Note that spindle rotation is clockwise. For Case B, wrapping occurs only below the false-twister, with the S-wraps per unit length generally equalling the preset value. It is found that Case B gives the better yarn properties, as lower core tension occurs (see Figure 6.64).

The HS wrap-spun structure may be spun with a parallel or crimped profile, depending on the relative tensions of the filament and the core, when twisted. As Figure 6.65 illustrates, if the tension, F_s, of a staple core, when twisted, is greater than the filament tension, F_f, during wrapping, then the core will not be crimped when untwisted; the converse gives the crimped profiles shown in the figure. The tension of the core is controlled by the difference in surface speed between the front drafting rollers, V_s, and the delivery roller, V_d. The percentage ratio $[V_s/V_d]$ 100 is

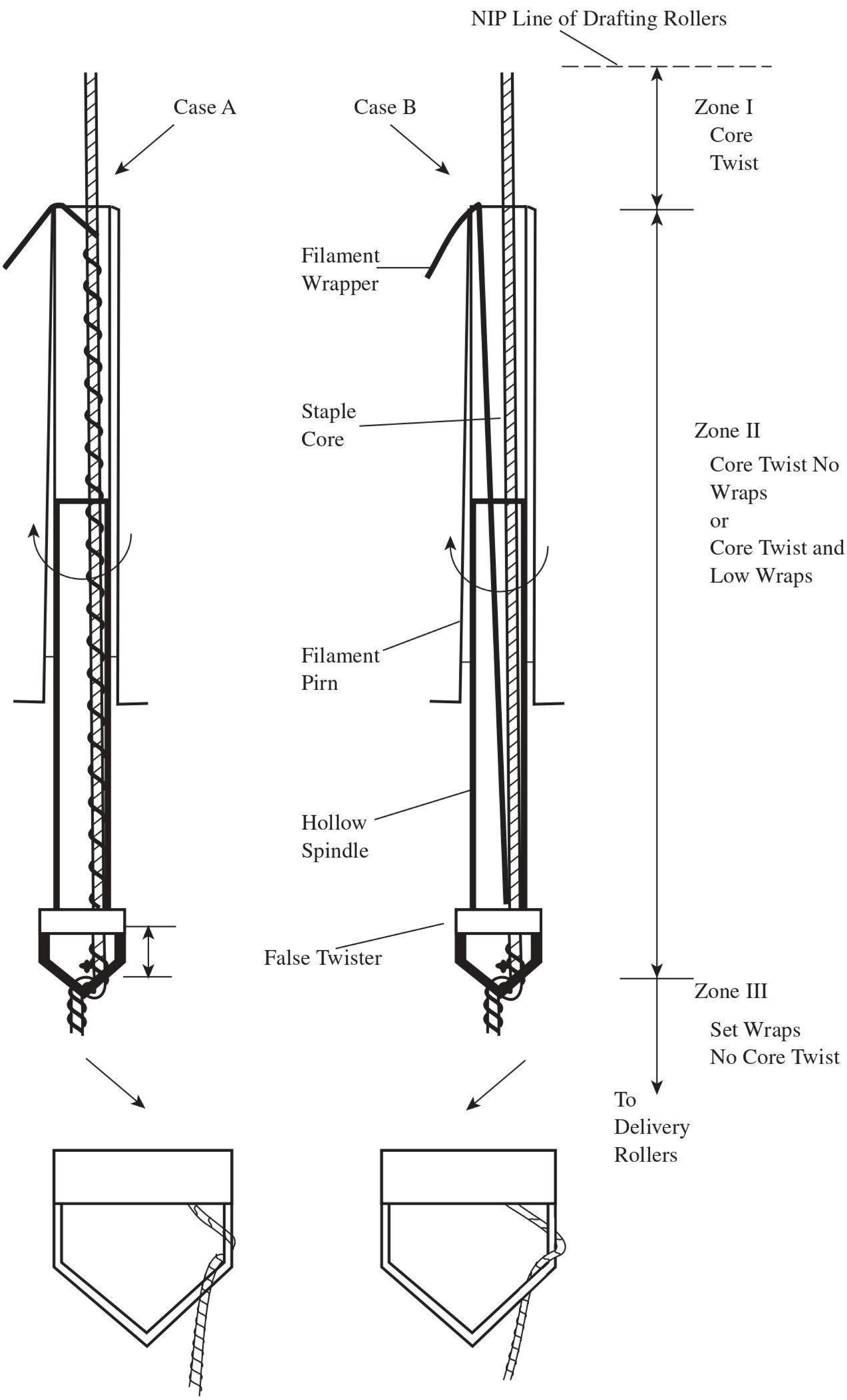


FIGURE 6.63 Hollow-spindle wrap-spun yarn formation. (Courtesy of Srinivasan, K. V., *A Study of Hollow Spindle Yarns,* M.Sc. thesis, U.M.I.S.T, 1984.)

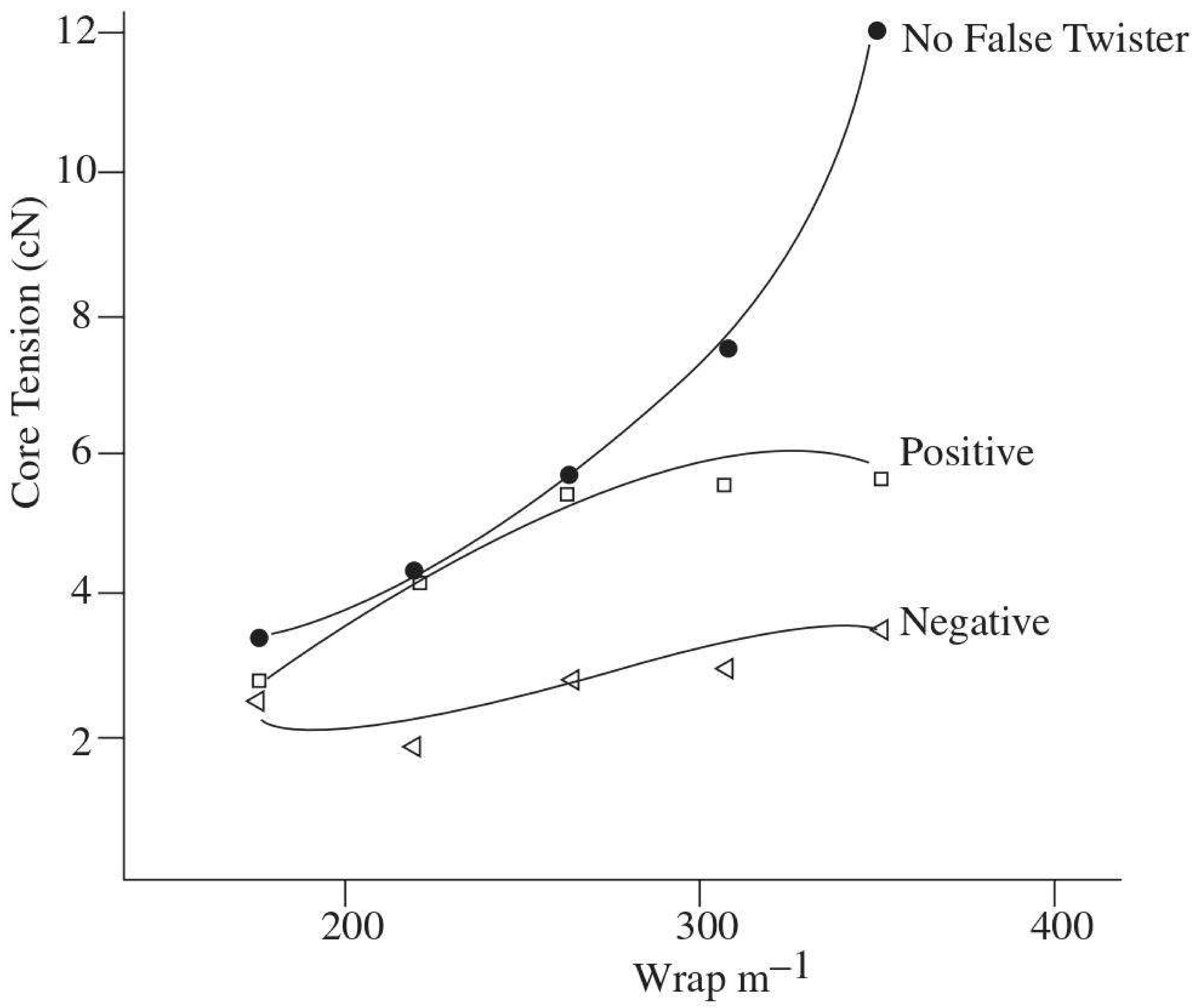


FIGURE 6.64 Spinning tension for Case A and Case B.

referred to as the *overfeed*. If it is less than or equal to unity, a parallel profile can be obtained; if greater than unity, the crimp profile occurs, the amount of crimp being dependent on the overfeed. This facility for structuring the profile makes the HS yarn process suitable for producing fancy yarns (see Chapter 9).

In principle, all staple fibers can be combined with any type of continuous filament. However, monofilament wraps the staple core in such a way that the filament becomes almost imperceptible among the bulk of the yarn, whereas multifilament appears as a ribbon spirally wound around the yarn.

6.2.3 Structure Property Relation of Yarns

Yarn properties are usually evaluated from two perspectives:

- The likely performance of the yarn in subsequent fabric manufacturing processes
- The fabric surface appearance and mechanical properties, often of importance to the visual and tactile aesthetics of end products

In weaving and knitting, tensile properties give an indication of the work rupture to withstand cyclic tensioning, the coefficient of variation of breaking load giving a measure of the weak places. Yarn surface friction, compression, and hairiness are also important to the yarn running behavior with respect to peak tensions that may result in yarn breaks and the liberation of fiber fragments from the yarn surface. Although not commonly measured, the bending rigidity and compression are linked to the ease of deforming the yarn around thread guides and in attaining precise fabric geometry.

Of prime importance to fabric appearance are yarn irregularity, the absence of periodic faults, neps, conspicuous thick and thin places, and hairiness. All of these

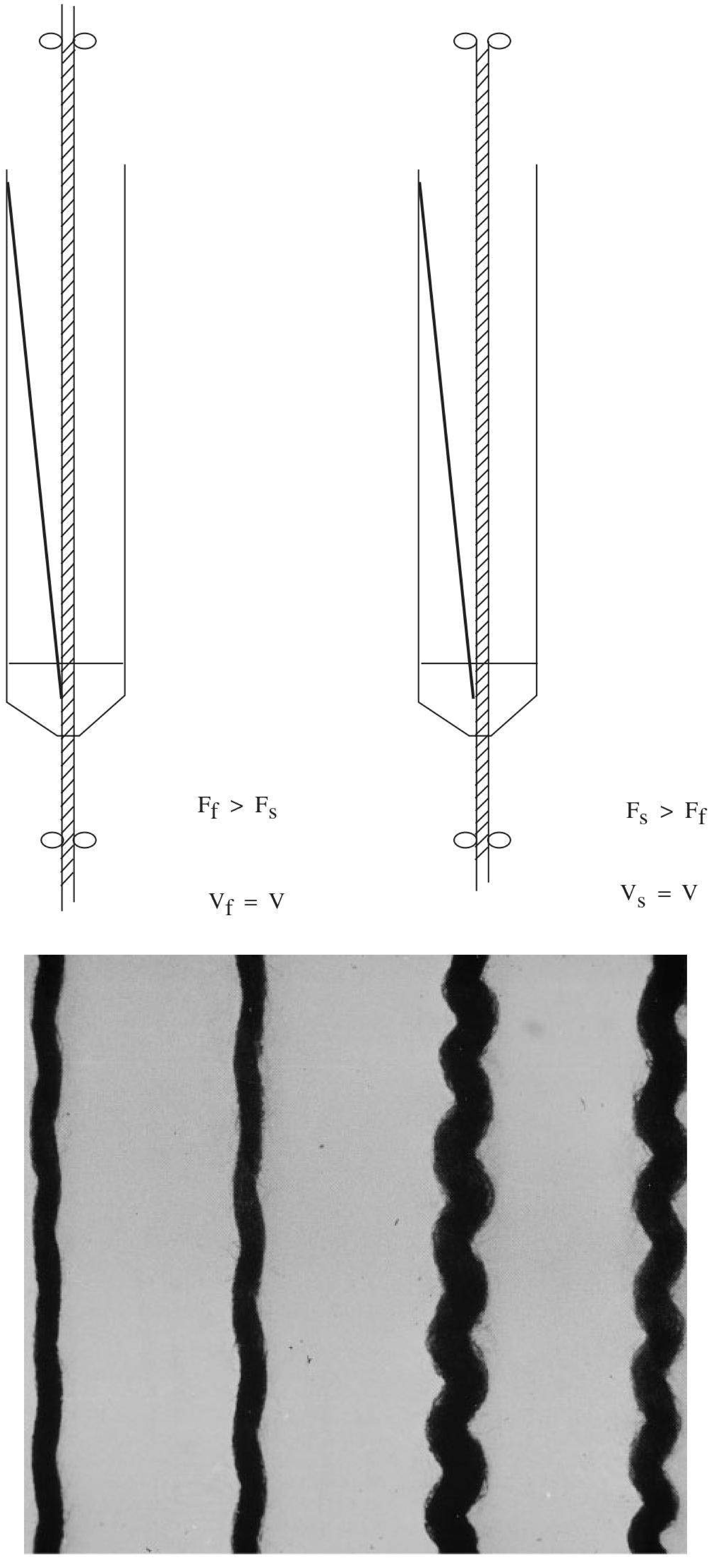


FIGURE 6.65 HS wrapped profiles.

are usually measured to quantify the quality of a yarn. The degree of parallelism of the surface fibers of the yarn strongly influences the light reflectance from a fabric. Even though neither is measured, it is well appreciated that, subject to the effect of the optical properties of the fiber, the higher the degree of parallelism and the lower the hairiness, the more lustrous the yarn will appear in, say, a woven fabric. A more random surface arrangement gives a matt look to the cloth.

Fabric mechanical and surface properties, which may be determined by objective methods,* have been correlated with fabric handle.† These fabric properties are dependent on fabric structure but also on the constituent fiber and yarn mechanical properties. The most basic types of fabric deformation are in-plane extension and shear, bending in a perpendicular plane, and out-of-plane buckling.[75] In the daily use of fabrics, the deformation that occurs is likely to involve a combination of the basic types. However, it is useful to consider, as a simple example, the part that a yarn plays in the deformation of a plain woven fabric under tensile loading in either warp or weft direction, as this may help to illustrate the importance of some of the properties considered later in this section.

When a plain-woven fabric is subjected to tensile stress in one of the principal weave directions, it is useful to know the physical changes occurring in both directions of the structure.

Figure 6.66 shows a diagrammatic cross section of a plain weave fabric. Since Peirce's[99] geometrical model of plain cloths, a number of modifications have been made to take account of flattening of the constituent yarns.[75] We can see that flattening of the yarns is important because this gives the fabric a better cover factor,‡ but it also reduces the fabric crimp§ and thickness. The flattening of the yarns will give more frictional contact at their crossover points and this, along with bending rigidity of the yarns, is important to fabric mechanical properties, particularly at low fabric extensions.

Figure 6.67 shows a typical load-extension curve for a plain weave fabric which can be divided into three distinct zones. 0–I is a high initial modulus zone. This

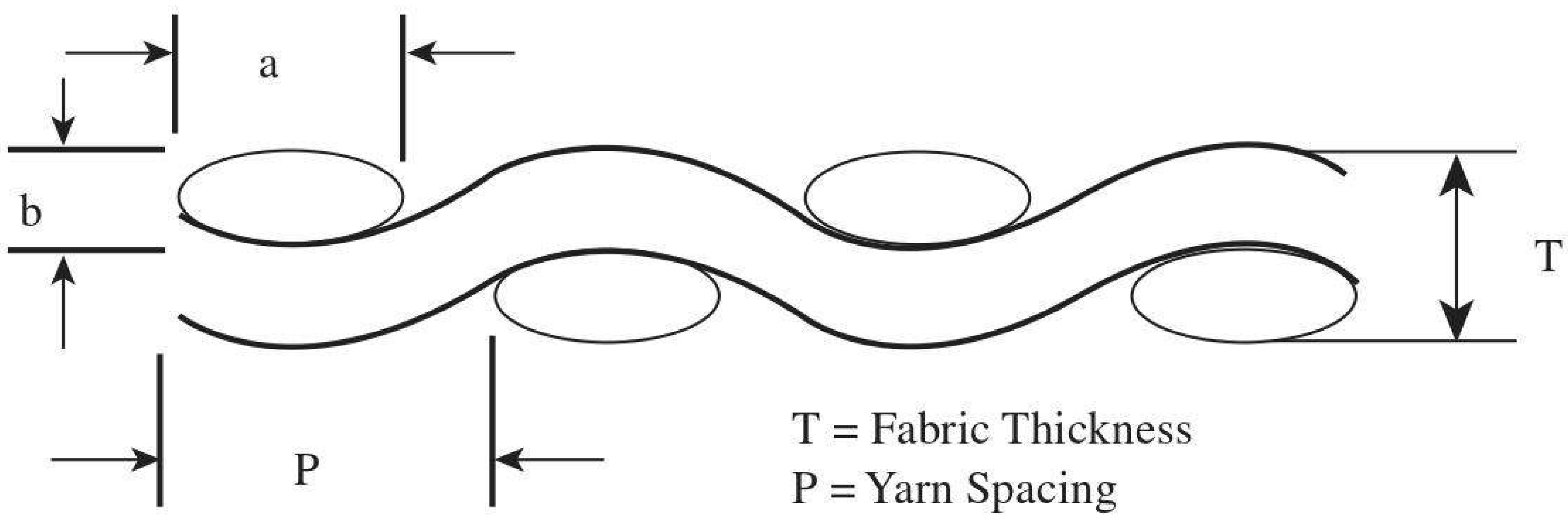


FIGURE 6.66 Diagrammatic cross of plain-weave fabric.

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* Kawabata and FAST Systems.

† Defined (in the Textile Institute's *Terms and Definitions*) as the quality of a fabric or yarn assessed by the reaction obtained from the sense of touch, i.e., with regard to roughness, smoothness, harshness, pliability, thickness, etc.

‡ The area of a fabric covered by the constituent yarns.

§ The waviness or distortion of a yarn that is a result of interlacing in the fabric (as defined in the Textile Institute's *Terms and Definitions*).

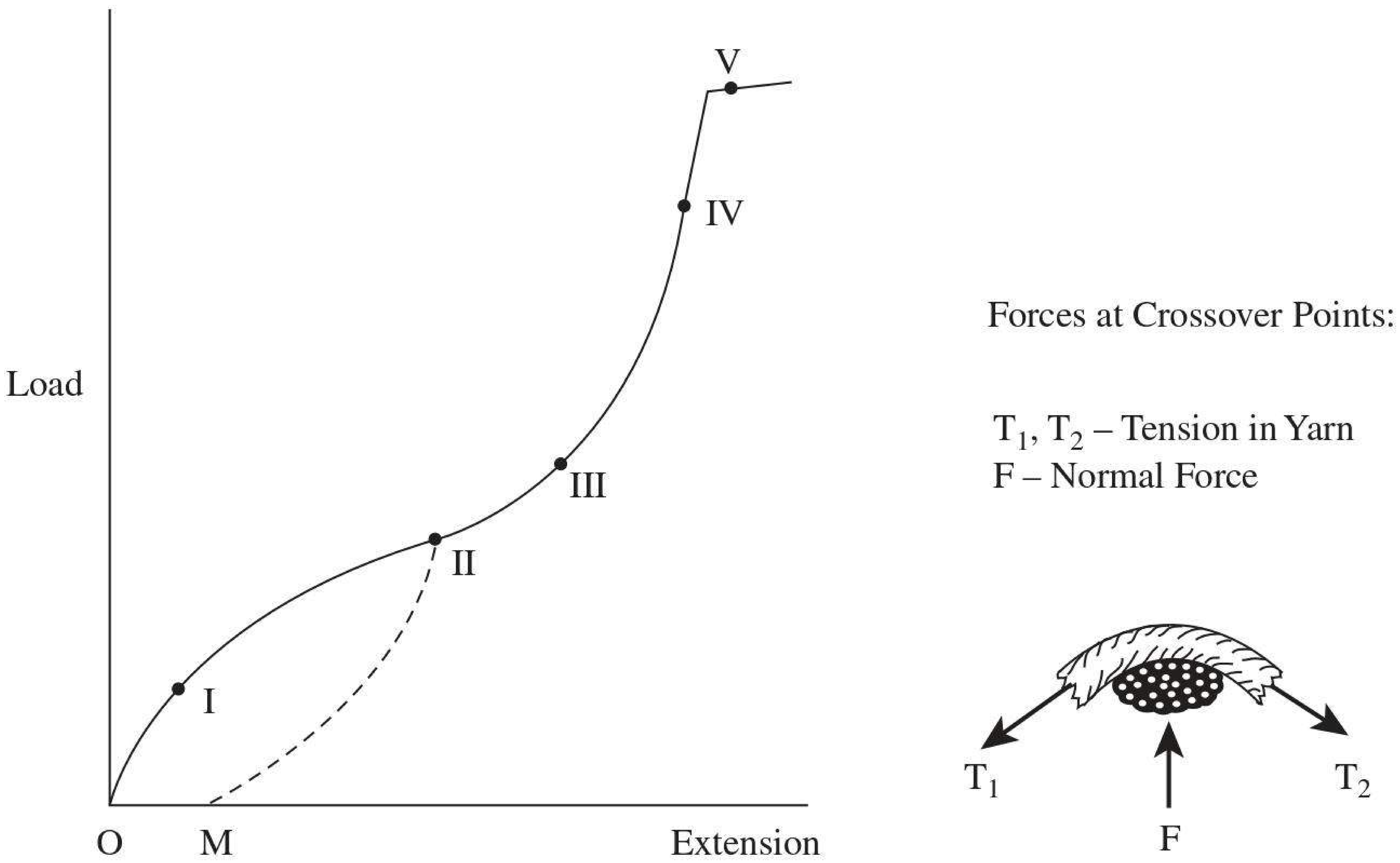


FIGURE 6.67 Load-extension curve of plain-weave fabric.

high resistance to extension is largely caused by the initial bending modulus of both warp and weft yarns as a result of interfiber frictional resistance. I–II is the yarn decrimping zone. Once the load exceeds the frictional resistance to yarn bending, increasing extension occurs at much lower increases in load. The increases in load is required for the following:

1. Decrimping, by unbending, the yarns in the direction of the applied load
2. Increasing the crimp of the orthogonal yarns
3. Increasing the compression at the crossover points

The reduction in crimp in the applied load direction will increase the fabric length, and the increase in crimp in the orthogonal direction will reduce fabric width. The increase in pressure at the crossover points will tend to prevent fiber slippage. This effect is termed *fabric assistance.*

When the crimp has been considerably reduced, further extension causes the fabric modulus to rise (Zones II–III–IV). The compression at the crossover points enables yarn and fiber extension to take place. Beyond point III, the tensile modulus is almost comparable to the fiber modulus and remains constant until the fiber yield point. Beyond the yield point, the modulus decreases rapidly, and the fabric breaks at the point of fiber rupture.

The tensile properties of the fabric within the region III–V and during the process of yielding are largely governed by the fiber and yarn properties rather than the fabric structural properties. However, fabric assistance increases the strength of the fabric, so the fabric strength is greater than the sum of the strengths of the individual threads in the direction of applied stress.

From the above discussion, we can infer that the yarn properties listed in Table 6.12 are important to both post-spinning processing and fabric properties.

Therefore, they are the ones we shall now consider in terms of yarn structure-property relation. The various methods for measuring these properties will not be described in this book. The reader unfamiliar with textile testing is advised to study in parallel with the remainder of this chapter the relevant text in the books listed in the Recommended Readings section of Chapter 3.

TABLE 6.12
Yarn Properties Influencing Post-Processing and Fabric Properties

Yarn properties
• Compression
• Bending rigidity
• Tensile
• Irregularity
• Hairiness
• Moisture transport

6.2.3.1 Compression

Yarn compression is considered in terms of the changes in yarn diameter, or thickness, with compressive load. There are several definitions[100,103] of yarn compression, but essentially most take the form

$$\text{Compression\%} = 100\frac{(d_O - d_w)}{d_O} \tag{6.27}$$

where d_O = yarn diameter at minimum load (1 g/cm^2)
d_W = yarn diameter at w g/cm^2

Figure 6.68 illustrates how yarn diameter varies nonlinearly under compressive loading. The percentage ratio of the work done in recovery (i.e., area under the curve EC) to that for compression (i.e., area under the curve FC) is referred to as the *resilience*[104] and may be defined as the ability of the material to recover from compressive loading,[105] or the net recoverable energy.

Much research has been done, primarily on conventional ring-spun yarns, aimed at establishing an understanding of the factors governing yarn compression and deriving general equations for compression and recovery curves. Theoretical studies[102,106,107] have been based on the simple helix model, assuming that yarn compression may be related to the bending and twisting of the fiber helices (the *compressive resistance* being the resistance of the individual fiber helix to undergoing deformation into a flattened shape). The strain energy of individual helices are then determined, and the strain energy of the yarn is then the sum of the strain energies of the individual units. Figure 6.68 shows that close approximations have been obtained for the general form.[102] The difference between the theoretical and experi-

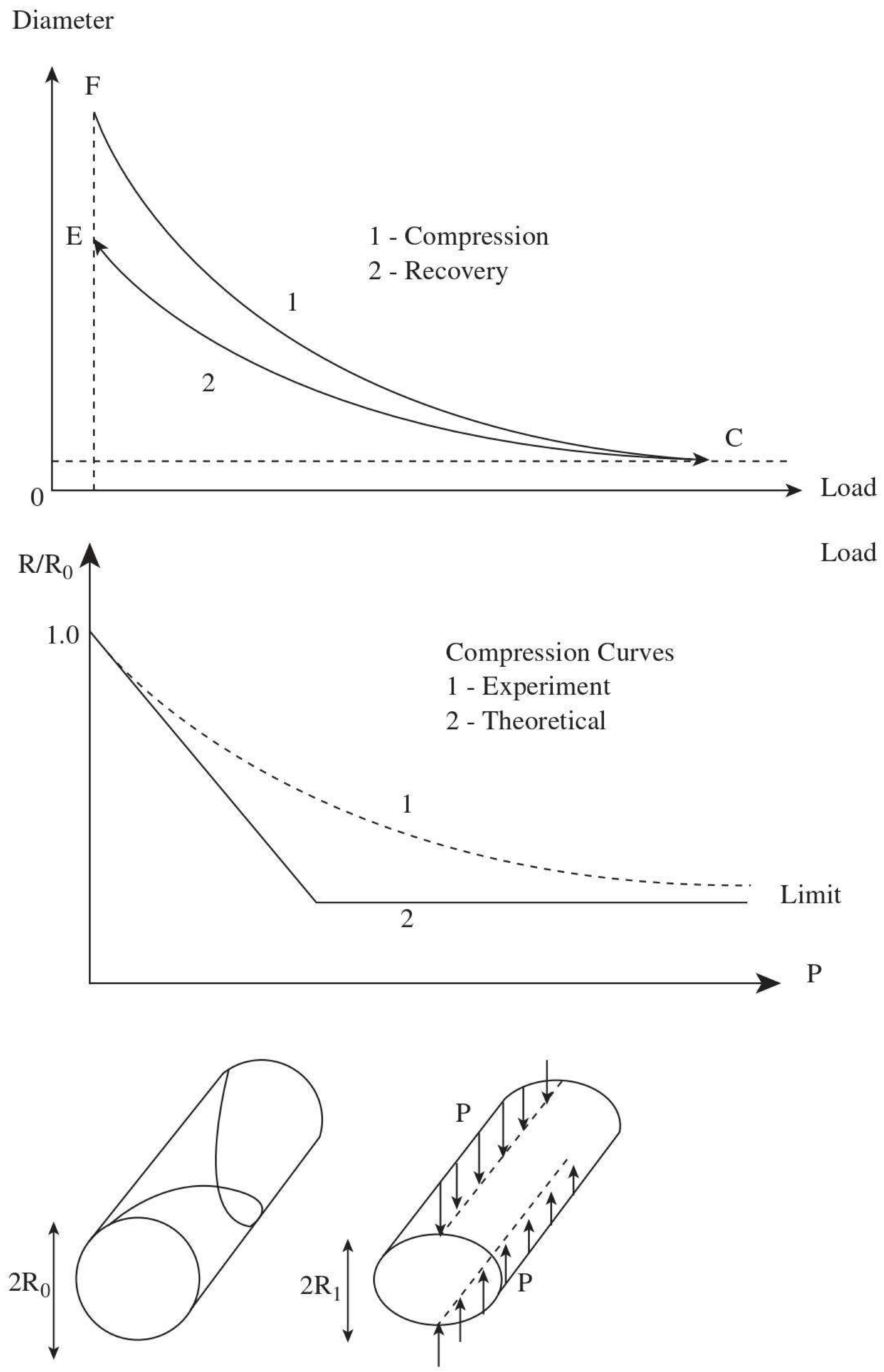


FIGURE 6.68 Idealized yarn compression and recovery curves. (Courtesy of Goktepe, F., *The Effect of Yarn Structure of the Deformation of the Yarn Cross-Section,* Ph.D. thesis, University of Leeds, 1997.)

mental results is attributed to, among other factors, the departures of real yarns from the simple helix model. Empirically derived equations show differences, probably a result of differences in test methods. However, it was generally found that spinning twist and fiber crimp were the most important factors; the compression resistance increased as these increased. Fiber length and cross-sectional shape have less effect.

The word *bulk* is another commonly used term relating to the compression characteristics of textile materials, particularly in relation to the *handle,* which, as an aesthetic property, has a subjective element. However, the bulkiness of a yarn may be considered in terms of the volume occupied by the constituent fibers or more simply the yarn's specific volume, which is related to the yarn count, T_t, by

$$T_t = \pi R^2 \frac{10^5}{v_y}\,{}_y \tag{6.28}$$

where R = yarn radius (cm)
v_y = specific volume (cm^3/g)

Yarn specific volume is an indication of the fiber packing in a yarn. Ignoring the effects of irregularities, we can consider the fiber packing density, Φ_d, of a yarn to be the number of fibers per unit area perpendicular to the helix angle, in which case

$$\Phi_d = \frac{T_t}{T_f} \pi R^2 \tag{6.29}$$

where T_f = fiber fineness

Alternatively, the degree of fiber packing may be given by the fiber packing fraction, Φ_f, of the yarn, which is the proportion of the yarn cross-sectional area, perpendicular to the yarn axis, occupied by the constituent fibers. If ν_f is the fiber specific volume, then the fiber packing fraction is

$$\Phi_f = \frac{v_f}{v_y} \tag{6.30}$$

In Chapter 1, the helix model was illustrated with fibers in what is termed an *open packing arrangement.* Another idealized packing arrangement of fibers is called *hexagonal close packing,* which is depicted in Figure 6.69 along with open packing. Hexagonal packing involves a single or a multiple fiber core around which layers of fibers may be packed to give a hexagonal outline. However, for a large number

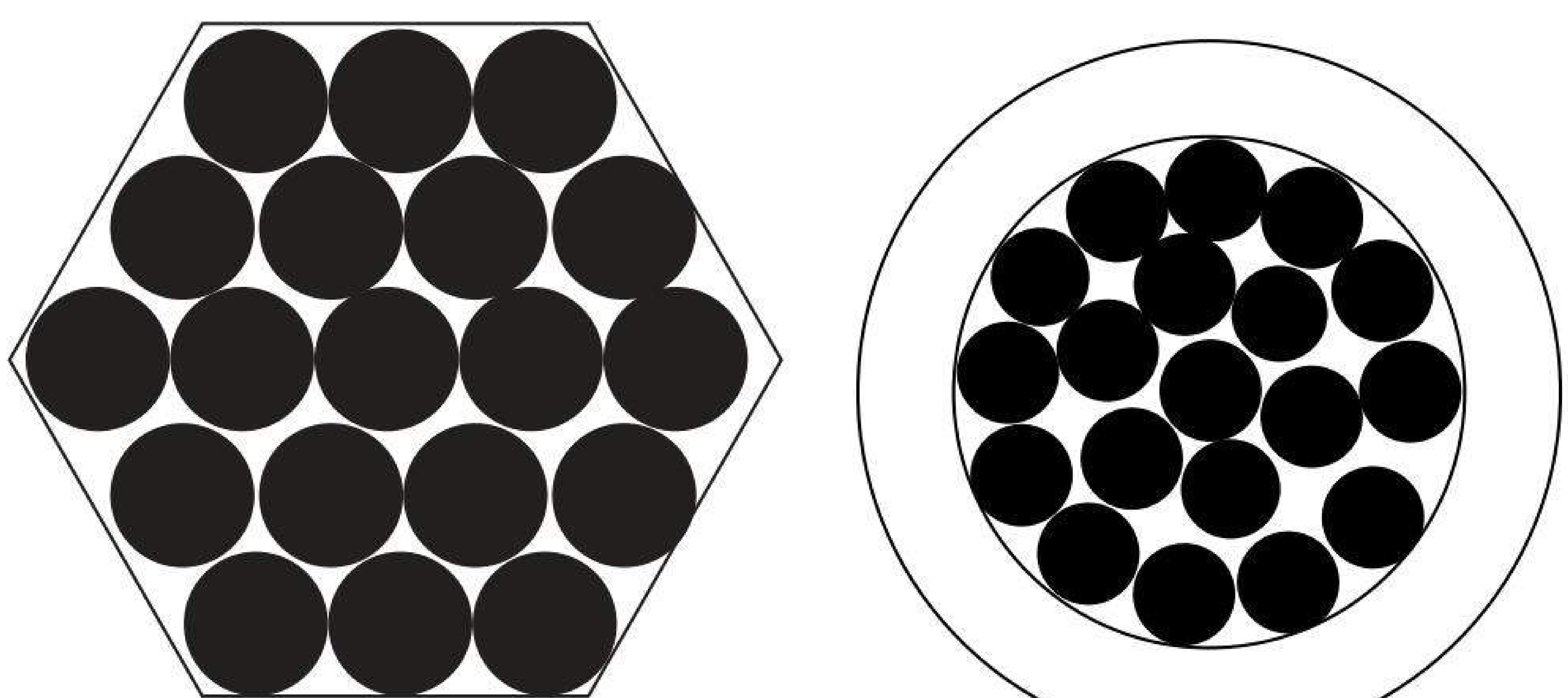


FIGURE 6.69 Hexagonal close packing and open packing.

of fibers typical of real yarns, hexagonal packing can approximate a circular shape.[75]

Real yarns deviate from the above idealized form[75] because of factors such as differing fiber cross sections, compaction caused by twist, the actual number of fibers in the yarn cross section not precisely filling an exact number of layers, and the effects of migration and wrapper fibers. The net effect is that the packing density of yarns is not uniform over the cross section.

Figure 6.70 shows the cross section for several differing yarn structures spun from polyester fibers/filaments to similar counts and twist, and the deviations with respect to completion of the outer layers is evident. The concentric circles with black dots indicate locations of fibers in the yarn cross sections. It is evident that packing density varies across the yarn cross sections. Figure 6.71 shows that packing density of the filament and ring-spun yarns are fairly similar except at the high-twist levels. However, in both cases, the decrease in Φ_d from the yarn center to the periphery is initially small until the outer zone, where there is a significant decrease. With the rotor-spun structure, Φ_d decreases almost linearly from the center to the outer region of the yarn. It is fairly clear from the microphotograph that the HS yarn has a uniformly low Φ_d over the cross section. It may be expected that, with rotor yarns

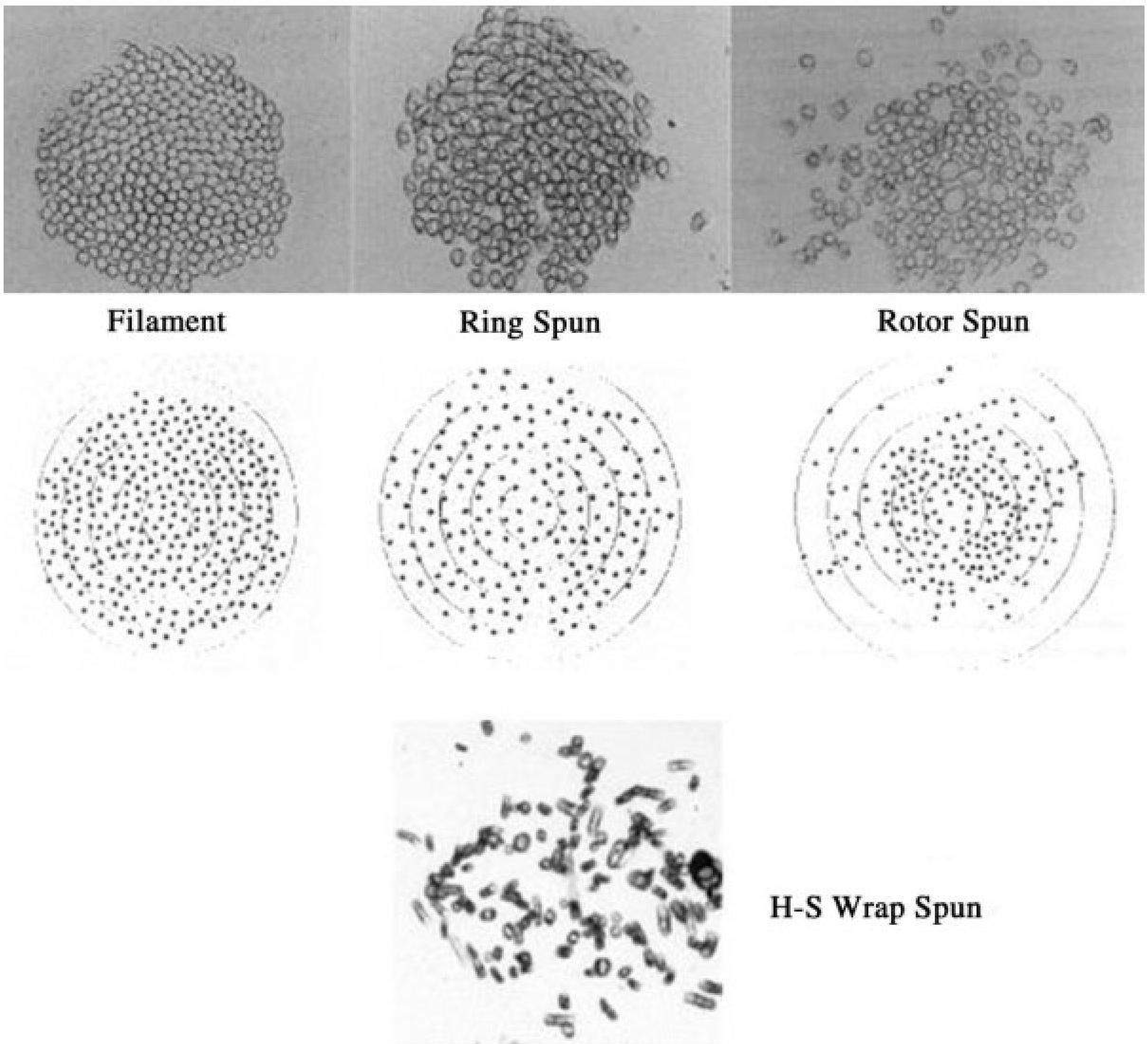


FIGURE 6.70 Cross section of differing yarn structures. (Courtesy of Goktepe, F., *The Effect of Yarn Structure of the Deformation of the Yarn Cross-Section,* Ph.D. thesis, University of Leeds, 1997.)

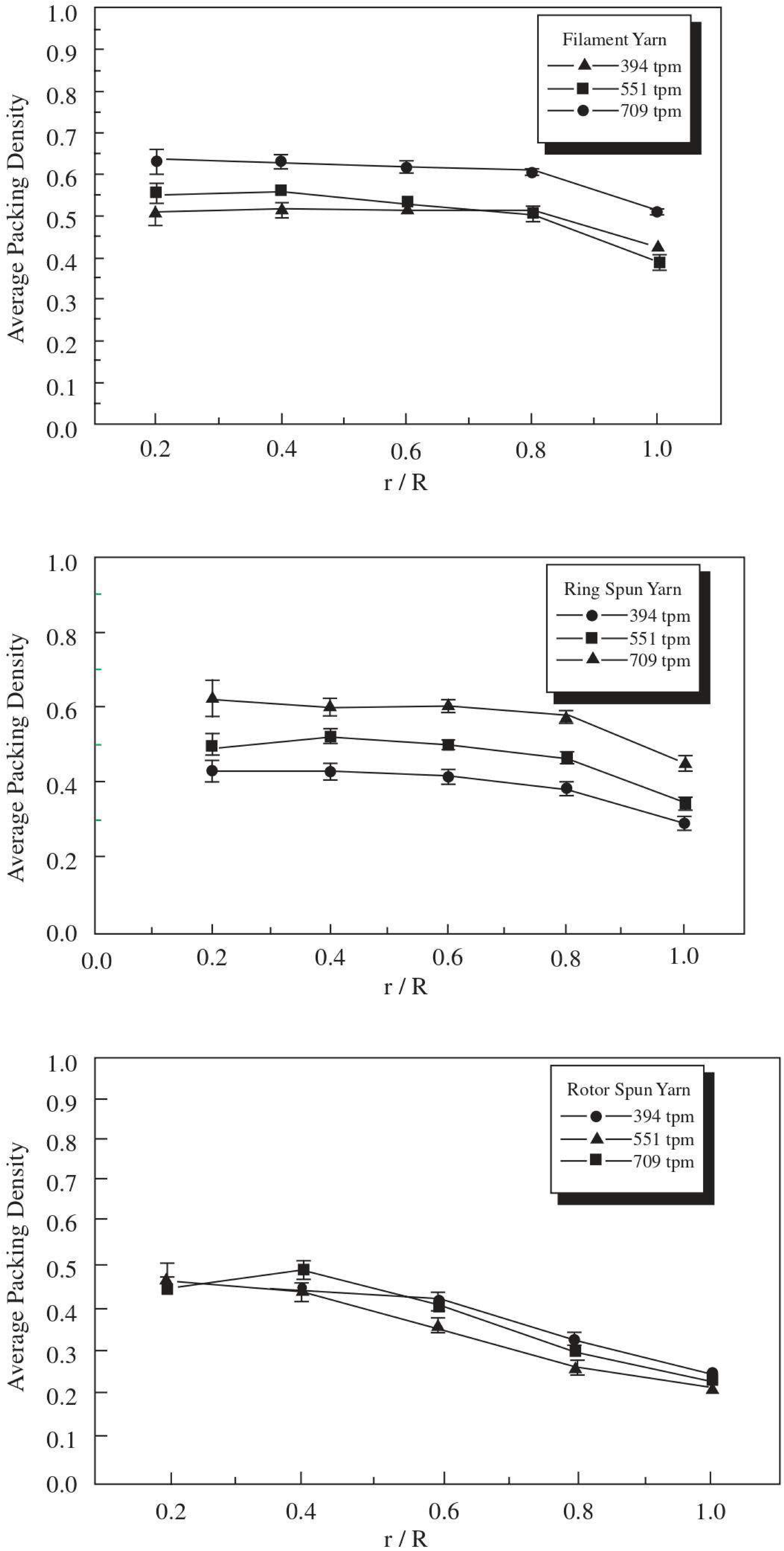


FIGURE 6.71 Packing density according to yarn types. (Courtesy of Goktepe, F., *The Effect of Yarn Structure of the Deformation of the Yarn Cross-Section,* Ph.D. thesis, University of Leeds, 1997.)

being of a lower density than ring-spun yarns, they would flatten more easily at crossover points in a woven fabric. However, because of the presence of wrapper fibers, this not the case, and the effect of the wrapper fibers is also apparent in the flexural characteristics of the yarn.

From observations of yarn cross sections,[109] the following relationship was found to suitably represent the fiber distribution in the cross section:

$$-f(r) = a_1 + a_2 + a_3 r^2 \tag{6.31}$$

In the equation, a_1, a_2, and a_3 are constants determined from observations of the yarn cross section.

A simplified form of the parabolic equation is

$$-f(u) = f_o(1 - u^2) \tag{6.32}$$

where u = normalized radius $u = r/R$
f_o = packing density at the yarn central zone, which is related to the packing density $f_o = 2\Phi$

It is claimed[74] that this model for fiber distribution in a yarn cross section can be fitted to any yarn by estimating the yarn radius and the yarn average packing density.

6.2.3.2 Flexural Rigidity

The minimum stiffness of a yarn should be the sum of the bending rigidities of the constituent fibers. However, for a closer approximation to real yarns, the effect of twist and yarn structures must be considered, i.e., the obliquity of the fibers and interfiber friction. If we assume that fibers in a yarn are sufficiently elastic to closely follow a linear relationship between the bending moment applied to them and their curvature of deformation, then, in the absence of the effects of twist and yarn structure, the yarn should also show a linear relationship given by $M = B/r$, where M is the bending moment, $1/r$ is the curvature, and B is the bending rigidity of yarn. Deviations from this linear relation should indicate the effect of twist and yarn structure.

Figure 6.72 shows a typical bending characteristic curve for yarns. For a yarn to bend, the constituent fibers must be free to move (i.e., to slip past each other). At the start of bending, interfiber friction at fiber contact points, as well as fiber stiffness, resists bending, and a rapid rise in M occurs for small changes in $1/r$. B is therefore greater than the theoretical minimum. Once the friction is overcome and the fibers are free to slip at their contact points, M becomes closer to the theoretical minimum, provided there are no further friction effects with increase $1/r$, and the fibers remain free to bend. Reversing the bending moment gives the hysteresis loop. A similarly shaped hysteresis curve is applicable to fabrics but with the added effect of yarn crimp. As indicated in Figure 6.72, the characteristic parameters of curve are M_O (the coercive couple or bending moment required to overcome the initial

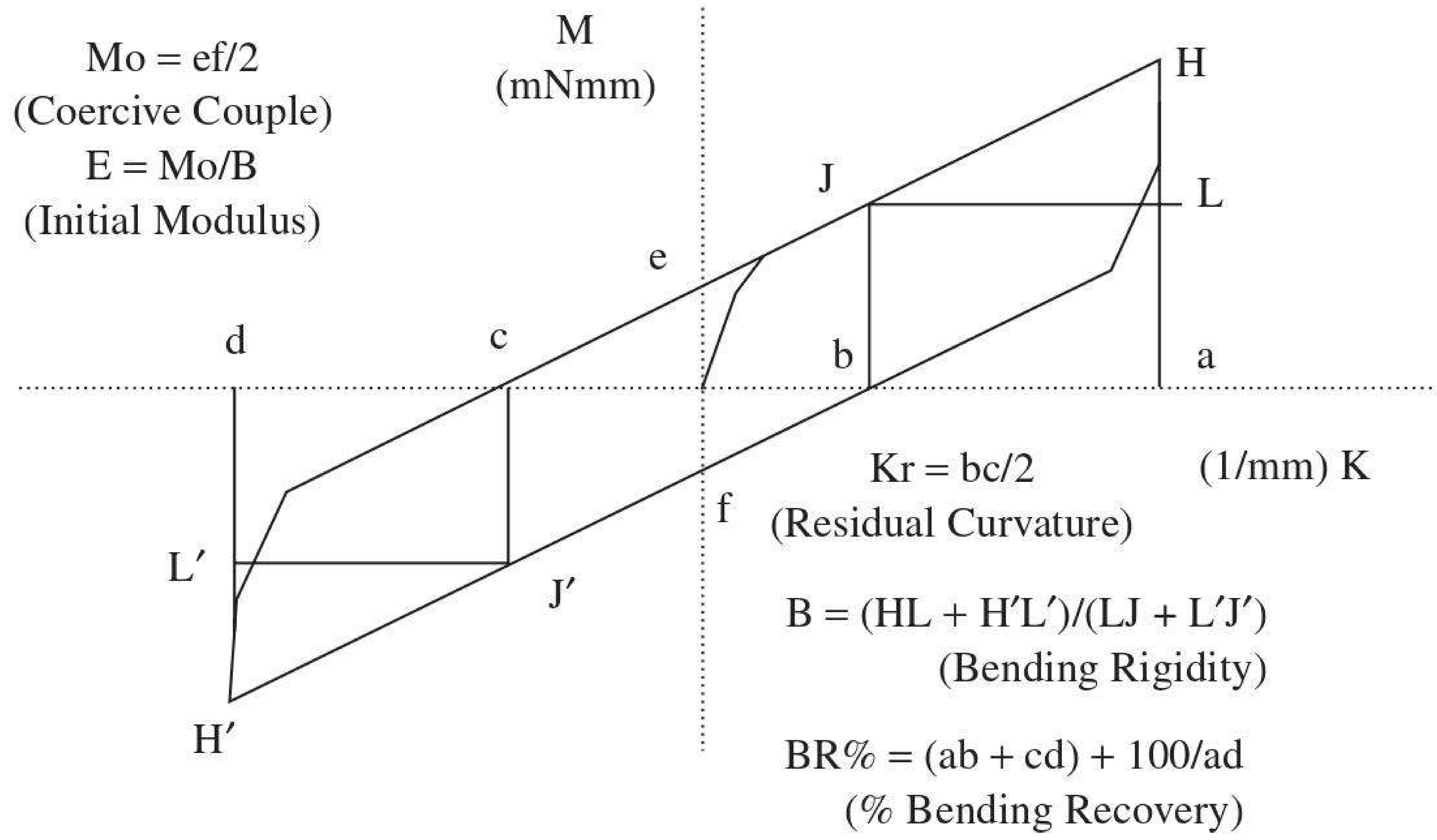


FIGURE 6.72 Yarn bending characteristic curve.

frictional resistance), the residual curvature, the percent bending recovery, the initial modulus E, and the bending rigidity B.

Using the comparison of a steel spring, the helix of twist should reduce the bending rigidity. However, fiber migration, fiber configuration, and other yarn structural features will have counterbalancing effects. Table 6.13 shows the effect of twist on a 28-tex, 48-filament polyester yarn, a 60-tex, 54s-quality worsted yarn, and a 59-tex rotor-spun cotton yarn. The yarns were steam set to prevent snarling. It is evident that twist had no effect on the bending rigidity of the filament or cotton yarn, but the rigidity of the worsted yarn decreases with twist.

Theoretically, B should decrease with twist, as seen with the worsted yarn. In the case of the filament yarn, any reduction due to the twist helix angle is counterbalanced by the increase caused by increased packing density of the filaments and radial compression. With staple yarns, the discontinuities at the fiber ends cause the torsional stresses in the fiber to be lower than in continuous filament yarns. Therefore, for the worsted yarn, this factor, along with the lower packing density resulting from the wool fiber crimp, obviates any significant counterbalance to the effect of the helix angle of twist. This is not the case with the rotor-spun cotton yarn. Here, the counterbalance effect may be attributed to the wrapper fibers, which increase with twist.

The effect of wrapper fibers in the rotor-yarn structure is applicable to air-jet yarns but not to HS yarns, where the packing density of the yarn is very low. Figure 6.73 shows B and M_O values for friction, rotor and air-jet polyester/cotton yarns of similar counts, and the resultant woven fabrics. The values are normalized with respect to ring-spun yarns, and it is evident that these structures are stiffer than the ring-spun structure. Since Table 6.13 indicates that the effect of the helix angle of twist in rotor yarns is negligible, it is likely that the difference in values between the air-jet and rotor is attributable to the frequency, length, and tightness of the wraps as well as the number of fibers wrapping a given point. The values for the friction-spun yarn are shown to be greater than rotor-spun yarn, and this may be the result of fiber compaction in the central region of the yarn caused by the characteristically highly twisted core.

TABLE 6.13
Effect of Twist and Yarn Structure on Yarn Flexural Rigidity

Twist factor ($tex^{1/2}/cm$)	Rigidity, B (mN/mm^2)	Coercive moment, M_o (mN/mm^2) $\times 10^{-2}$	Residual curvature ($mm^{-1} \times 10^{-2}$)	M_o/B ($mm^{-1} \times 10^{-2}$)
		Polyester filament (28-tex/48 fil) yarn		
10	7.2	6.2	1.1	0.9
20	7.1	10.4	1.9	1.5
30	6.8	29.8	4.5	4.4
40	7.3	46.7	6.5	6.4
50	7.2	51.8	7.1	7.2
60	8.5	76.6	8.7	9.0
		Worsted (60-tex, 54s-quality wool, conventional ring-spun) yarn		
16	11.4	16.5	1.5	1.5
28	10.8	20.0	1.8	1.9
40	10.4	21.5	1.8	2.1
51	9.6	12.1	1.3	1.3
62	8.4	8.8	1.3	1.0
		Rotor spun cotton (59-tex) yarn		
43.1	15.0	12.8	8.5	–
52.6	16.2	15.4	9.5	–
62.2	16.0	19.3	11.4	–

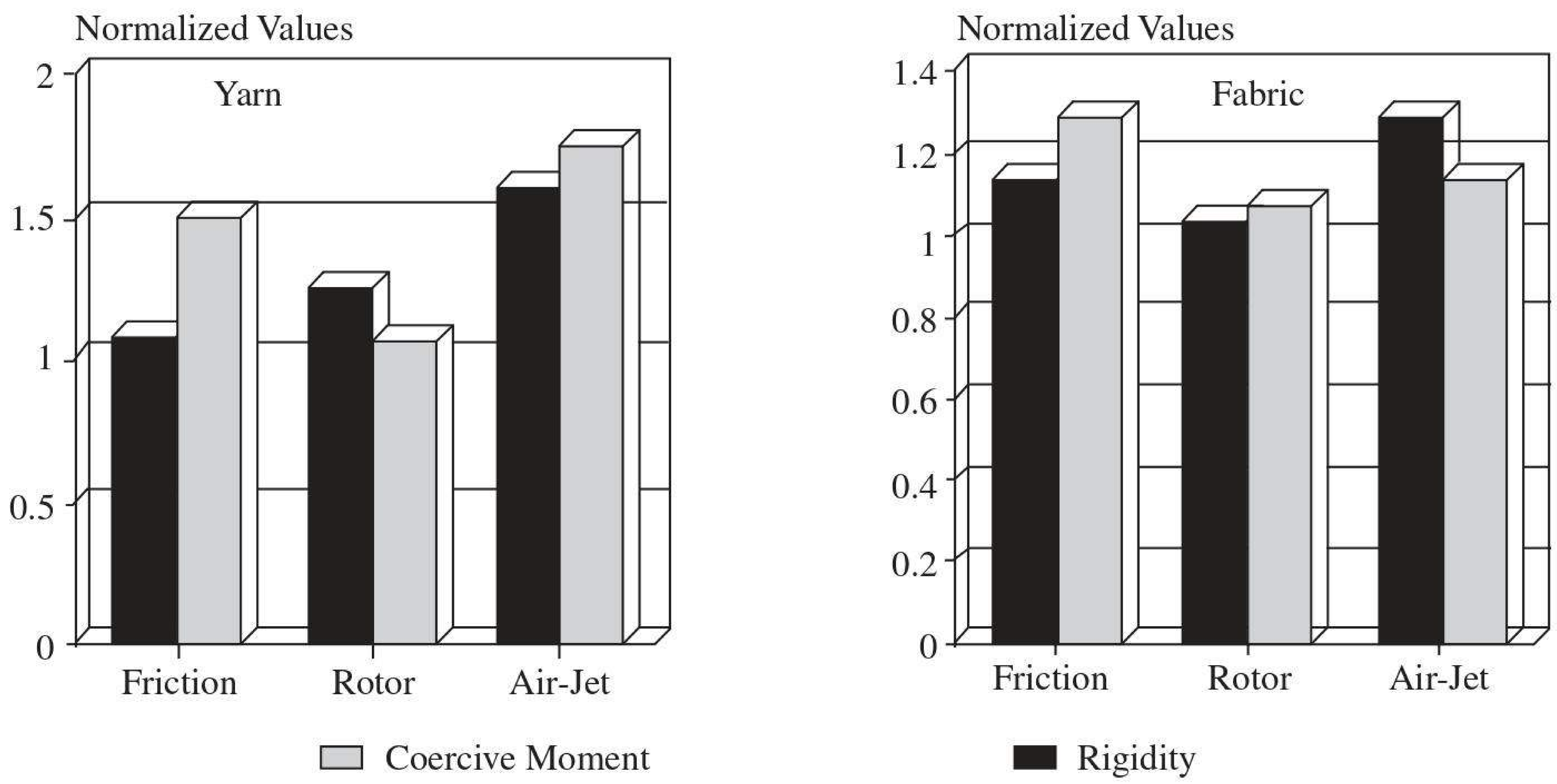


FIGURE 6.73 Effect of yarn structure on coercive moment and bending rigidity. (Courtesy of Looney, F. S., E. I. Du Pont de Nemours & Co., Wilmington, DE, private communication, 1989.)

Usually, with conventional ring-spun yarns, a finer fiber gives lower bending rigidity for a given count. However, Figure 6.74 shows that this is not necessarily the case for rotor and air-jet yarn; for both yarns, B and M_O increase with increased fineness. Figure 6.75 illustrates the results of various steps taken to modify the stiffness of the air-jet yarn, which included replacing a singles yarn with a two-ply yarn, applying a softening agent to the singles, and twisting the singles yarn in the opposite direction to the wrap helix. As may be expected, reverse twisting to loosen

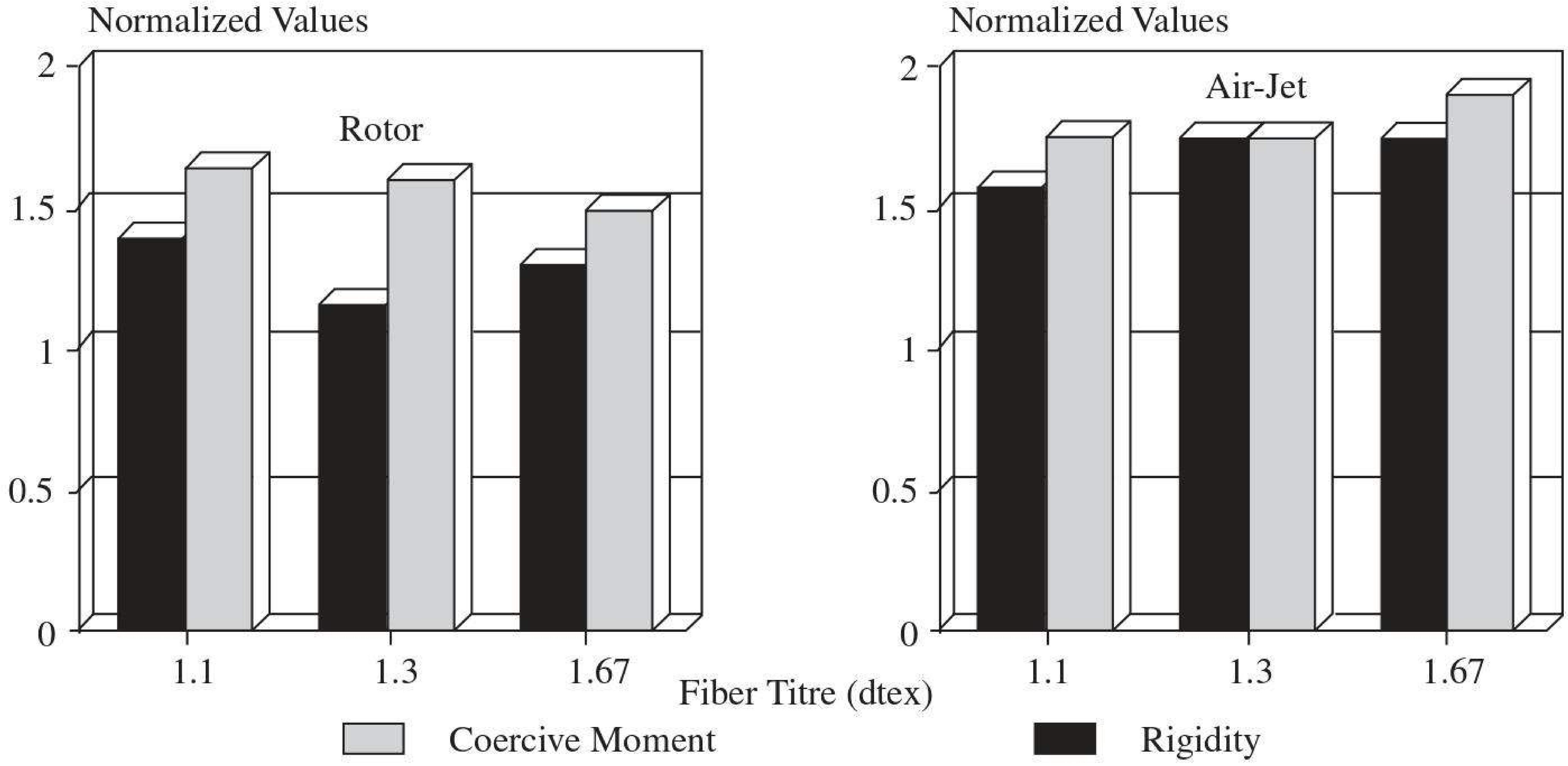


FIGURE 6.74 Effect of fiber fineness and yarn structure on bending characteristics. (Courtesy of Looney, F. S., E. I. Du Pont de Nemours & Co., Wilmington, DE, private communication, 1989.)

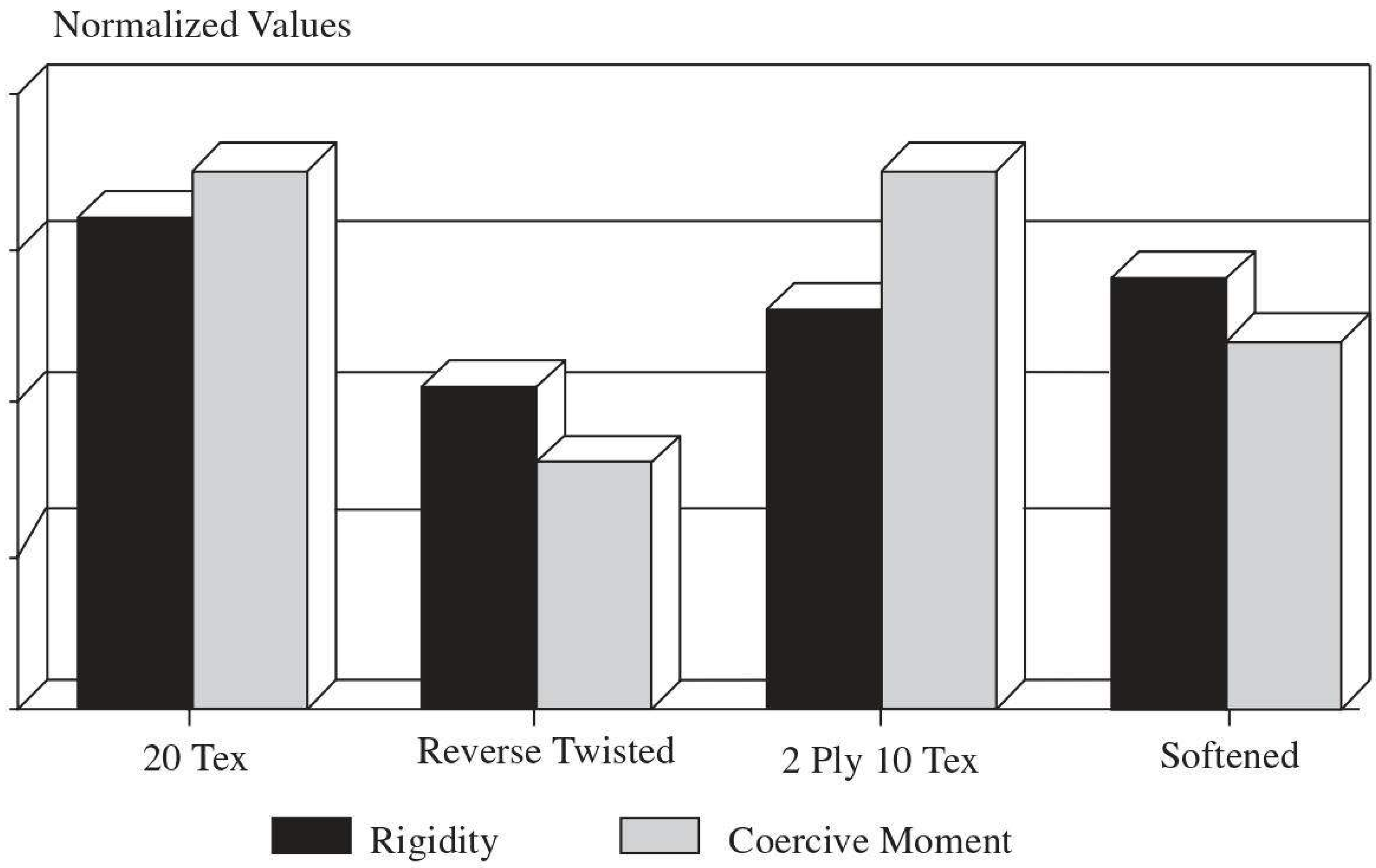


FIGURE 6.75 Effect of modifications to air-jet yarn. (Courtesy of Looney, F. S., E. I. Du Pont de Nemours & Co., Wilmington, DE, private communication, 1989.)

wraps confirms the effect of the wrapper fibers on the bending characteristics of the yarn.

6.2.3.3 Tensile Properties

The strength and extension of spun yarns are two very frequently measured properties, since they govern the processability of a yarn.[108] Much of the understanding of the tensile characteristics and failure mechanism of yarns has resulted from attempts to develop theoretical models simulating yarn behavior. An extensive amount of work has been published on yarn mechanics,[75,110–114] which primarily consists of theoretical models of yarn structure and application of these models to predict yarn tensile properties based on the properties of the constituent fibers, generally one type of fiber. Because of the complexity of staple yarn structures, no theoretical model for predicting the staple yarn properties has yet reached the position where it is widely accepted to be of practical use. Empirical models[115,116] have also been reported but have the limitation of being applicable to specific yarn types, usually over a narrow range of conditions. The theoretical and empirical studies have nevertheless given useful insight into the relationship between yarn structure and properties and the effect of processing conditions.

With respect to yarn tensile properties, the failure mechanism of staple yarns containing twist is generally explained in relation to their nonlinear tensile behavior, typified by Figure 6.76. When load is applied to a yarn, tension is induced in each fiber through shear forces between the fibers. The amount of tension induced in a given fiber will depend on the load distribution over the yarn cross section in relation to the fiber position in the yarn, the yarn twist level, and, importantly, the spun-in length of fiber. Figure 6.77 illustrates that relative shear stress is greatest at the fiber ends and that tension builds up from the fiber ends. It can be seen that low twist levels, because of low fiber packing, do not facilitate a good transfer of the load applied to a yarn. It should also be evident that low K_F values and short fiber length do not enable effective utilization of fiber strength.

As a proportion of load pulls on a fiber end, the fiber helix extends until it tightens onto the other fibers around which it is twisted, compressing these fibers together. As the load increases, the fiber itself starts to extend, simultaneously increasing the compression. The relative changes in yarn cross section and length, i.e., the Poison's ratio for the yarn, σ_y, is given by

$$\sigma_y = \frac{dR/R}{dL/L}$$

where R and L = the yarn radius and length
dR and dL = changes in the parameters with tensile load

Considering the simple helix model and the geometry for one turn of twist, it is evident that the actual extension of a filament will be greater as the filament is closer to the yarn axis; a filament on the yarn axis will begin extending with the onset of loading, i.e.,

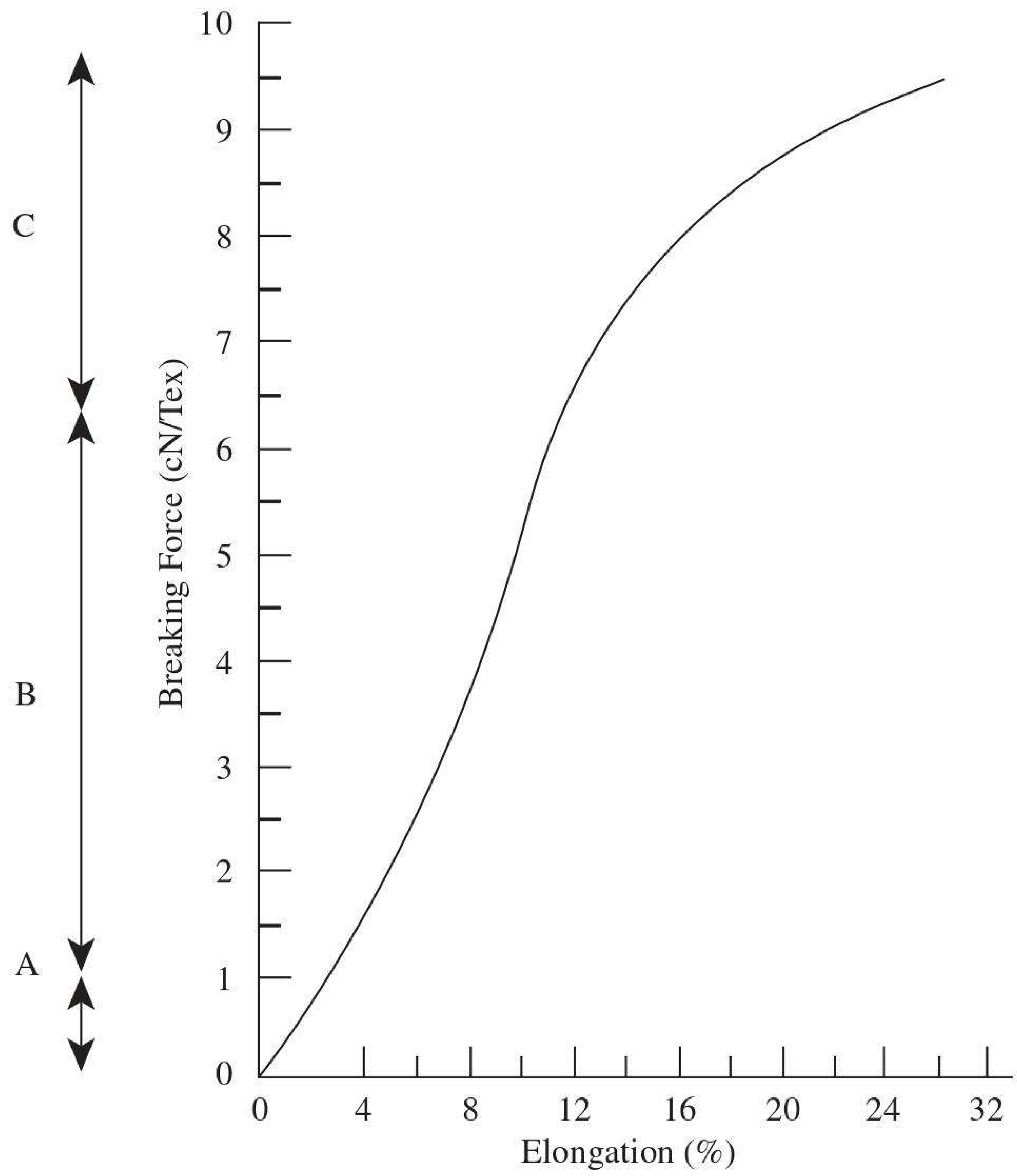


FIGURE 6.76 Example of tenacity-extension characteristics of a twisted yarn.

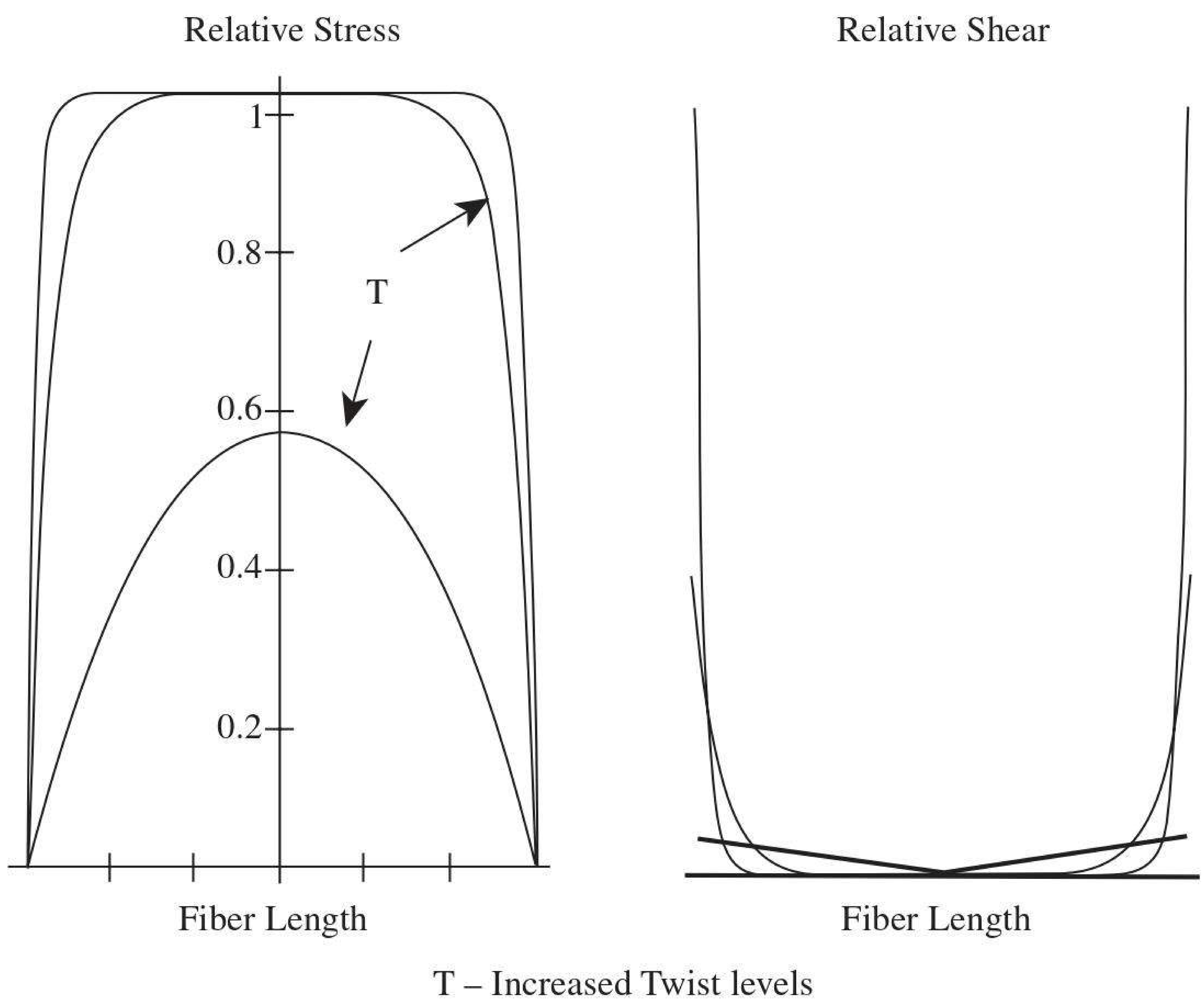


FIGURE 6.77 Stress induced in fiber with applied load to yarn.

$$\varepsilon_f = \varepsilon_y[\cos^2\theta - \sigma_y \sin^2\theta] \quad (6.33)$$

$$\varepsilon_f = dL_f/L_f = \text{filament extension/fiber filament length}$$

$$\varepsilon_y = dL_f/L_f = \text{yarn extension/yarn length}$$

where ε_f = filament strain
ε_y = yarn strain
θ = the helix angle of the filament at a given radial distance from the axis (see Figure 1.4, Chapter 1)

For the case of staple yarns, Hearle[40] has modify the above equation to give

$$(1 + \varepsilon)^2 = (1 + \varepsilon_y)^2 \cos^2 \alpha + (1 - \sigma_y \varepsilon_y^2) \sin^2 \alpha \quad (6.34)$$

where ε_f, ε_y, σ_y, α are the parameters relating to staple yarns.

All fibers in the spun yarn will be performing the above task and, by doing so, resist slipping past each other. The tensions induced in the fibers have radial and axial components. The twist inserted into the yarn causes residual stress in the fibers. This also has radial and axial components, and therefore the induced tension adds to it. The relative size of the tension components will depend on the changed helix angle corresponding to the applied load. The inward pressure from the radial component increases with fiber extension as the load increases; consequently, the interfiber friction increases.

The initial part of the curve in Figure 6.76 (region A) denotes a linear behavior where the increasing inter fiber friction prevents fiber slippage when small stress is initially applied. With increased stress, fibers begin to slip (region B) as the helix begins to extend and then locks, and the structure tightens to take further loading. From here on (region C), the load increases with a combination of fiber slippage and fiber breakage that eventually result in the yarn break. To increase the proportion of fiber breakage to slippage and thereby the yarn strength, the twist may be increased so that the induced tension on fibers has a larger radial component.

With a higher level of inserted twist, the helix angle is greater, and the effect of resisting fiber slippage under yarn loading should increase. With the helix model, however, it can be shown that, at low yarn strains, the obliquity of the helix reduces the contribution of filament modulus, E_f, to yarn modulus, E_y, i.e.,

$$E_y = E_f \cos^2 \alpha \quad (6.35)$$

Thus, as the tenacity is given by $S_y = E_y \varepsilon_y$, the yarn strength should decrease with increased twist. Therefore, in staple yarns, there are two opposing effects of twist: the resistance to fiber slippage and the reduced contribution of fiber modulus. Hearle[75] has modified Equation 6.35 for the case of staple yarns to take into account the effect of migration and discontinuities.

$$E_y = E_f \cos^2\alpha[(1-k)\operatorname{cosec}\alpha] \tag{6.36}$$

$$k = \frac{2[(r_f Q)/\mu]^{1/2}}{3L_f} \tag{6.37}$$

where L_f = fiber length
r_f = fiber radius
μ = coefficient of interfiber friction
Q = length of fiber in one migration cycle

6.2.3.3.1 Effect of Twist

Based on the modified equation, Figure 6.78 shows the modulus for staple yarns should increase with twist to a maximum value and then decrease with further increases in twist, whereas, for filament yarn, the modulus decreases with twist. A plot of staple yarn strength against twist or twist multiple gives a similar characteristic curve. Figure 6.79 shows examples for various staple yarn structures. In the case of the Dref-2 and air-jet yarns, the twist and wrap measurements were difficult to obtain; the yarn strength values are therefore plotted against friction drum speed and air-jet pressure, since these parameters are directly related to the degree of twist and level of wraps.

With regard to the ring-, rotor-, and Dref-2 yarns, their strengths initially increase with twist up to a maximum, the corresponding twist or twist-multiple being the optimal twist (t_{op}) or twist multiple (TM_{op}). This part of the curve is attributed to the interfiber frictional resistance to fiber slippage and is called the *coherence region*. Yarn breaks are usually the result of a combination of a proportion of the constituent

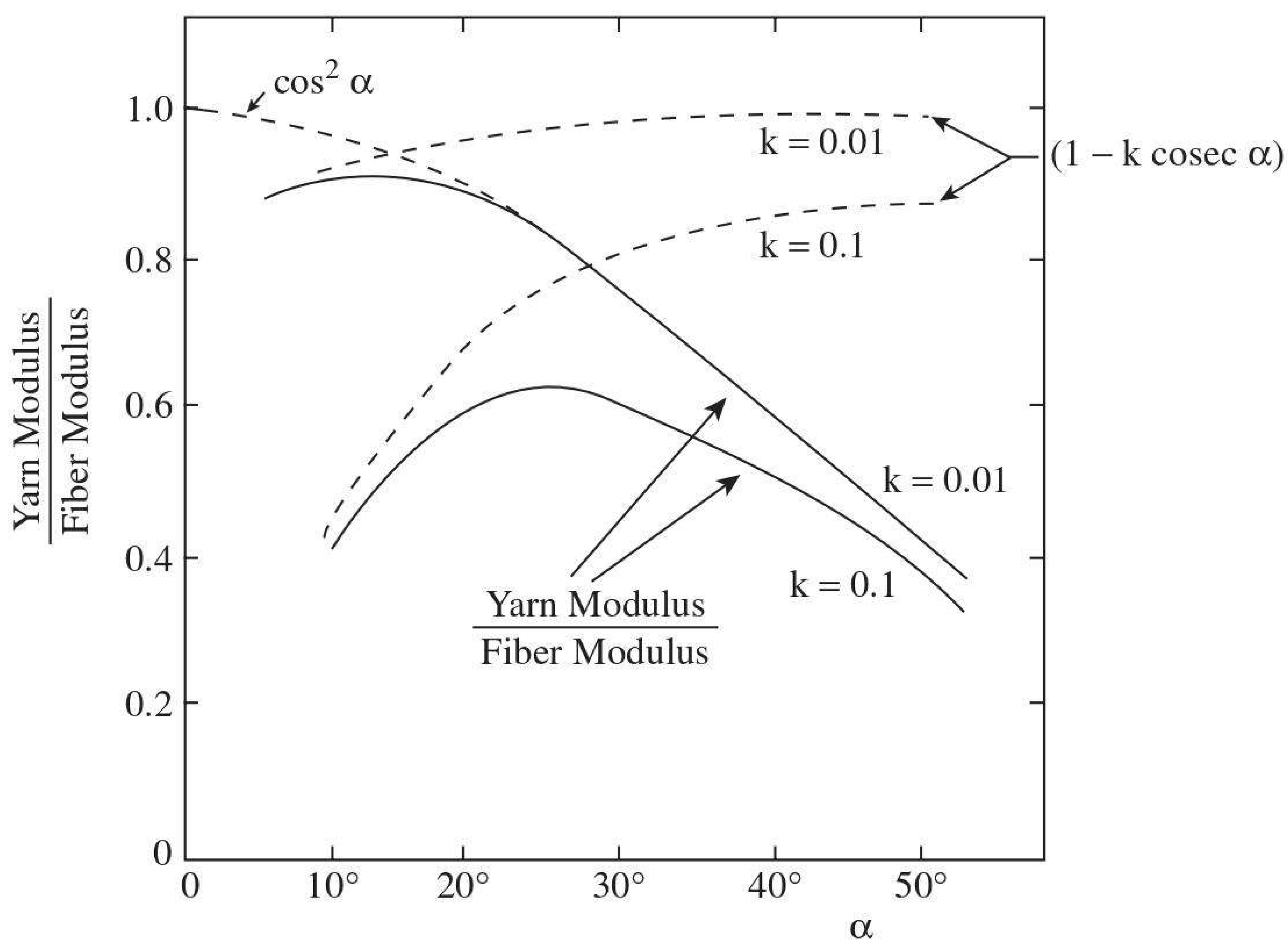


FIGURE 6.78 Effect of twist helix angle on yarn modulus.[75]

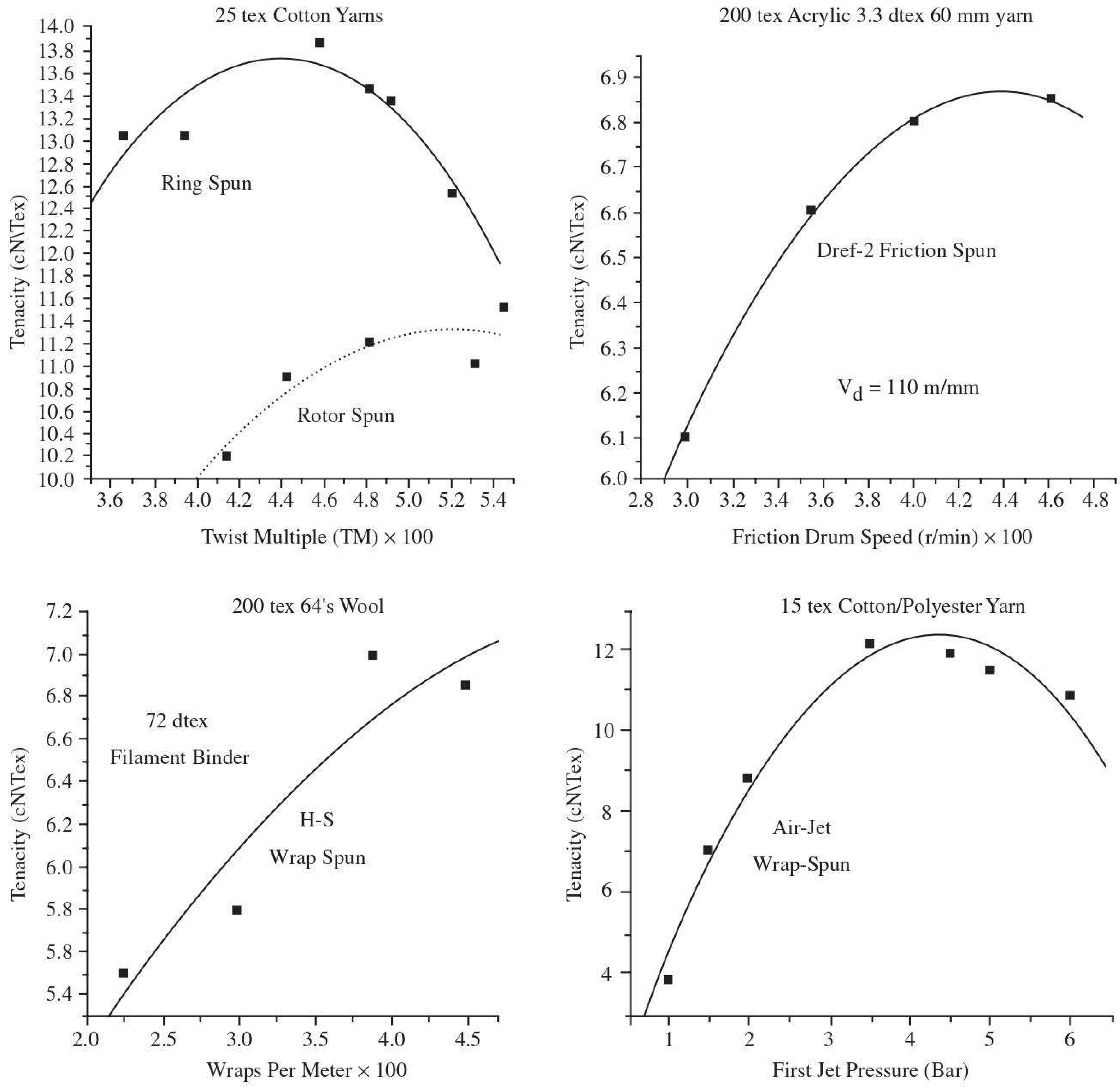


FIGURE 6.79 Effect of increasing twist on yarn strength.

fibers breaking and the rest slipping; the greater the amount breaking, the stronger the yarn. At low twist, yarn failure will be mainly the result of fiber slippage. With increasing twist, yarn diameter decreases, while fiber packing and frictional contact increase, thereby enabling an increasing number of fibers to be extended to break. It is reported that about 60% of fibers break at the peak yarn strength.[117] Beyond the optimal twist, the strength decreases with twist resulting from a reducing contribution of the fiber modulus to the yarn modulus as the fiber helix angle becomes more oblique. Physically, this means that more of the yarn extension is being used to extend the helical shape of the fiber rather than the fiber itself. Therefore, the contribution of fiber modulus to yarn modulus decreases.[110] This latter part of the curve is termed the *obliquity region.* It is likely that from TM_{op} onward, increasing the twist increases the residual strain in some fibers, particularly those in the outer zone of the yarn, to the point at which their breaking strain is now reached at lower applied loads.[117] Thus, added factors to the obliquity effect may be (1) reduced radial pressures, i.e., lower than that at optimal twist, and (2) an associated increase in slippage as more and more fiber lengths reach their breaking strain at lower applied loads as result of further increases in twist. TM_{op} may therefore be seen as the twist multiple at which fibers begin to break because of twist.

Rotor and Dref yarns are, respectively, 21 and 25% weaker than conventional ring-spun yarns of similar counts. The much lower strengths of these yarns are largely the result of their much lower K_F values; both open-end yarns have lower packing densities than ring-spun yarns, and this is therefore a further reason for their lower strengths. Compact ring-spun yarns can be up to 10% stronger than conventional ring-spun yarns.

The above effects of increased fiber helix angle are applicable to wrap-spun yarns. For air-jet yarns, the initial increases in strength with jet pressure suggest increased wrap angles and levels of wrap, and associated increases in cohesion between the parallel fibers of the yarn core. From the peak strength onward, a combination of the breaking of wrapping fibers at lower applied loads, along with fiber slippage and breaking within the core, causes the decreases in yarn strength with further increases in jet pressure. Hollow-spindle yarns are normally spun at the low wrap levels shown in the graph, which are much below the equivalent TM_{op}. However, it can be seen that the coherence trend is present with increased wraps.

For ring-spun yarns, the elongation at break increases continually with twist, initially at a rapid rate, until TM_{op} is reached, after which the increase is at a much-reduced rate (see Figure 6.80). As the figure shows, this is also the general trend for the other yarn structures.[88,118,119] Like the coherence-obliquity curves, the initial

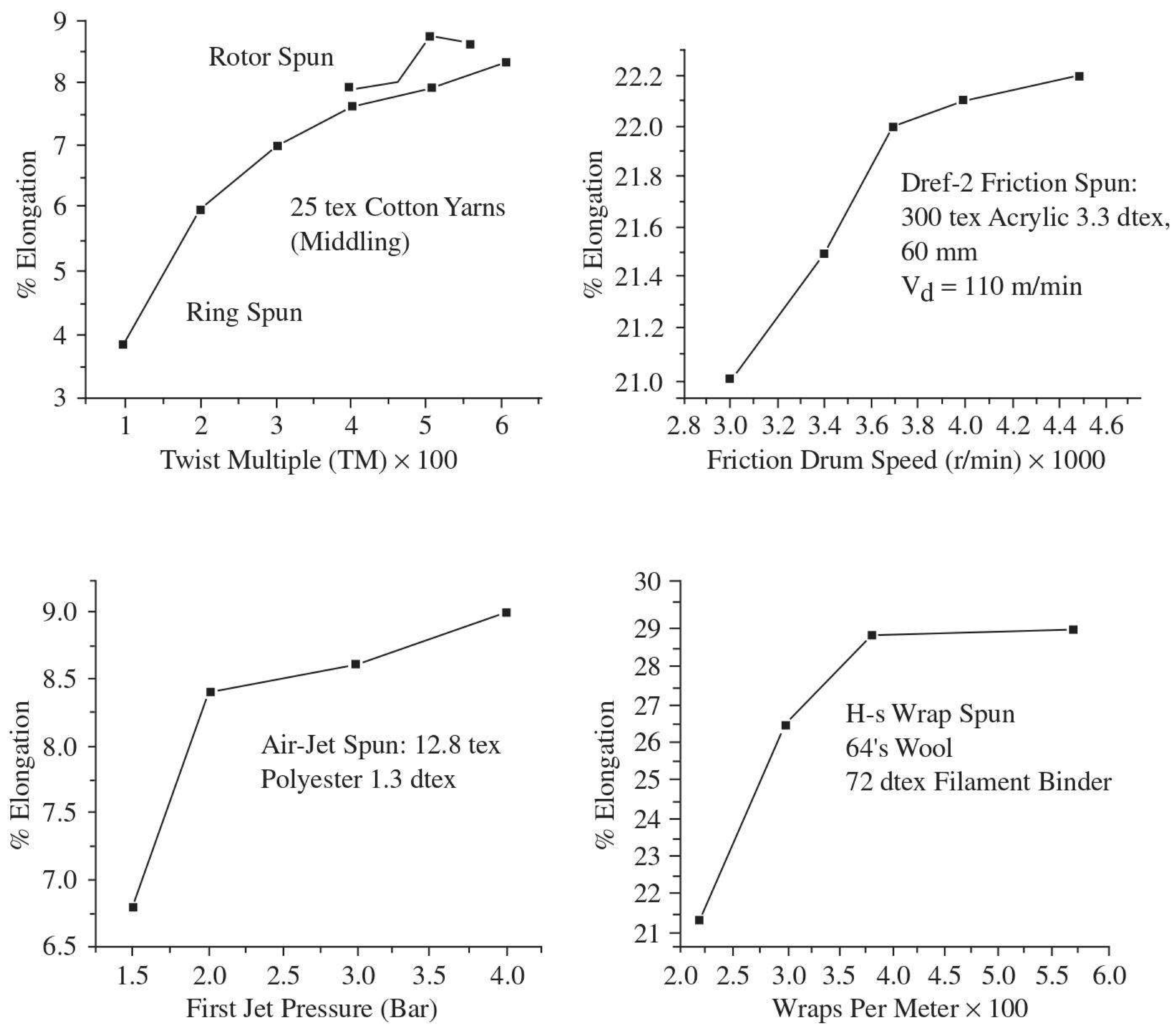


FIGURE 6.80 Effect of twist on yarn elongation at break.

rise in extension is the result of increased interfiber friction; as slippage between fibers decreases, and more and more fibers undergo extension. As fiber breakage, attributed to the effects of increased twist, begin at TM_{op}, the corresponding reduction in radial pressures lead to increased fiber slippage and, consequently, the rate of increase in yarn extension becomes much lower.

The coherence-obliquity curves for yarn strength and elongation follow the same trend for all yarn counts. However, whereas the strength of twisted yarns increases with count, the converse occurs for wrap yarns. In twisted yarns, each fiber helix contributes to the radial pressures that give frictional resistance to fiber slippage; so, at a set twist level, the greater the number of fibers in the yarn cross section, the stronger the yarn. With wrap-spun yarns, only the surface fibers or the wrapping filament impart the radial pressures to give coherence to the core of parallel fibers. Therefore, for the same material and wrap level, as the count increases, the relative proportion of binder and core is insufficient to increase or maintain the yarn strength.

The TM_{op} for a given fiber and yarn structure is not always used in practice. TM values used for spinning twisted yarns in particular largely depend on the end use and fiber type. Table 6.14 gives examples of typical twist multiples used in the spinning of short- and long-staple yarns.[3] Because of the difference in required aesthetics and wear, yarns for knitting (knitting yarns) are of lower twist levels, and, generally, wool and wool blends have lower twist that cotton and cotton blends. The latter, being the much shorter fiber, requires greater twist to effect stress transfer through relative shear (see Figure 6.77).

TABLE 6.14
Typical Twist Multipliers

Cotton and blends			
Short cottons	**Long cottons**	**Wool and blends**	**End use**
3600–4800	3170–3650	2050–2400	Weaving (warp)
2170–3650	2400–2860	1750–2050	Weaving (weft)
	2050–2550	1420–1750	Knitting

TM values based on the yarn tex count system.

Yarn irregularity essentially consists of the variations of the number of fibers in the yarn cross section, and such variations will have a greater reducing effect on the mean yarn strength of fine-count yarns. This is particularly true with twisted yarns, because the inserted twist concentrates in the thinner areas of the yarn. Although irregularity is a contributing factor to the yarn count-strength relationship, the influence of radial pressure is fundamental.

Commonly, spinning systems employing opening rollers for drafting the material feed produce yarns of lower irregularity than those using roller drafting. This difference is reflected in a comparison of the yarn-strength distributions, as is illustrated in Figure 6.81 for ring- and rotor-spun yarns. Even though the mean strength of the rotor yarn is generally lower, it has the better strength variation. The narrower distribution means fewer weak places in the rotor yarn, and this can be an advantage

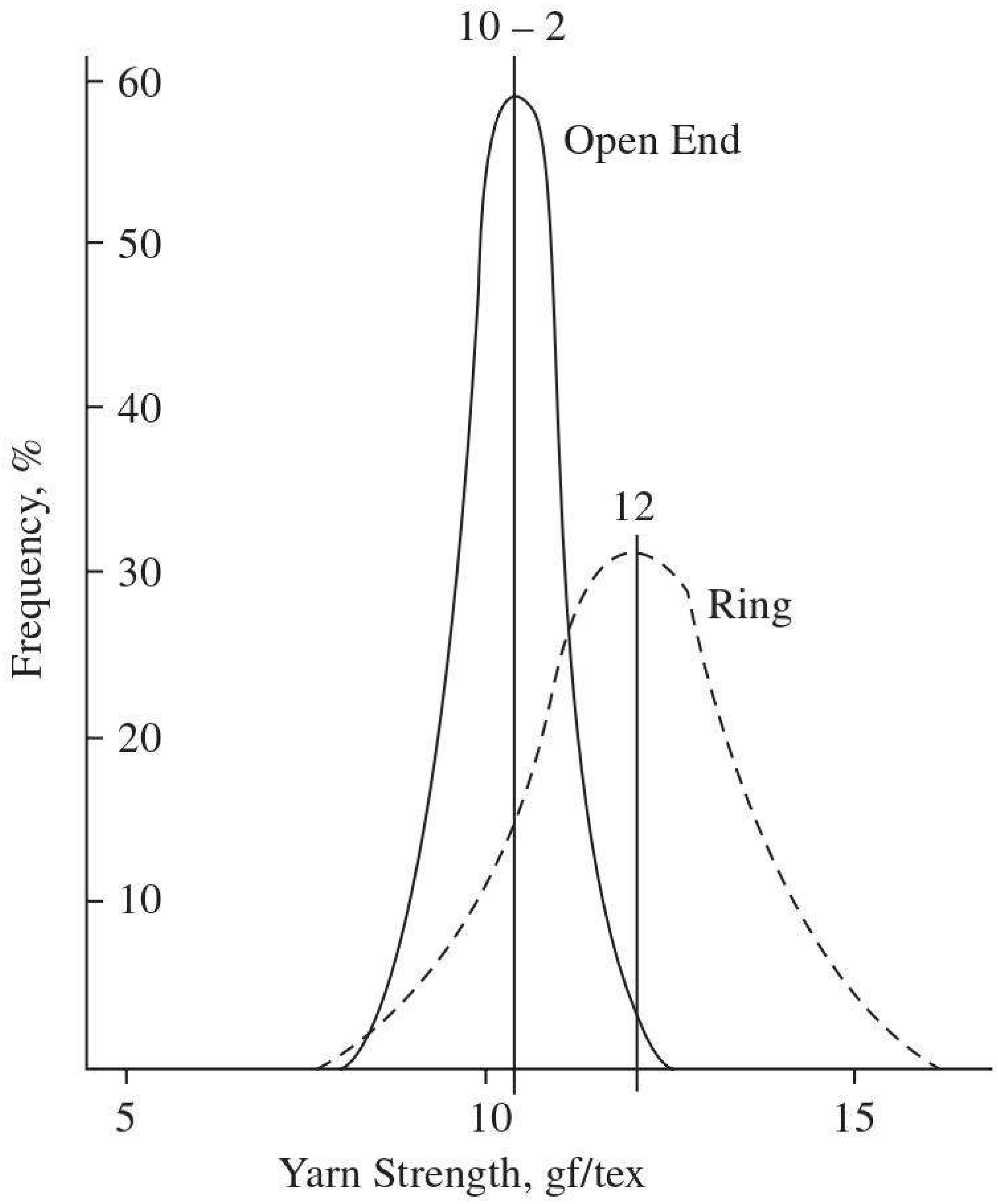


FIGURE 6.81 Yarn strength distribution.

in post-spinning processes where fluctuation in the tension of a running yarn during the process may cause tension peaks to break the yarn. With the appropriate setting of mean tension, there should be fewer peak-tension breaks for rotor yarns than for ring yarns. As explained latter, the rotor yarn irregularity can become greater than ring yarns at the very high production rates possible in rotor spinning. However, for a given count, rotor yarns are the most consistent in strength (CV% 5.1 to 10.8), followed by Dref (CV% 4.36 to 17.5), and then ring (CV% 7.22 to 20.95). This is because rotor-spun and DREF yarns, being made from sliver and with opening roller drafting, are not as affected by roller drafting waves as are ring yarns. For Dref-3 yarns, the CV% increases with count, possibly because of an uneven distribution in the wrapping of fibers around the core. But a staple-fiber core will give a lower CV% than filament core, suggesting that there is good cohesion between the staple-fiber core and the wrapper fiber sheath.[120]

6.2.3.3.2 Effect of Fiber Properties and Material Preparation

From the above discussion, we can reason that, in addition to the obvious properties of strength and elongation, the fiber parameters important to yarn strength are fineness, length, and length distribution. Generally, the finer and the longer the fiber, the stronger the yarn.

Although fiber strength is an obvious principal property, the utilization of the fiber strength is the key factor. In this regard, we can infer from Figure 6.77 that the ratio of the surface area to volume of a fiber has importance in that, with adequate surface frictional properties, long and fine fibers will enable, through relative shear, more efficient transfer between fibers of any load applied to the yarn. Thus, for a given fiber type, the finer and longer the fibers, the stronger the yarn should be.

The efficiency of load transfer is a function of the cohesion of the fibers facilitated by the yarn structure. In essence, this is represented by k in Equations 6.36 and 6.37. However, in more qualitative terms, we may write[124]

$$\text{Cohesion} \rightarrow \mu \times N_Y \times L_f \times P \tag{6.38}$$

where $\rightarrow$ = proportional to the parameters listed
μ = fiber/fiber coefficient of friction
N_Y = number fibers in yarn cross section
P = a yarn structure factor, which enables the occurrence of radial pressures for interfiber friction to come into effect

Thus, for the case of the twisted yarn structures,

$$P \rightarrow \sin\alpha \times E_f \times \varepsilon_f \tag{6.39}$$

and for wrap-yarns

$$P \rightarrow N_F \times \sin\alpha \times E_f \times \varepsilon_f \tag{6.40}$$

where N_F = number of fasciating fibers or filaments
α = mean twist or wrap angle
E_f = fiber modulus
ε_f = fiber strain

It can be seen from the above expressions of proportionality that, the finer the fiber, with regard to N_Y and N_F, the better the cohesion and, hence, the yarn strength. This is illustrated in Figure 6.82. These figures are not strictly representative of commercial values, since a 20-tex yarn count is not within the favorable count range for air-jet yarns (see Figure 6.1); the figures are presented only to illustrate the point being made.

With filament wrap-spun yarns, the load-elongation characteristics of the filament play a significant part in the P factor with respect to the effect changes in E_f, with increasing extension, have on yarn strength. Figure 6.83 illustrates this by showing the load-elongation characteristics of two polyester filaments of different modulus and that of the resultant yarns. The figure also shows the difference in the strength and elongation of the two yarns with increasing wraps per meter. It is clear that the filament with the lower extension but higher breaking load gave the stronger, more extensible yarns. Monofilament and multifilament yarns of similar load-elongation characteristics gave wrap-spun yarns of equivalent tensile properties.

With respect to length, the importance of having the extent of a fiber approximately equal to its full length when twisted into the yarn (see Figures 6.51 and 6.56) has led to the direct association of fiber length utilization, L_U, with fiber strength utilization, n_L where

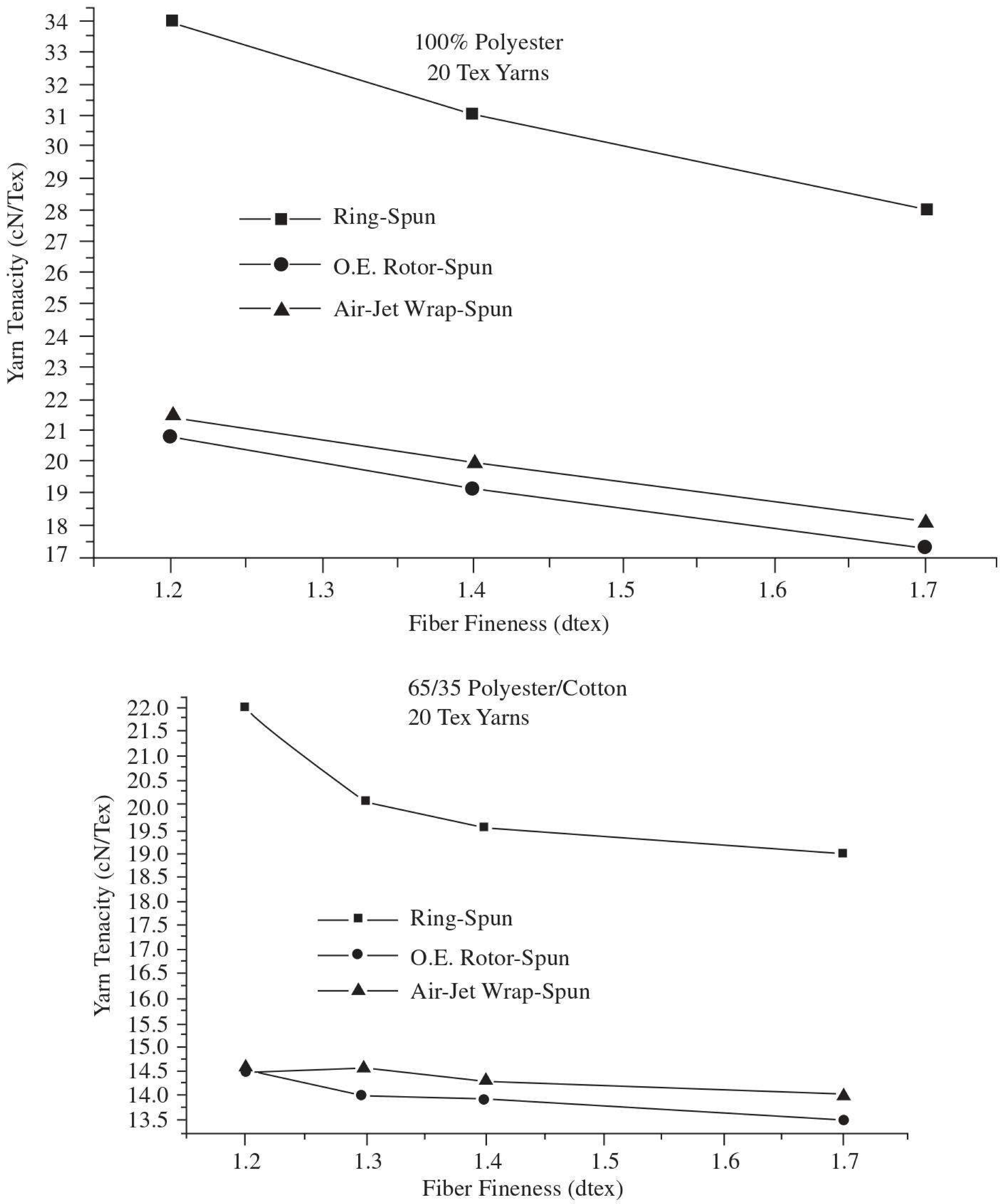


FIGURE 6.82 The effect of fiber fineness on yarn tenacity.

$$n_L = \frac{\text{Actual yarn tenacity}}{n \times \text{single-fiber tenacity}}$$

where n = the number of fibers in the yarn cross section

and

$$L_U = \frac{\text{Mean fiber extent}}{\text{Mean fiber length}}$$

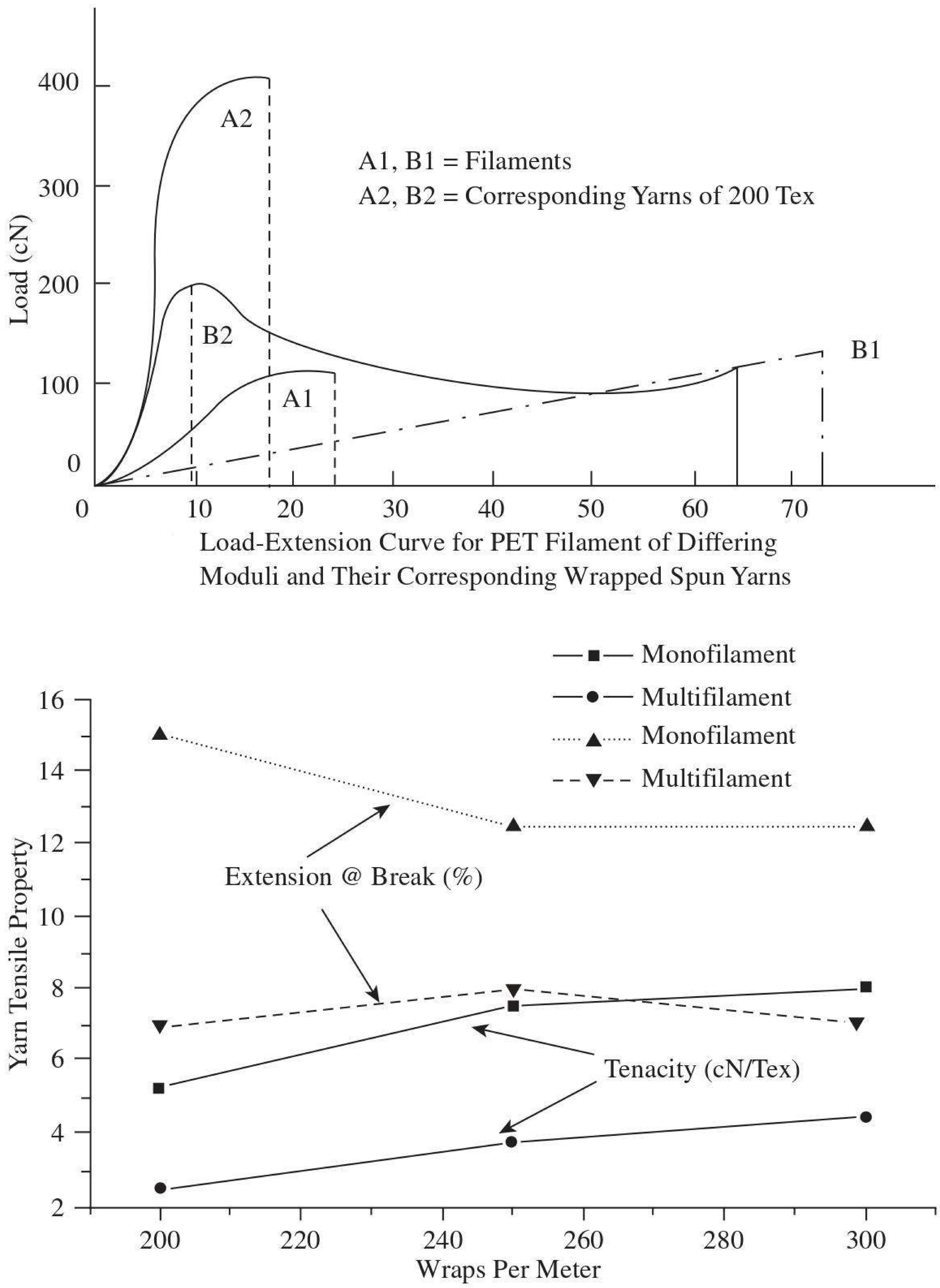


FIGURE 6.83 The effect of filament characteristics on the tensile properties of hollow-spindle wrap-spun yarn.

If lengths equal to 50 to 60% of the staple length were cut from different yarn types (e.g., ring and rotor yarns) and the fibers in the cut lengths of each yarn type straightened and aligned to give comb-sorter diagrams, then the diagrams obtained would be similar to Figure 6.84.[125]

If all the fibers lengths were fully utilized (i.e., fiber extent approximately equal to fiber length), the ideal length distribution would be obtained. The shaded section would be short lengths due to overlapping of the fiber lengths in the yarn. In practice, the ideal distribution is never achieved, but we have seen that material preparation has a major effect on the fiber extent in yarns, particularly ring-spun yarns; combing gives the most straightened fibers in the feed sliver and this is reflected in the yarn.

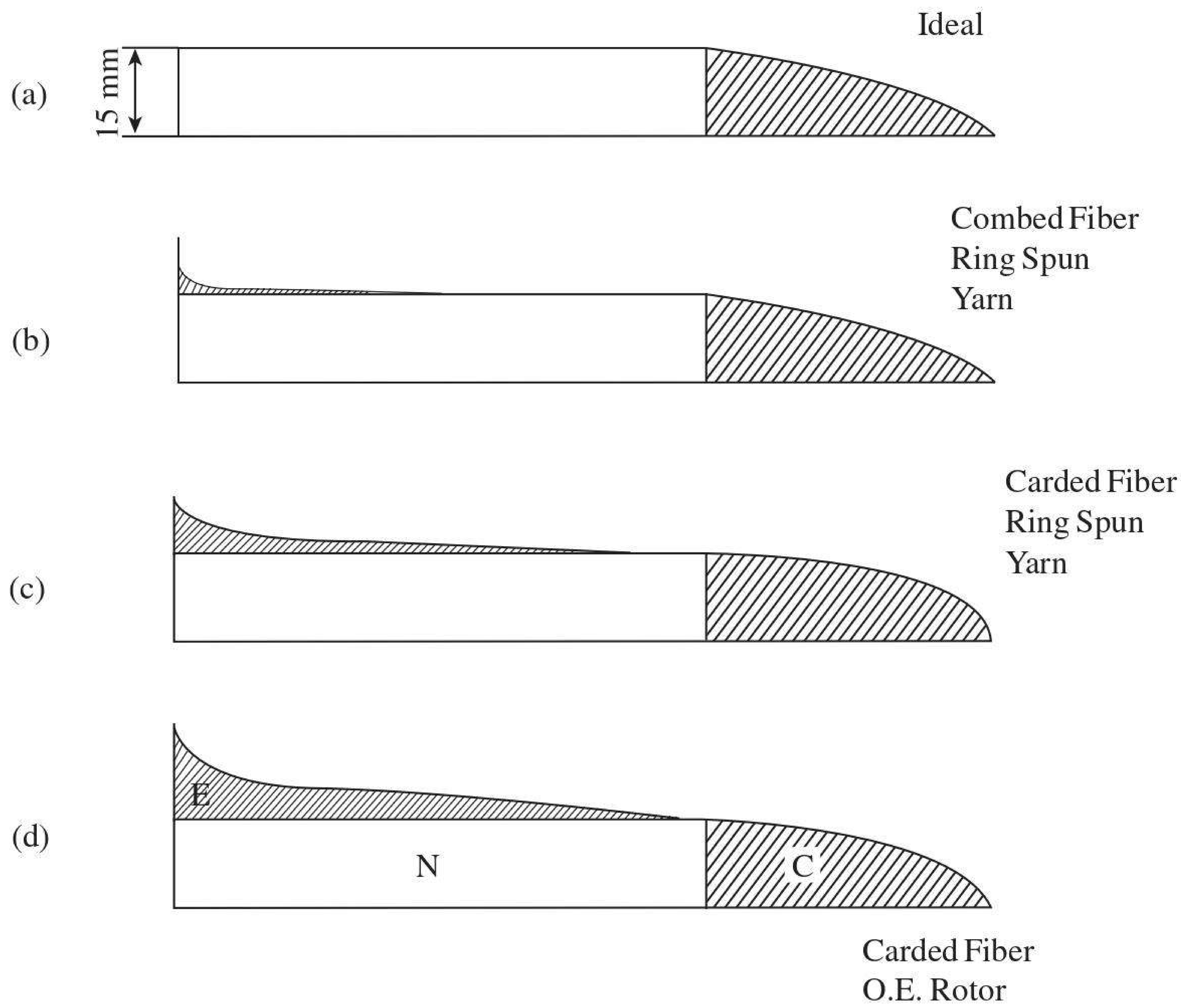


FIGURE 6.84 Fiber parallelism in yarn structure.[125]

Hence, with (b), (c), and (d) in Figure 6.84 showing departures from the ideal length distribution for combed and carded ring-spun yarns, and for OE rotor yarns, it can be seen that combed yarns give the better length utilization. If we ignore the shaded section, C, of the diagram, then the departure from the ideal length utilization can be quantified by what is termed a *parallel factor,* P_π, given by the formula,

$$P_\pi = 1 - E/N \tag{6.41}$$

where E and N are as shown in the Figure. 6.84.

As may be anticipated, P_π values follow a similar trend to K_F values, i.e., spun-in length coefficient, for the three yarn types. However, importantly, Figure 6.85 shows a linear relationship between fiber strength utilization and P_π, the correlation coefficient being 0.959 ± 0.023. The linear relationship is given by the equation

$$n_L = 1.32\ P_\pi - 0.59 \tag{6.42}$$

P_π and K_F will follow similar trends with regard to yarn structure. It therefore may be expected that spinning systems employing drafting roller units for fiber mass attenuation will produce stronger yarns when fiber lengths are increased. With an opening-roller system, possible fiber breakage with increased length and the buckling of fibers during deposition on to collecting surfaces may tend to limit the beneficial effect of increased fiber length, and this would largely explain the contradicting findings reported in the literature.

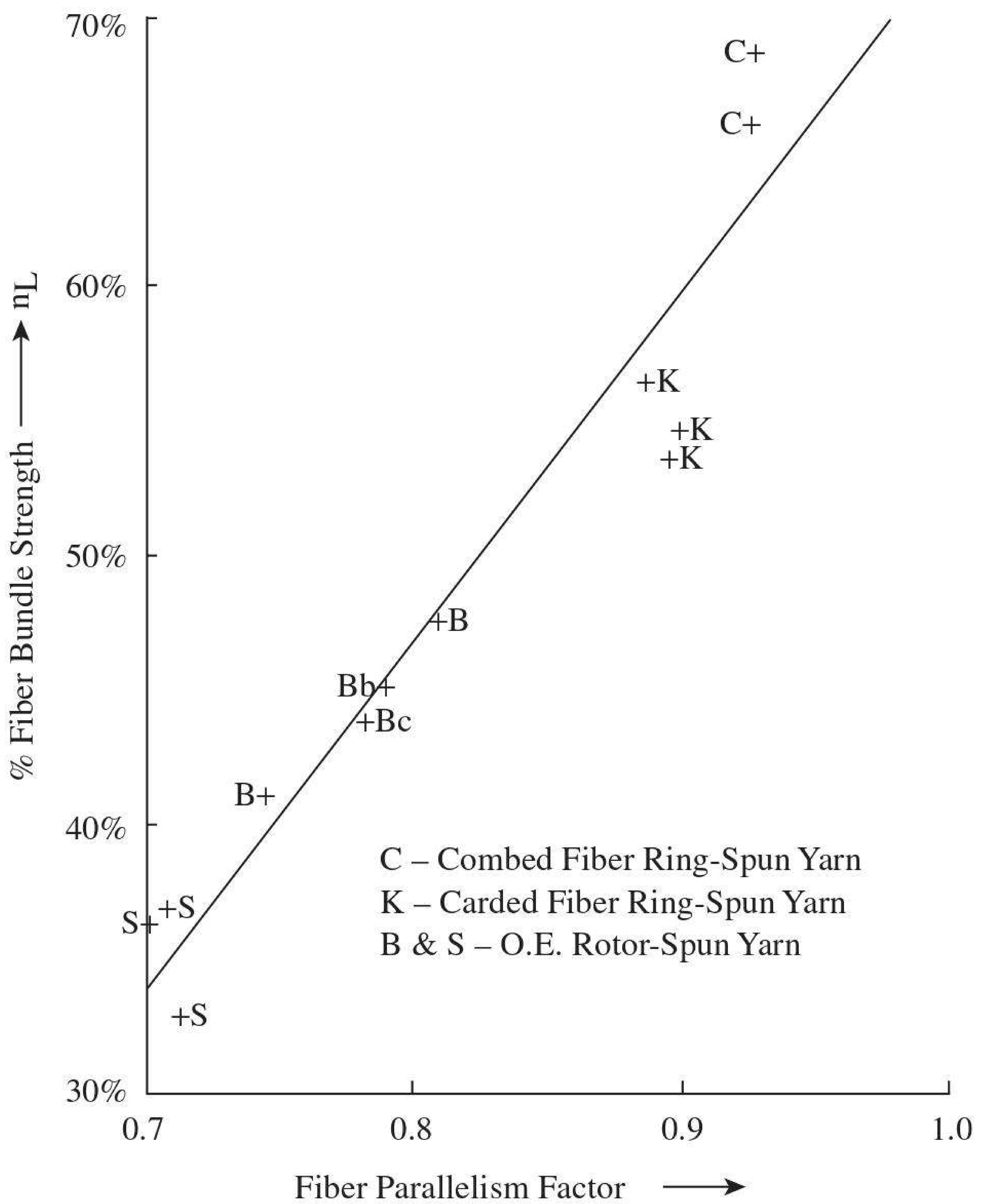


FIGURE 6.85 The effect of fiber parallelism in yarns on fiber strength utilization.[125]

Vaughn and Rhodes[126] found that increased fiber length contributed to increased strengths of rotor yarns. Solhotra[127] concluded from his work with viscose fibers that there should be an optimal staple length for obtaining the maximum strength in OE rotor yarns. Stalder[128] found that rotor yarn strength initially increases with staple length up to 40 mm and then remains constant, although, with coarse fibers (>1.7 dtex), instead of a leveling out, there is a slight increase up to 60 mm. Bancroft and Lawrence[129] worked with polyester, nylon, acrylic, and polyolefin fibers and found that the best yarn properties were obtained with a near-rectangular staple diagram for staples lengths between 32 and 38 mm. Srinathan et al. claims that, for viscose fibers spun from 38-mm, 44-mm, and 51-mm fibers, the strongest yarn was obtained with the 38-mm fiber length. In contrast to these findings, London and Jordon[130] found little change in that rotor yarn strength when the mean fiber length was increased from 32 mm to 38 mm or even when 50 mm was tried. For these studies, a 45-mm rotor diameter was used with the shorter lengths and a 55-mm diameter with the 50-mm and 51-mm lengths. In general, the consensus view would appear to be that 38 mm is the optimal fiber length for rotor spinning.

Regarding length distribution, it follows from the discussion in Chapter 5, on the principles of roller drafting, that combed ring yarns are stronger than carded ring-spun yarns, not only because of improved fiber length utilization but also as a result of the removal of short fibers. Short fiber lengths do not enable a high relative stress to be induced in the short fiber as a result of slippage at the fiber ends. Also, importantly, the associated drafting waves would mean weak places within the yarn. However, owing to the cyclic aggregation of the fibers in rotor spinning and the low K_F of the longer fibers, short fibers have a less detrimental effect on rotor yarn strength.

It then follows that yarns produced from combed material (see Chapter 2) are stronger, as the short fibers removed in combing would contribute little to yarn strength and much to yarn irregularity. Figure 6.86 shows the effect of combing on ring and rotor yarns, and it is clear that the benefit seen with the conventional ring-spun yarns is not as evident with rotor yarns. The improvement in irregularity for the rotor yarn is not fully transferred to its strength because of the K_F factor. The benefit for the conventional ring-spun yarn would be greater for case of compact ring-spun yarn.

In general, combing makes it possible to spin more uniform and stronger yarns and is therefore widely used for production of fine-count short-staple yarns, including rotor-spun[121,122,123] and worsted yarns. The importance of the number of drawing passages in preparing the material for spinning is illustrated in Figure 6.87. The yarn strength increases because of the improved straightening of fibers, i.e., the associated increase in K_F, and the fiber length utilization. The figure also shows the advantage gained by feeding the prepared material to the spinning process so that any remaining hooked fibers have their hooked ends trailing (T) rather than leading (L) during drafting.

The points made above in relation to ring- and rotor-spun yarns are applicable to the other yarn types, particularly air-jet and HS yarns, where the core fibers are required to be straight and parallel to obtain maximum yarn strength.

In Section 6.1.4.1, it was explained that short-staple air-jet yarns are generally made from 100% polyester or polyester-cotton blends. We can reason from the above discussion that, for the spinning of air-jet yarns, it is necessary to have a well combed

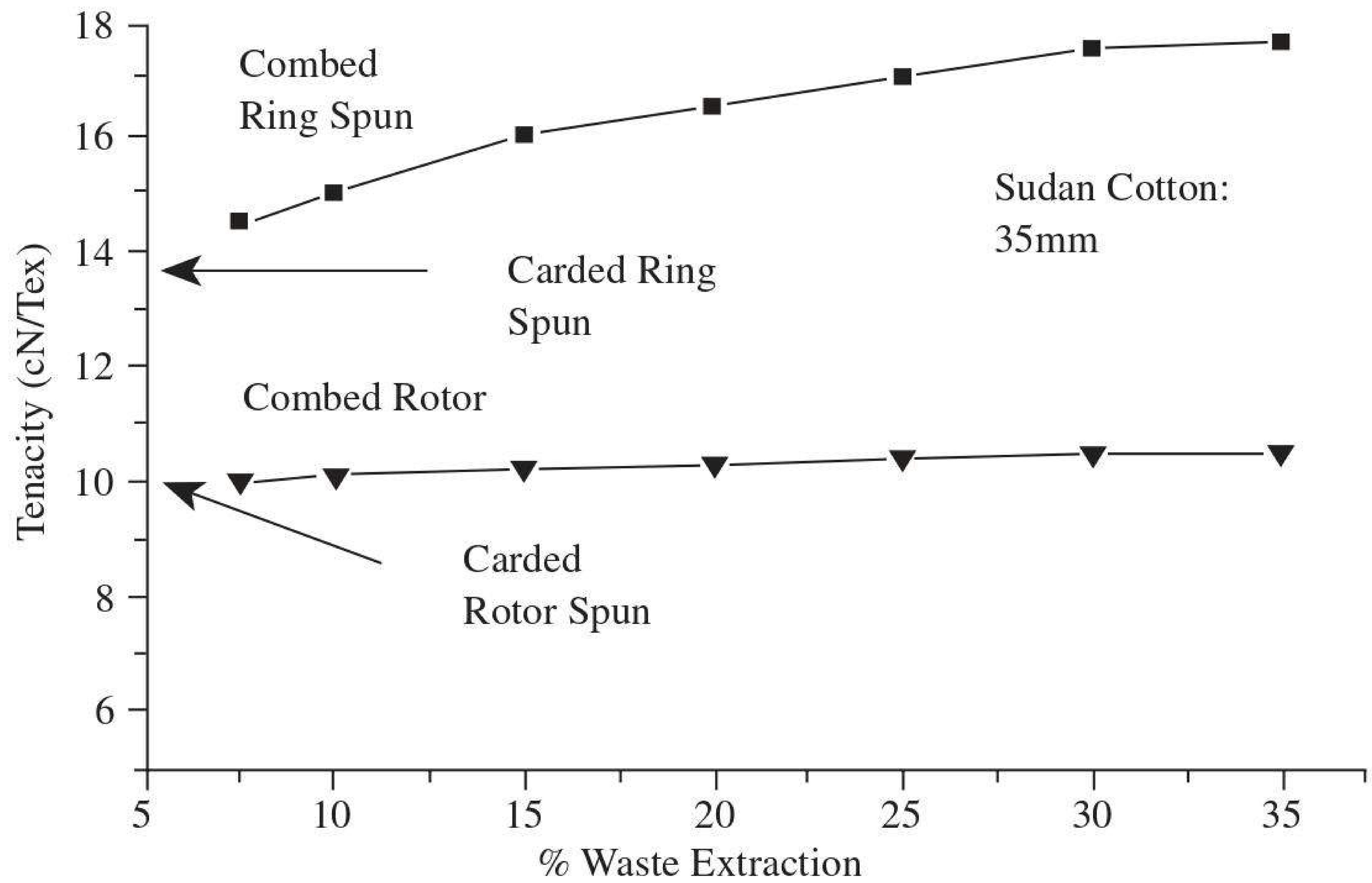


FIGURE 6.86 Effect of combing on yarn strength.

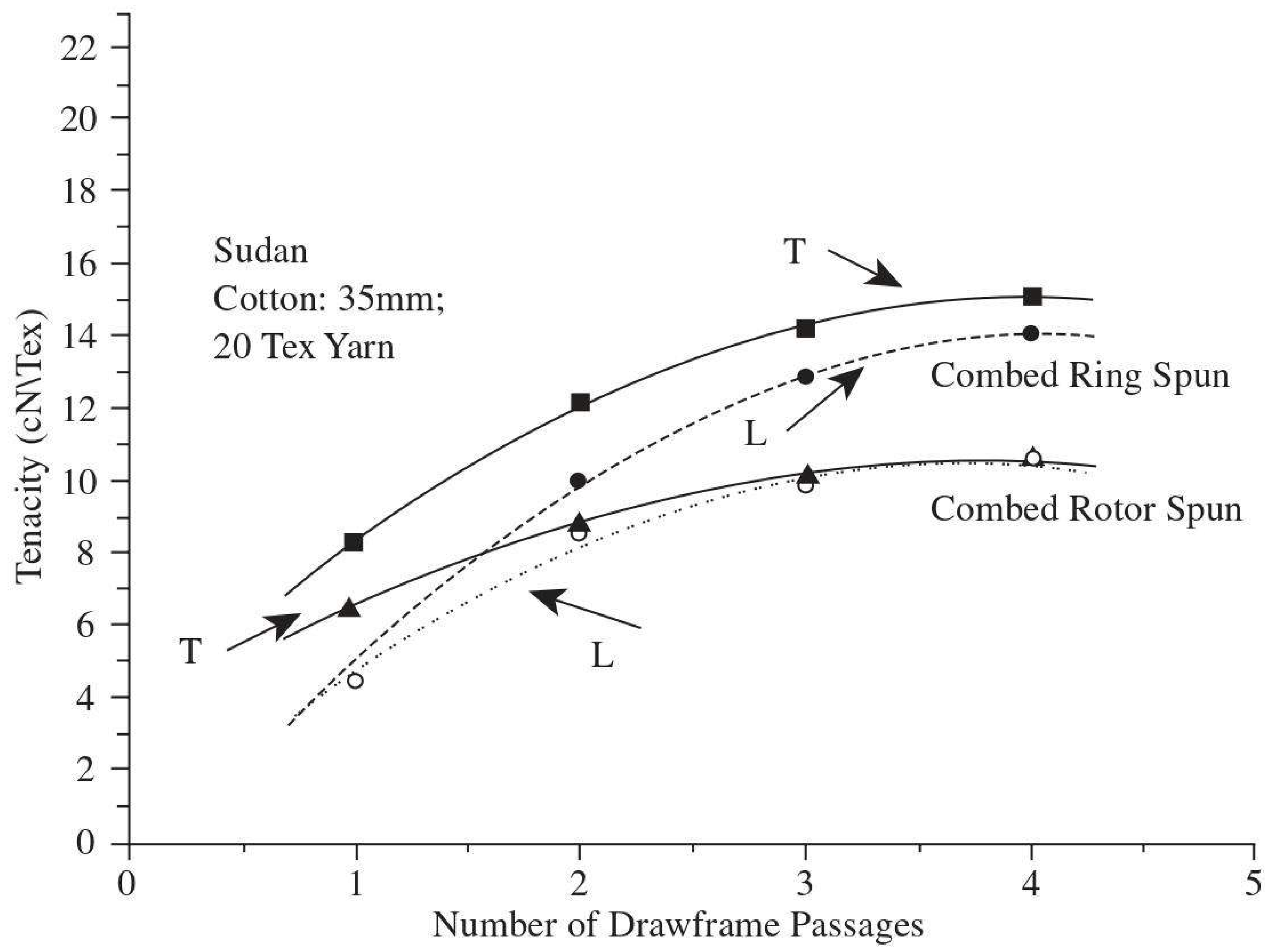


FIGURE 6.87 Effect of drawframe passages and direction of fiber presentation on yarn strength.

cotton component in the blend and a suitable number of drawing passages so as to utilize as much as possible of the fiber length in wrapping.

6.2.3.3.3 Fiber Blends

The blending of fibers is carried out to either reduce the cost of a product or, more often, enhance the product's aesthetics or performance. The influence of fiber properties on yarn tensile properties makes knowledge of the effect of blend ratio an important issue in the production of yarn blends.

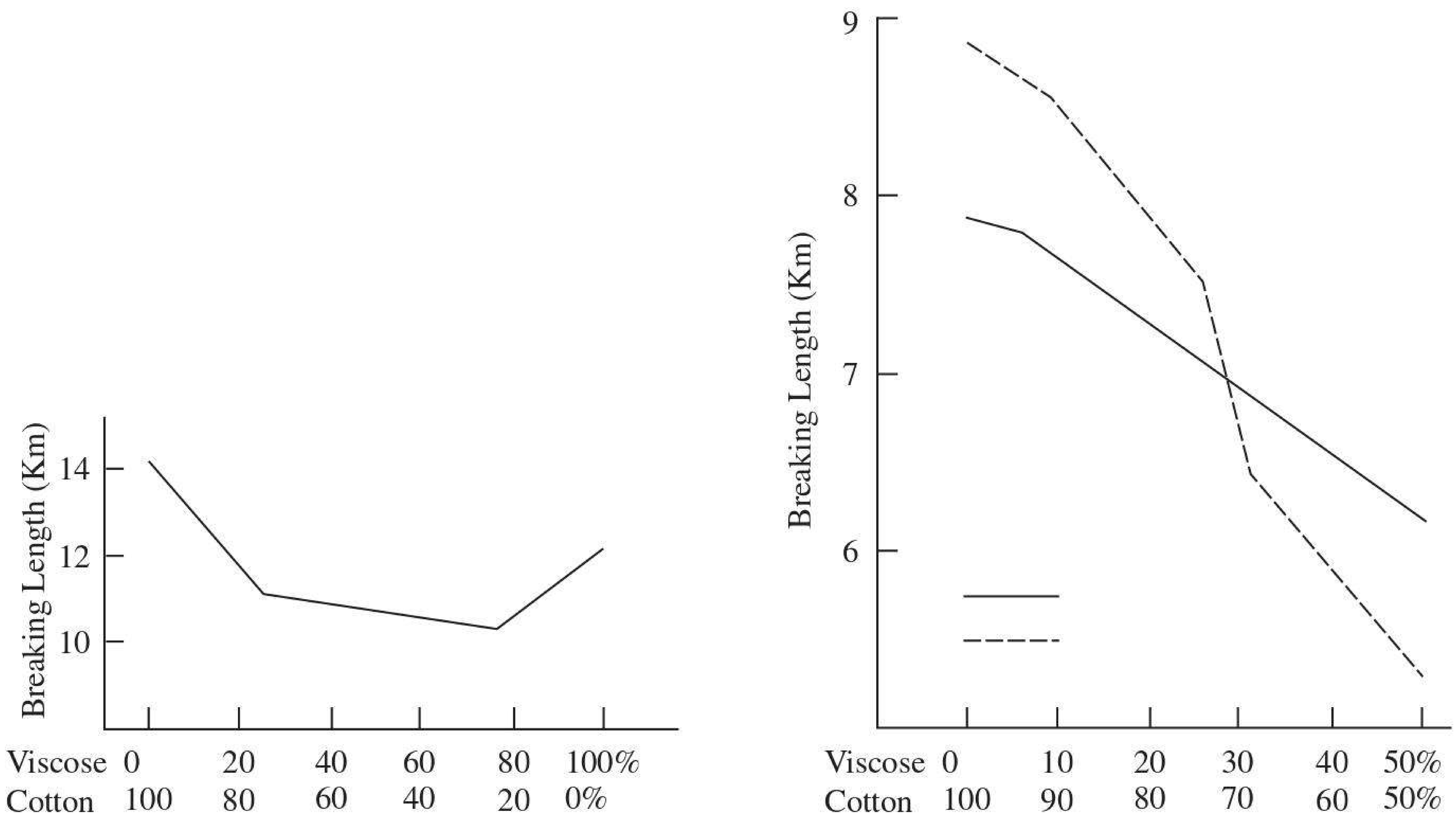
There are three possibilities of mixing textile fibers.

1. Mixing of yarns in a fabric
2. Doubling of different singles yarns
3. Raw fiber blending as discussed in Chapters 2 and 5

From the position of yarn manufacturing, we will concern ourselves only with items 2 and 3.

The strength of a doubled yarn will depend on the tensile characteristics of the constituent yarns. However, the folded yarn produced from, say, two yarns, each spun from a different fiber (i.e., 100% of fiber A and 100% of fiber B) will not be as strong as a folded yarn produced from yarns of the blended fibers.

In blending two different fiber types, the length and fineness of the fibers are important to the irregularity of the yarn, as will be explained below, and therefore are also of importance to yarn strength variation. Nevertheless, the mean strength of a yarn spun from a blend of fibers will always be less than the yarns of equivalent count spun from 100% of each component, as Figure 6.88 illustrates for a range of



Note: Breaking length is the calculated length at which, theoretically, the yarn should break under its own weight.

FIGURE 6.88 Effect of blend ratio on viscose rayon/cotton yarn strength.

cotton/rayon blend ratios of ring-spun yarns in the wet and dry states. This is largely the result of the difference in tensile properties of the component fibers. The induced stress in the fibers will differ between the blend components. On loading the yarn to break, the component fibers of the lower extensibility will take greater load and are likely to break before the more extensible fiber. To circumvent a premature yarn break, the load-elongation characteristics of the fibers should be similar. It is the difference between the extensibility of the fibers that accounts for yarns spun from blends being weaker than the 100% spun components.

6.2.3.3.4 Effect of Spinning Machine Variables

When describing the properties of the differing yarn structures, it is important to consider the effect of machine parameters, particularly of the open-end and wrap-spinning systems, which have been the focus of much research. The results of most factorial experiments carried out show no substantial interactions between the principal variables, so, for the sake of simplicity, only the main effects will be considered.

As mentioned earlier, opening-roller drafting provides for lower yarn irregularity than roller drafting systems. The factors of importance in opening-roller drafting are the opening roller saw-tooth or pin type clothing, the point density of the clothing, and the opening-roller speed. Similar to carding, different types of clothing are used, based on manufacturers' experiences in spinning a wide range of fiber types. Not surprisingly, then, with several machine and ancillary component manufacturers within the market, there are differences in specifications. But, basically, there are three types of opening rollers, and Table 6.15 gives a typical example of their specifications. Several studies have been published on the effect of opening-roller clothing in rotor spinning.[131,133] The main findings relate to the required angle of tooth and point density to obtain effective fiber separation with minimal fiber breakage. The point densities and tooth angles listed in the table are within the range found for optimal performance with regard to the particular fiber types indicated.

TABLE 6.15
Examples of Opening Roller Types

Type	Clothing details
Suitable cotton and viscose, saw-tooth type	80° rake, 120 teeth per 2.54 cm^2
Suitable for synthetics, saw-tooth type	90° rake, 60 teeth per 2.54 cm^2
Suitable for cotton and man-made fibers, pin type	85° rake, 100 teeth per 2.54 cm^2

Figure 6.89 shows the effect of opening roller speed on yarn tenacity. As the speed increases, the degree of fiber separation improves. However, above the peak value, fibers can be broken, and fiber configuration during removal from the roller is not favorable to K_F. Studies into the straightening of fibers during rotor spinning[134,137] have shown the importance of the ratio of the airflow speed to surface speed of the opening roller, and also of rotor surface speed to the airflow speed at the exit of the transport channel. For improved fiber straightening, these ratios must be greater than unity.

In contrast to friction-drum surface speed, rotor surface speed has a deteriorating effect on yarn tensile properties.[138,139] Two factors govern rotor surface speed: the rotor rotational speed and the rotor diameter. The effect of increasing the rotational speed of the rotor is illustrated in Figure 6.90. There is a slight decrease in strength with increasing speed but a sizeable decline in the extension at break.In the published data from which the graphs were obtained, the opening-roller speed and machine twist level were kept constant. The production speed increases with increasing rotor

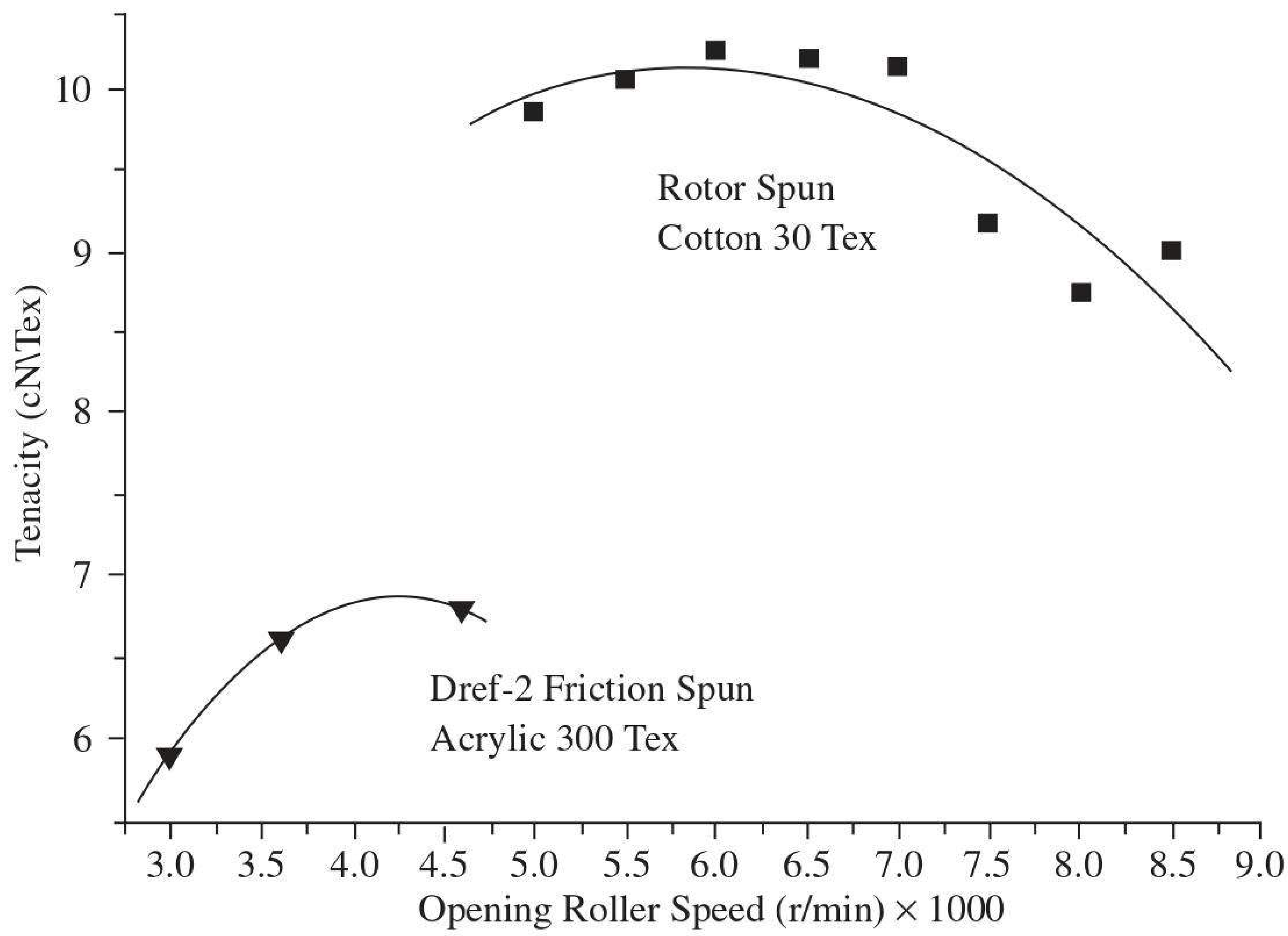


FIGURE 6.89 Effect of opening-roller speed on yarn strength.

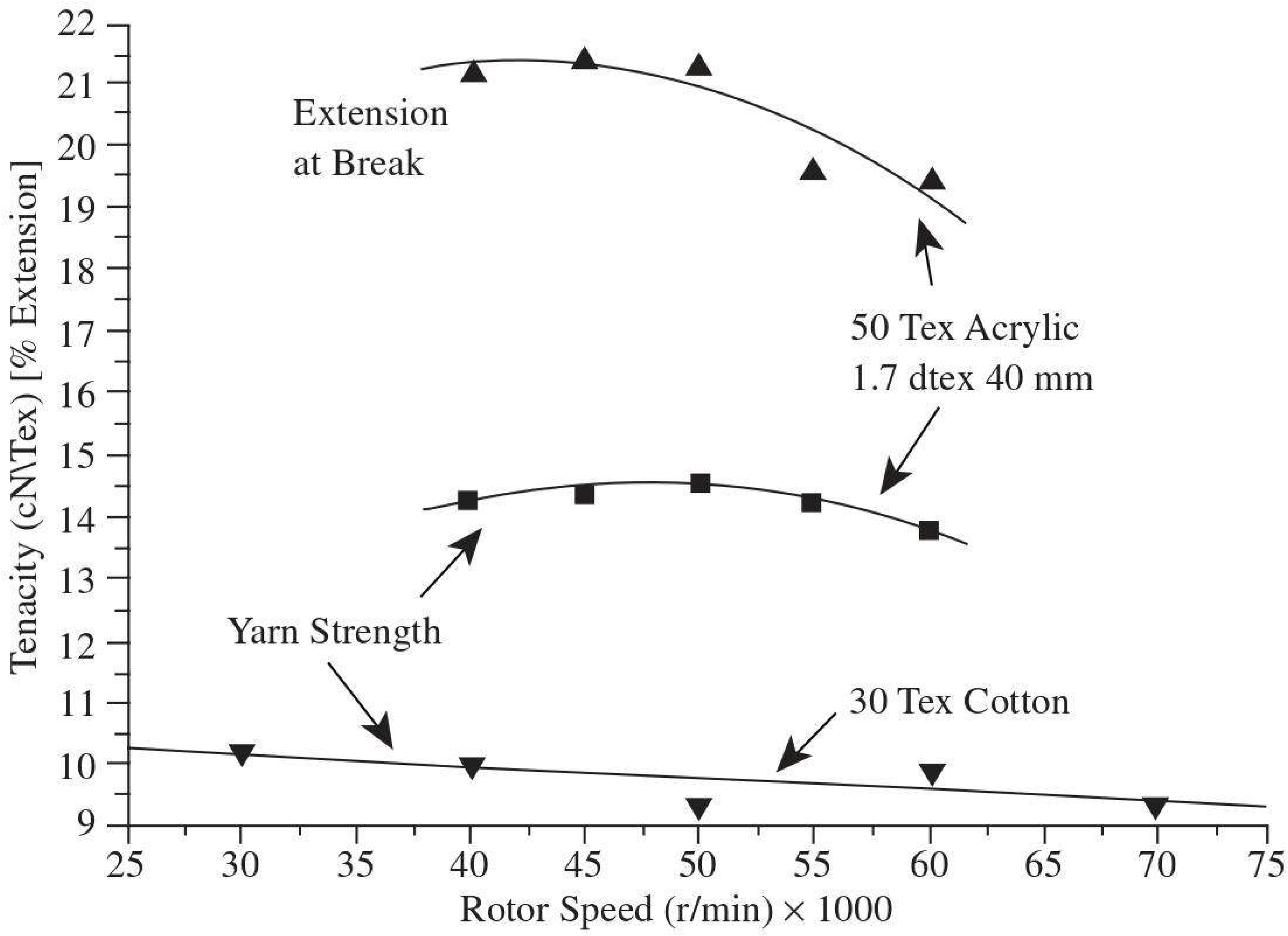


FIGURE 6.90 Effect of rotor speed on yarn strength and elongation at break.

speed, and this means a greater mass flow rate to the opening roller. The degree of fiber separation will therefore decline with increased rotor speed, resulting in reduced yarn strength. Increasing the opening roller should improve the result but, if the increase required is high, any advantage gained may be offset by fiber breakage. The breaking elongation decreases with increased rotor speed because of the increased spinning tension, which causes a permanent strain in the yarn.

To spin at high rotor speed, it is necessary to use a small rotor diameter and narrow rotor groove, which enables tighter packing of the fibers in the yarn. An example of the effect of tightness of the rotor groove is shown in Figure 6.91 and Table 6.16, and it evident that the tighter rotor groove gives stronger, more extensible yarn. However, the tabulated values show a deterioration in other yarn properties, which will be discussed later.

With respect to the yarn tension within the rotor, it is recommended that this should not exceed 10 to 20% of the yarn breaking load.[138] The tension in the yarn is largely the result of centrifugal forces and is therefore proportional to the square of the product of the rotor speed and diameter. Reportedly,[138] a rotor speed and rotor diameter of 70,000 rpm and 40 mm, respectively, give optimal tension. To maintain a optimal tension with increased rotor speed, the following relationship may be used (see Figure 6.92):

$$n = 3.2 \times 10^6/D \tag{6.43}$$

where n = rotor speed (rpm)
D = rotor diameter

With ring spinning, the spinning tension increases as a quadratic function of the spindle speed (see Chapter 8). Therefore, similar to rotor spinning, elongation

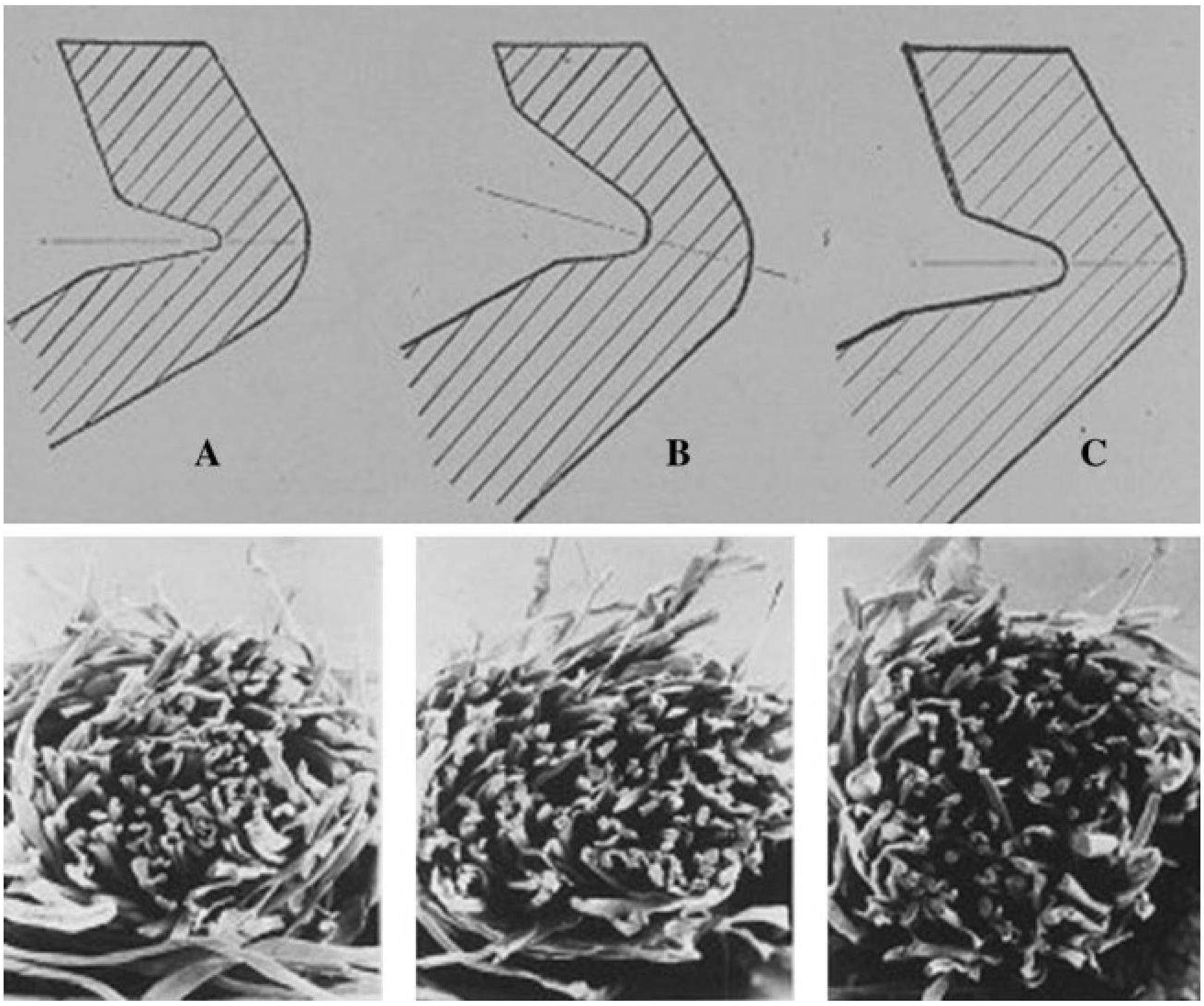


FIGURE 6.91 The rotor groove profiles and corresponding yarn cross sections.

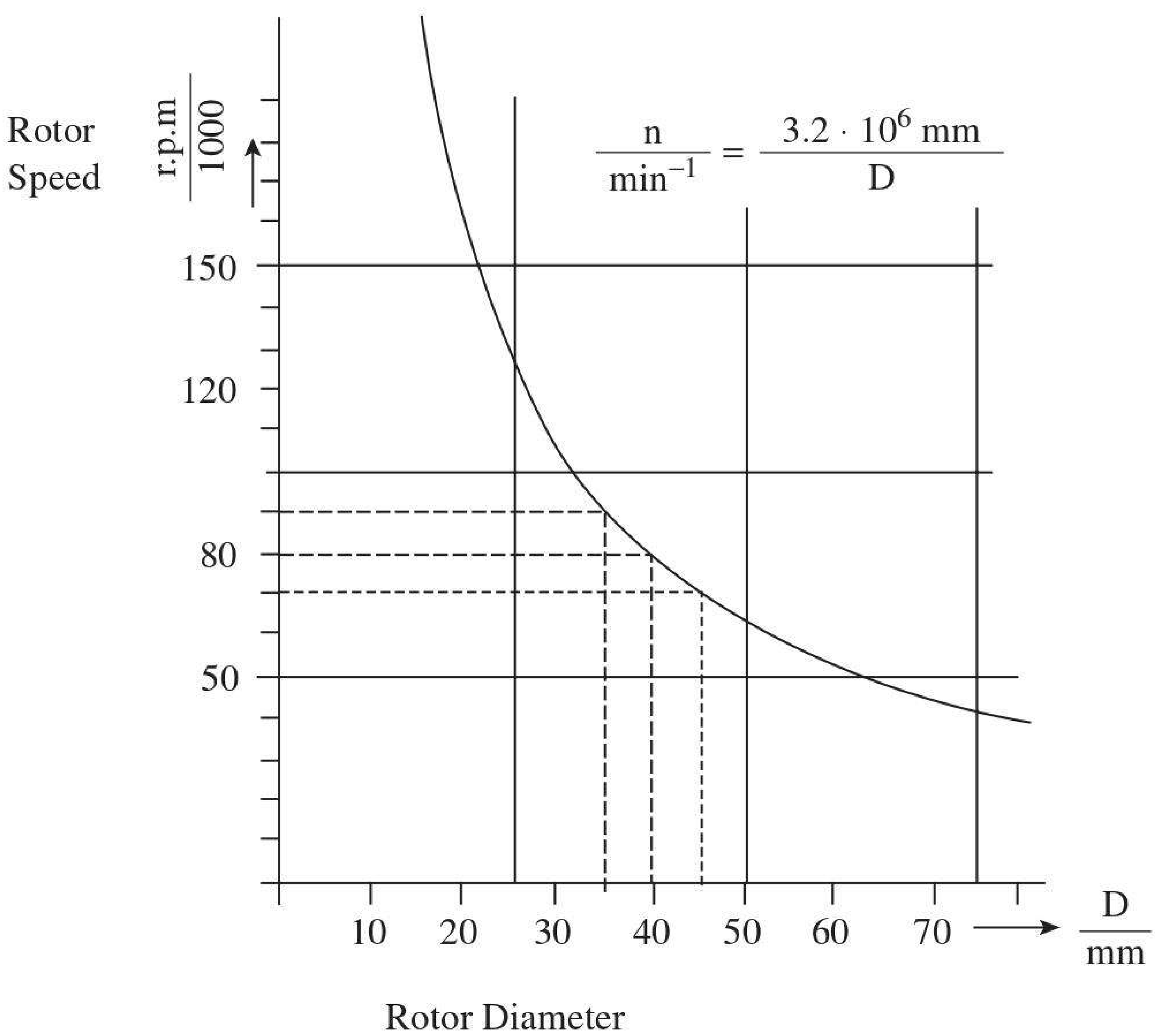


FIGURE 6.92 Relation between rotor speed and rotor diameter for optimal yarn tensile properties. (Courtesy of W. Schlafhorst AG & Co.)

TABLE 6.16
Effect of Rotor Groove Profile of Yarn Properties

Yarn parameter	50/50 Central African/Pakistani cotton, 100 tex		Polyester, 1.7 dtex, 38 mm	
Rotor type	**A**	**B**	**A**	**C**
Strength (cN/tex)	12.3	10.9	8.7	8.4
Percent extension at break	7.7	6.0	17.9	14.1
Irregularity (CV%)	113.4	10.1	13.7	14.0
Thin places	8	8		
Thick places	48	8		
Neps	320	8		
Hairs/m	256	340	175	196

Rotor speed = 60,000 rpm, rotor diameter = 40 mm, opening roller type and speed = optimal for fiber type.

decreases with spindle speed.[140] In air-jet spinning, increased jet pressures, as we have seen, improve yarn tenacity owing to the increased wraps. The spinning tension is also influenced by the ratio of the speed of the front drafting rollers to the yarn take-up speed. Yarn strength improves as this ratio increases from 0.9 to 1.00; above unity, the tension in the yarn restricts the ballooning of the yarn and therefore the optimal initial wrapping by the edge fibers below the twist insertion point. Figure 6.64 shows that, for H-S wrap spinning, the increase in spinning tension with wraps per meter is the result of increased spindle speed, and, as stated earlier, Case B results in the better yarn because of the lower tension.

6.2.3.4 Irregularity Parameters

The concept of irregularity with respect to a linear fiber assembly (LFA) has been explained in Chapter 5. It should be understood that, as an LFA, the random and periodic variations along a given sample length of yarn can be determined by the capacitive method as well as by other methods referred to in Chapter 5. That is to say, we can determine the percentage coefficient of variation of overall mass per unit length (CV_T%, or percentage variation in thickness) along the sample length. We can also derive an irregularity spectrograph to identify periodic variations and, if required, determine a variance-length curve. Usually, the practice is to obtain the former two measurements by the capacitive method and to determine the yarn count variation, i.e., $CV\%_{100m}$.

The variations in the yarn length that contribute to CV_T% irregularity of the yarn, commonly called the Uster CV, include sizeable thin and thick places and some very sizable thin and thick places; the very sizeable ones may be termed *objectionable faults*. It is important to know their size and frequency of occurrence. Besides these sizeable thick and thin faults, there are other faults (e.g., manual thread piecings) that are referred to as *special faults;* these are less attributable to the spinning process and more to the working practice.

Both Chapters 4 and 5 discuss the issue of neps and nep removal. Of all yarn defects, neps are considered to be the most serious. If neps are not removed prior to spinning, they can appear on the yarn surface and become a degrading fault in the yarn and in the final fabric. Neps are likely to have a different uptake of dye from that of the main fibers in the yarn. Consequently, they may give a spotty appearance to the fabric, so the frequency of occurrence of neps is another irregularity parameter to consider. Actual neps are more of a problem with twisted yarns spun on systems using roller drafting (e.g., ring spinning) as opposed to opening-roller drafting (e.g., rotor spinning), since with the latter, the separation of the fiber mass feed into individual fibers gives the opportunity to eject trash and neps from yarn formation. With ring-spun cotton yarns, seed coat fragments with fibrous attachments are a main cause of neps, because the attached fibers can become twisted in the yarn (see Figure 6.93). Although these particles can be removed during the finishing treatments of the final fabric, they leave behind fibrous clusters that were attached to the particles, and these show up as specks.[141–143]

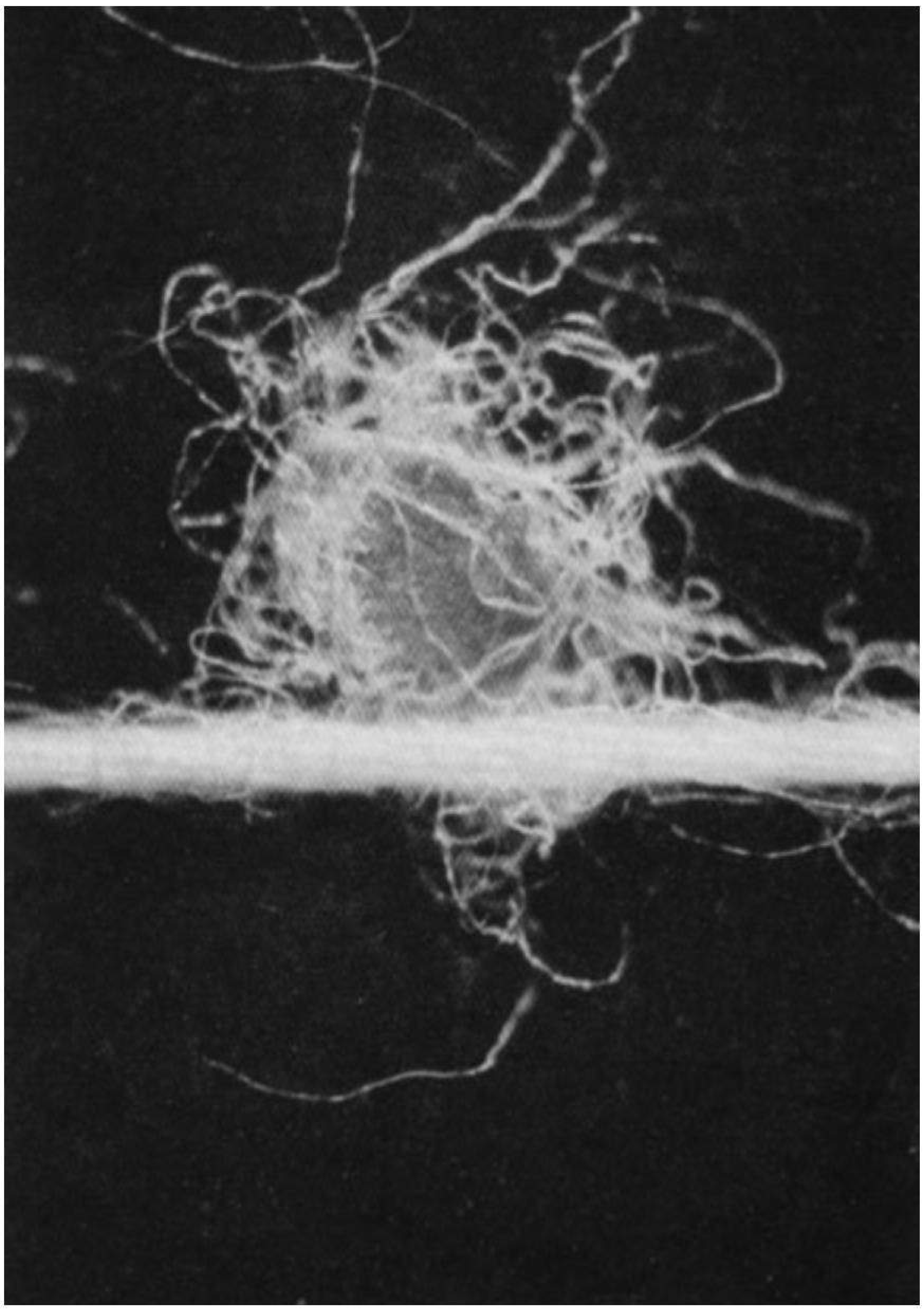


FIGURE 6.93 Example of seed fragment nep in ring-spun yarn. (Courtesy of Zellweger Uster.)

Table 6.17 gives a summary of the above irregularities with regard to size and frequency. Two points must be remembered with respect to the table. First, the numbers 1 through 4 are for convenience labeling and have no significance in terms of value or order. Second, no attempt is being made here to distinguish which among these types of irregularities constitutes a fault, in the statistical sense. The practical stand is taken that all are faults, because they are unwanted and therefore should be minimized. Where feasible, they should be removed from the yarn, provided the piecing is less conspicuous than the fault it replaces.

TABLE 6.17
Summary of Types of Yarn Irregularities

Type of irregularity	No.	Frequency	Size*	Measured parameter
General random cross-sectional variations along the yarn length	1	Very frequent	Variable thickness; lengths ≤ shorter fiber lengths	$CV_T\%$ and $CV_{100m\%}$
Periodic variations	2	Frequent	(As above)	Wavelength, determined from irregularity spectrogram
Thin places (a) thin places, (b) thick places, (c) neps	3	Frequent: up to 5000 per 1000 m	(a) –40 to –70%† (b) +40 to +100%** (c) +140 to +400%‡	Number per 1000 m
Objectionable faults; slubs, very thin places	4	Seldom: 50 per 100,000 m	†	Number per 100,000 m

*Range of variation given with regard to mean yarn cross section

†Lengths ≤ shorter fiber lengths

‡Lengths ≤ 1 mm

Courtesy of the Uster system for yarn fault control, *Uster News Bulletin,* 29, November 1981; The Uster automatic electronic yarn clearing installation, *Uster News Bulletin,* 22, 1–28, July 1974; The source and frequency of yarn faults, *Uster News Bulletin,* 21, 1–20, November 1973; Uster statistics, *Uster News Bulletin,* 15, 1–28, January 1971.

This latter point is only applicable to Class 4 faults, called *objectionable faults* because they are more conspicuous in a fabric. Were the worst of these faults to pass through into the fabric, corrective measures[144] would have to be taken to prevent the resulting garment being down graded, and doing so becomes costly. The frequency of Class 4 faults is sufficiently low for it to be more practical to remove the most pronounced of them at the yarn stage. This is an action called *clearing* and is carried out during winding.[145] (See Chapter 7.)

Before any Class 4 faults are removed, it is necessary to determine the propensity and size of those present in the yarn. This can be done by the capacitive method and in relation to a visual reference chart, shown in Figure 6.94, known as the Uster Classimat System, by Zellweger Uster Ltd.[144] The Classimat system uses a 23-grade classification of objectionable faults, based on the thickness and length of a fault. Figure 6.94 shows 16 of the main types. For cotton yarns, the cause of the smaller types of faults, such as Class A and B, have been traced to seed fragments that were not removed in the fiber preparatory stages.[141] The larger slub-like faults are generally associated with insufficient opening of fiber tufts that largely comprise short fiber clusters and with "poor housekeeping practices," e.g., fiber accumulations on machines, bad manual piecings, and so on.[146] Once the number of each type of fault is known, a decision can be made regarding how many of which types are to be cleared from the spun yarns, bearing in mind the effect on the efficiency of the winding machine.

With regard to irregularity types 1 through 3, their frequency of occurrence makes it impracticable to remove them from the yarn. Quality standards have therefore to be agreed upon by the producer and the buyer. A set of data sheets is published every five to seven years by Zellweger Uster, based on measurements from a wide sample of commercially produced yarns from nearly all geographical locations of the world in which sizeable spinning installations are located. For a range of yarn counts spun from the most commonly used fiber types and blends, the data sheets give, for each irregularity type, a typical range of values, called *experienced values,* for the best 5, 25, 50, 75, and 95%, the best 5% meaning the lowest 5% of values. Collectively types 3a, b, and c are referred to as *imperfections* and denoted by IPI (sometimes called the IPI values).

In the hope that the reader may gain an appreciation of the importance of the effect the yarn $CV_T\%$ irregularity (Uster CV%) has on fabric appearance, Figure 6.95 gives a comparison of what may be considered acceptable, seconds quality, and unacceptable for ring-spun cotton yarns in woven and knitted fabrics. The effect seen is caused by effects of drafting waves (see Chapter 5), which looks like short flacks and give the fabric a cloudy appearance as the $CV_T\%$ increases. Table 6.18 is a summary of the effect of $CV_T\%$ and imperfection values in relation to fabric appearance.[147]

A similar set of data sheets is produced for Classimat values and yarn tensile properties, including CV% of strength. The collected data sheets are commonly known as the Uster Statistics. Table 6.19 gives an example of a yarn quality specification based on the 25% Uster values for 100% combed cotton yarns.

6.2.3.4.1 Effect of Fiber Properties and Material Preparation

Chapters 3 and 5 discussed, generally, the factors affecting the irregularity of linear fiber assemblies, particularly in relation to roller drafting. With regard to the effect of fiber properties, it is the number of fibers in the yarn cross section and the effect of fiber length distribution on drafting waves, and therefore the short fiber content, that are of importance to yarn irregularity. However, as explained earlier, short-fiber content has less detrimental effect with opening roller attenuation.

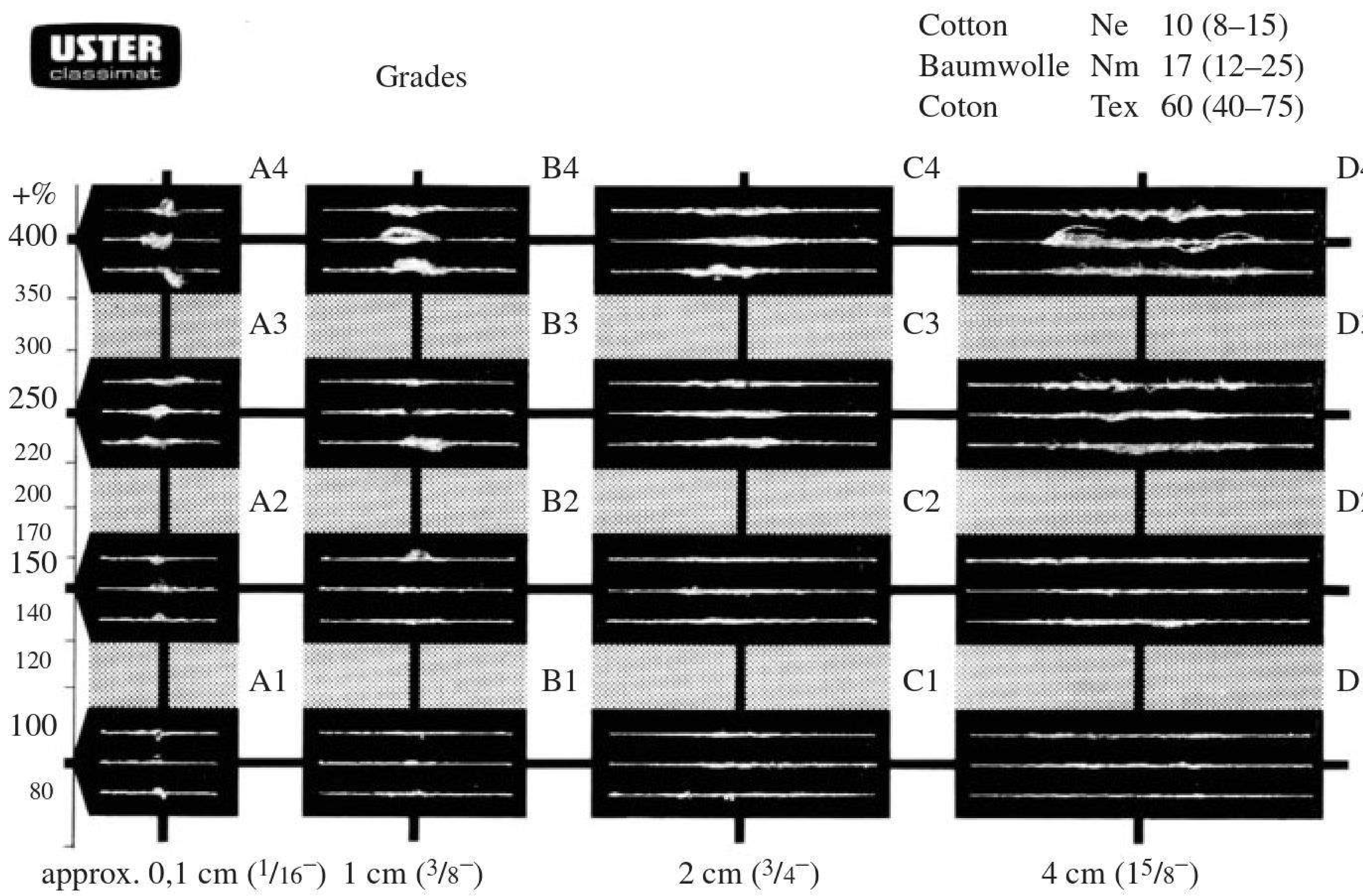


FIGURE 6.94 Uster Classimat (cotton: 16 of 23 grades). (Courtesy of The Uster automatic electronic yarn clearing installation, *Uster News Bull.,* 22, 1–28, 1974.)

For a given yarn count, the finer the fiber, the higher the number of fibers in the yarn cross section and the lower the yarn irregularity should be (see Equation 3.10, Chapter 3). Thus, as Figure 6.96 shows, yarn irregularity decreases with fiber fineness, irrespective yarn type.

Many yarn faults stem from inadequate material preparation, particularly at carding, where (as shown in Figure 6.97) increased production speed can increase yarn irregularities. If faults are already present in the prepared material feed to the spinning process, they will become prominent yarn faults.

A particular example of the importance of carding on yarn irregularity is shown in Figure 6.98 with respect to the production of woolen slubbing. As we learned in Chapters 3 and 4, the swift/doffer surface speed ratio influences the fiber transfer coefficient. With too high a transfer coefficient, the improved separation of microtuftlets obtained with the recycling layer is diminished. On the other hand, too low a transfer coefficient results in a high cylinder load to also give poor fiber separation and increased thick places within the slubbing and, ultimately, in increased Classimat yarn faults (Figure 6.99). Generally, the finer the fiber, the more important is the issue of fiber separation.

The following expression indicates, qualitatively, that the carding force, F_C, required to separate a single fiber from a tuft is dependent on the interfiber frictional forces and fiber entanglement:

$$F_C \to \frac{\mu \times L_f \times M_T}{E_f I \times T} \qquad (6.44)$$

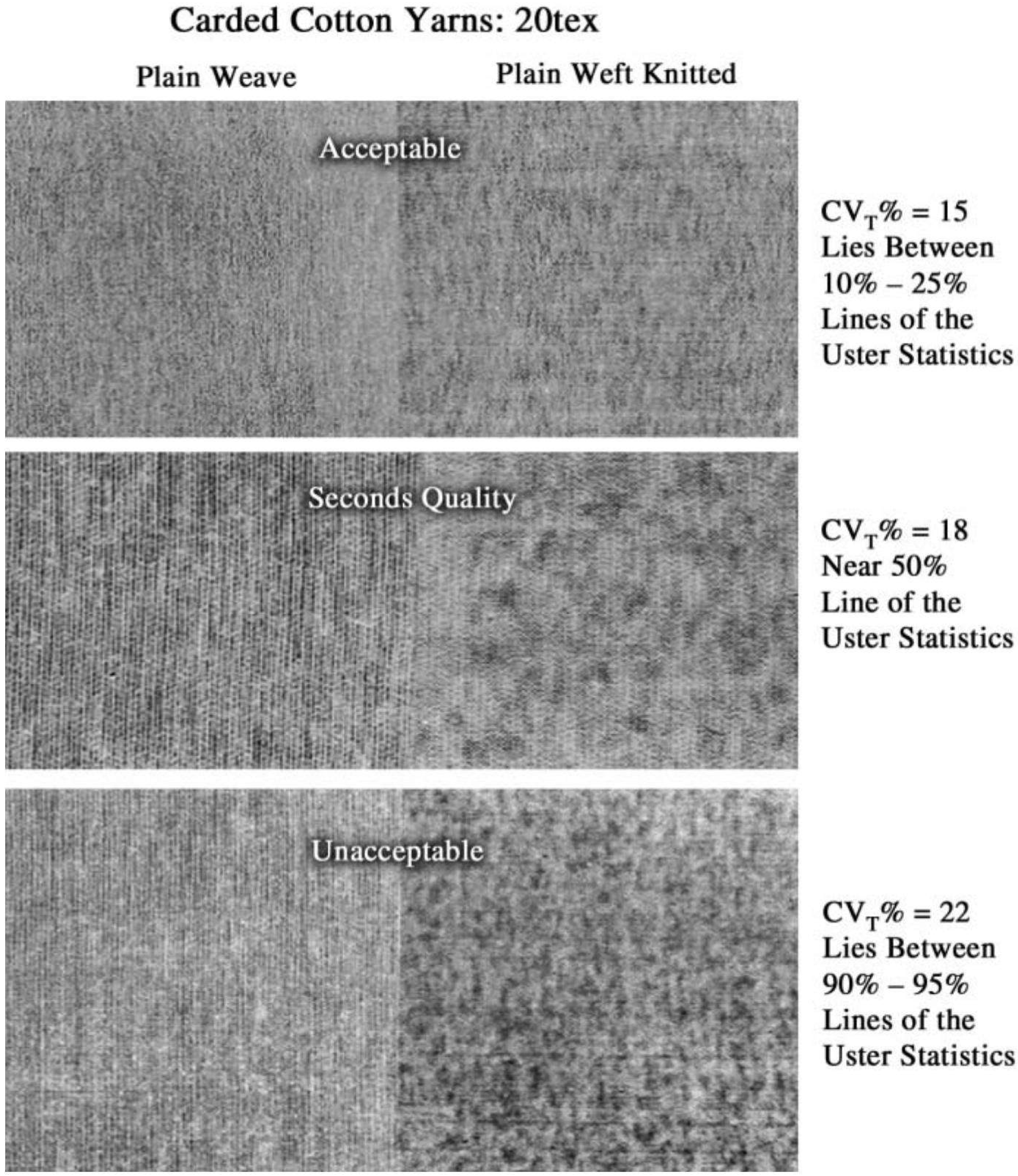


FIGURE 6.95 Effect of irregularity CV_T% on fabric appearance. (Courtesy of Uster Statistics, *Uster News Bull.*, 15, 1–28, 1971.)

See Figure 6.100.

The interfiber frictional force is governed by the fiber friction, μ, the staple length, L_f, the rigidity of the fiber, *EI* (see Equation 3.8, Chapter 3), and by the number of fibers contact points in the tuft, which is directly proportional to the mass of the tuft, M_T, and inversely proportional to fiber fineness, *T*. The bending rigidity varies to fourth power of the fiber diameter. Therefore, it may be reasoned that fine fibers should have a low-friction finish and a high modulus, *E*, to be easily separated and to avoid nep formation during carding, thick places in the card web and, ultimately, high yarn irregularity values. Figure 6.101 shows, with ring- and rotor-

TABLE 6.18
Uster Statistics in Relation to Yarn Quality

Parameter	Result	Guideline
	Effect of CV%	
High CV_T%	→ Stripiness, streakiness, Barré, cloudiness	• >75% line of Uster Statistics→ unacceptable • ≤50% line → average appearance • <25% line → good quality fabric
Periodic variations: wavelength on spectrogram	→ Patterning, e.g., diamond barring[103]	CV_T% only a useful indicator if no periodicity present in yarn
Count CV%	→ Patterning, e.g., bars	
	IPI (Imperfections)	
Thin places, thick places	→ Distorted fabric structure, damage machine components (e.g., knitting needles), downgraded fabric (e.g., needle lines in knitted fabrics)	• > 75% line of Uster Statistics → unacceptable • < 50% line acceptable for most fabrics
Neps	→ Missed stitches and consequential holes in fabric, damaged machine components, downgraded fabric appearance, differential dye uptake	(As above)

Note: Useful further reading: Hattenschwiler and Eberle, H., *Quality in Staple Fibre Spinning,* Melliand Textilberichte GmbH, 1987.

spun yarns as examples, that, as the fiber modulus increases, the yarn irregularity and imperfections decrease.

What is effective for carding is not necessarily applicable to opening-roller drafting. However, the advantage of high modulus and low friction for fine fibers is also applicable to roller drafting.

Figure 6.100 illustrates the forces present in the front drafting zone during roller drafting. N, the normal force on the fiber ribbon, is generated by the drafting aprons, and F_D is the drafting force.

Drafting occurs when the fibers nipped by the front rollers are extended by an amount that, as a result of the fibers' load-elongation characteristics, generates tension in the fiber to overcome the frictional restraint on the trailing ends of the fibers. The drafting force, F_D, may be represented by

$$F_D = E_f \, \varepsilon_f \qquad (6.45)$$

The fiber elongation, ε_f, would be dependent on the front-roller surface speed and short duration of time, t, the fiber was under strain, so that

$$\varepsilon_f = t \, V_2 \qquad (6.46)$$

TABLE 6.19
Yarn Specification Based on Uster Statistics

	Cotton quality
Description	100% white american cotton
Grade	Strict middling
Mean staple length	28 mm
	Yarn, cotton spun, fully combed
Count	17.5 tex $CV_{100m}\%$ = 2.5 based on mean of 10 × 100mm
Twist multiple (twist level)	350 $tex^{1/2}$/cm
Twist direction:	Z
	Performance
Yarn strength	Minimum 13 cN/tex
Elongation at break	7%
CV_T	15%
Imperfection (IPI) per 1000 m	Thin places, a maximum of 30 (i.e., –50%) Thick places, a maximum of 70 (i.e., +50%) Neps, a maximum of 110
Classimat values	Total number of grade 1 faults per 100,000 m should with 150 and 300 (i.e., A1 + B1 + C1 +D1) Maximum total number of grade 2 faults per 100,000 m < 18 Other grades unacceptable

Notes

- Percent comber noil: minimum 18
- Yarn cleared and waxed on cone (spliced piecings — see Chapter 8)
- Yarn conditioned to maximum 8.5% regain

Courtesy of a well known retailer.

Irregularity occurs in the drafting if the time, t, required to develop the force, F_D, to initiate fiber movement is long enough for the rear drafting rollers to advance more fibers into the drafting zone before those under strain are accelerated, so that the actual separated distance between sequential trailing and leading ends of fibers in the drafted ribbon is less than the intended value. Fine fibers will have greater frictional restraints on their trailing lengths, owing to the larger total surface area. Therefore, to ameliorate any deleterious effect from this, fine fibers should have a high-modulus and/or a low-friction finish.

6.2.3.4.2 Effect of Spinning Machine Variables

The $CV_T\%$ of yarns is largely dependent on the effectiveness of attenuation of the fiber mass. From the descriptions in the early part of this chapter, it should have been realized that the vast majority of modern spinning systems employ either roller drafting or an opening roller unit to draft either sliver or roving to the count required for the final yarn, bearing in mind the effect of twist contraction. Much of what has

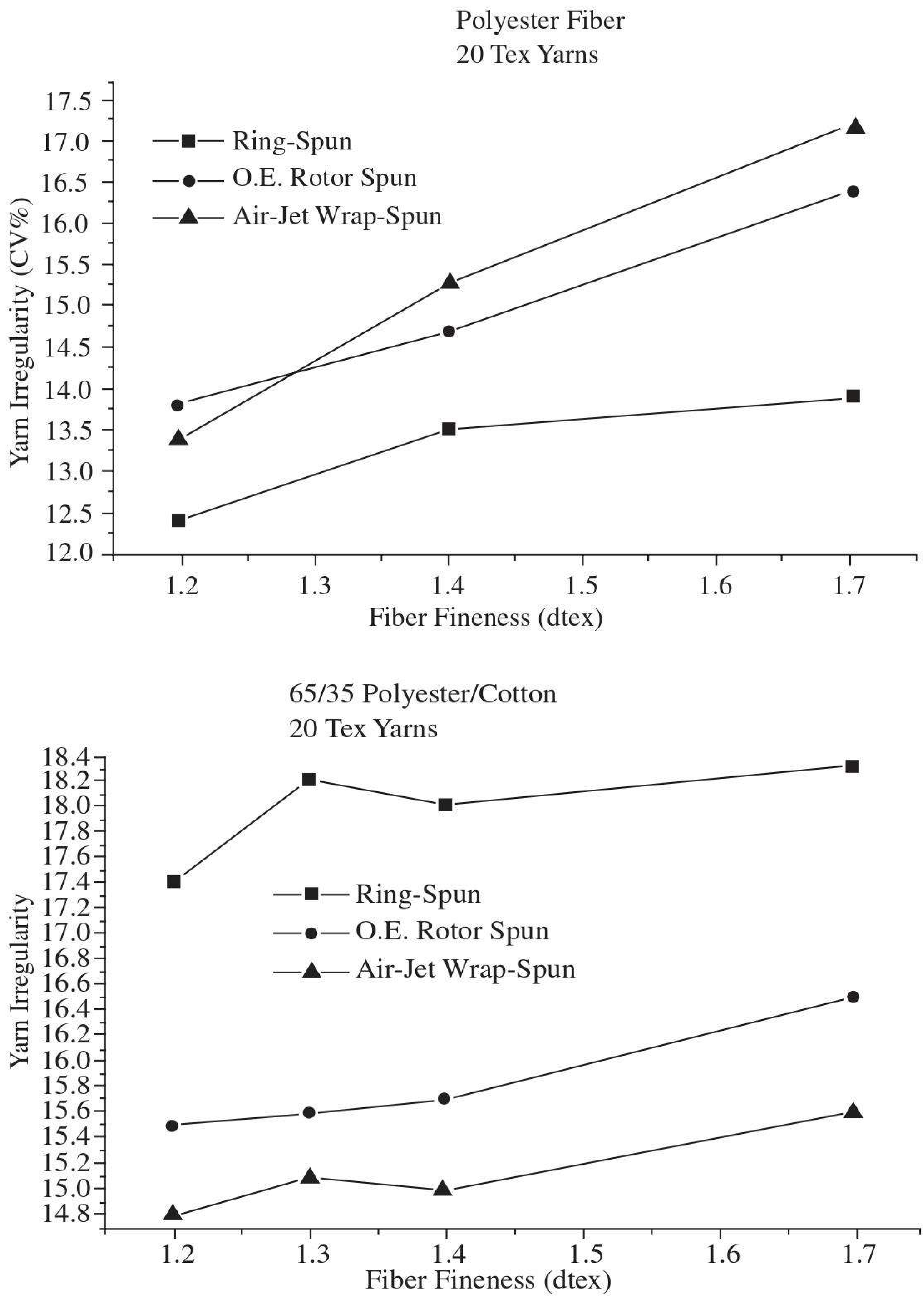


FIGURE 6.96 Effect of fiber fineness on yarn irregularity.

been written in Chapter 5 on the principles of roller drafting is applicable to roller-drafting systems used in spinning. However, of particular practical interest is the work of Anderson and Foster,[151] and subsequently by Ratnam and his co-workers,[152] the main points of which will be considered here. Following this, the key findings in opening-roller drafting will be described, based on the many studies cited in the reference on open-end spinning, mainly rotor spinning.

In Chapter 5, it was explained that roller drafting usually introduces an additional CV% of irregularity to that of the input material. Therefore, roller drafting systems that are used in, say, air-jet spinning and hollow-spindle wrap spinning to attenuate slivers to the required yarn count will impart an additional increase to the irregularity of the input sliver. The drafts used in spinning from drawn sliver are generally high,

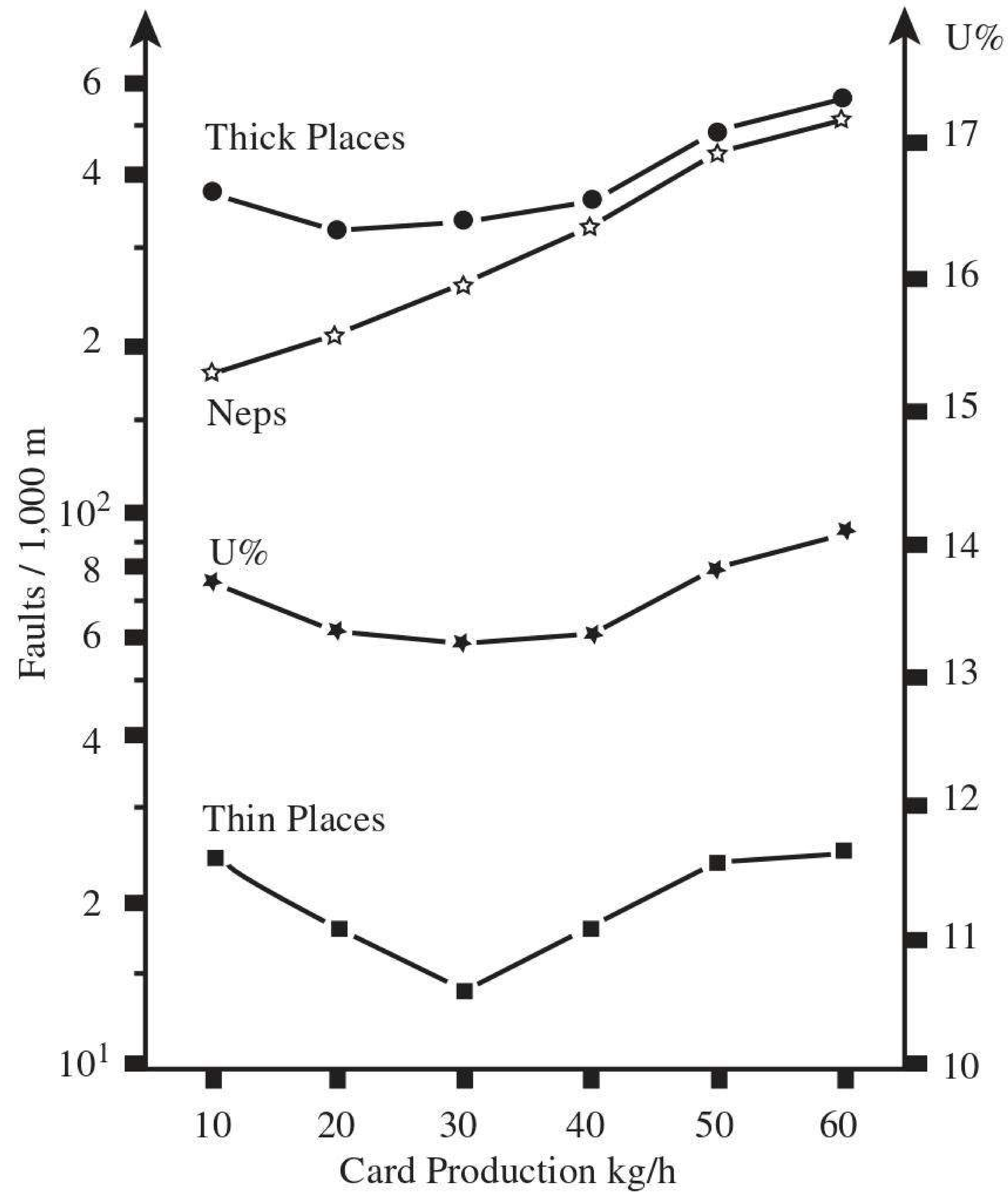


FIGURE 6.97 Effect of carding rate of irregularity values. (Courtesy of Quality control and supervision of yarn faults in the spinning mill, *Uster News Bull.,* 17, 1–15, 1971.)

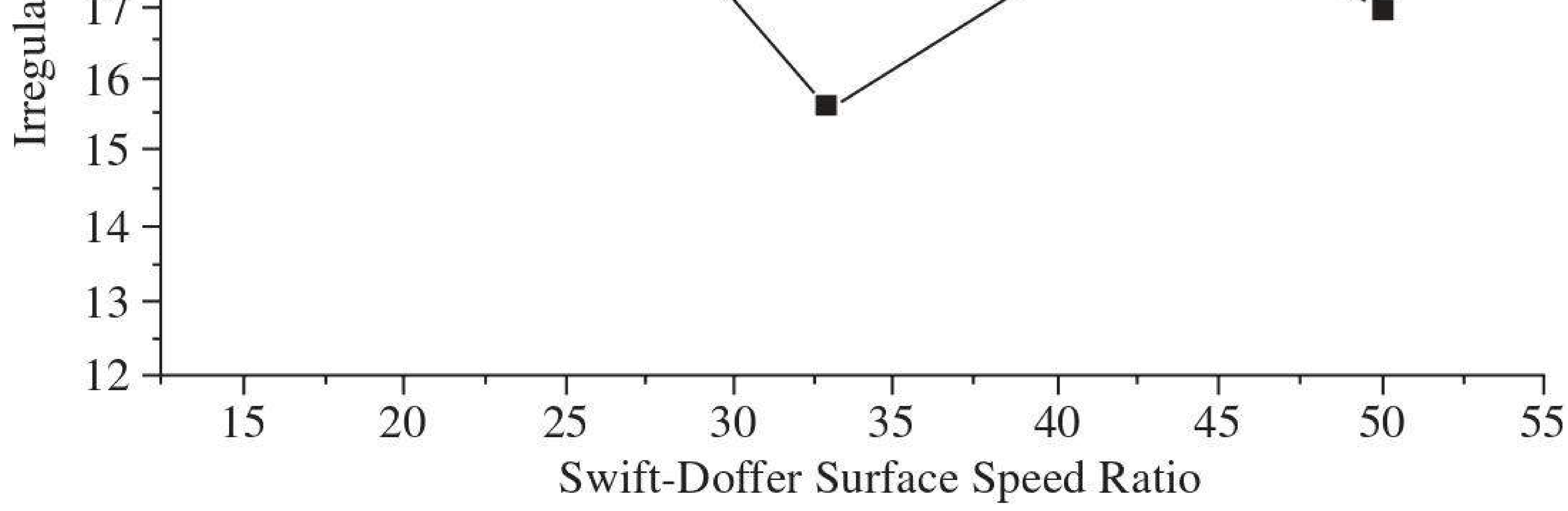


FIGURE 6.98 Effect of swift-doffer surface speed ratio on slubbing and yarn irregularity. (Courtesy of WIRA.)

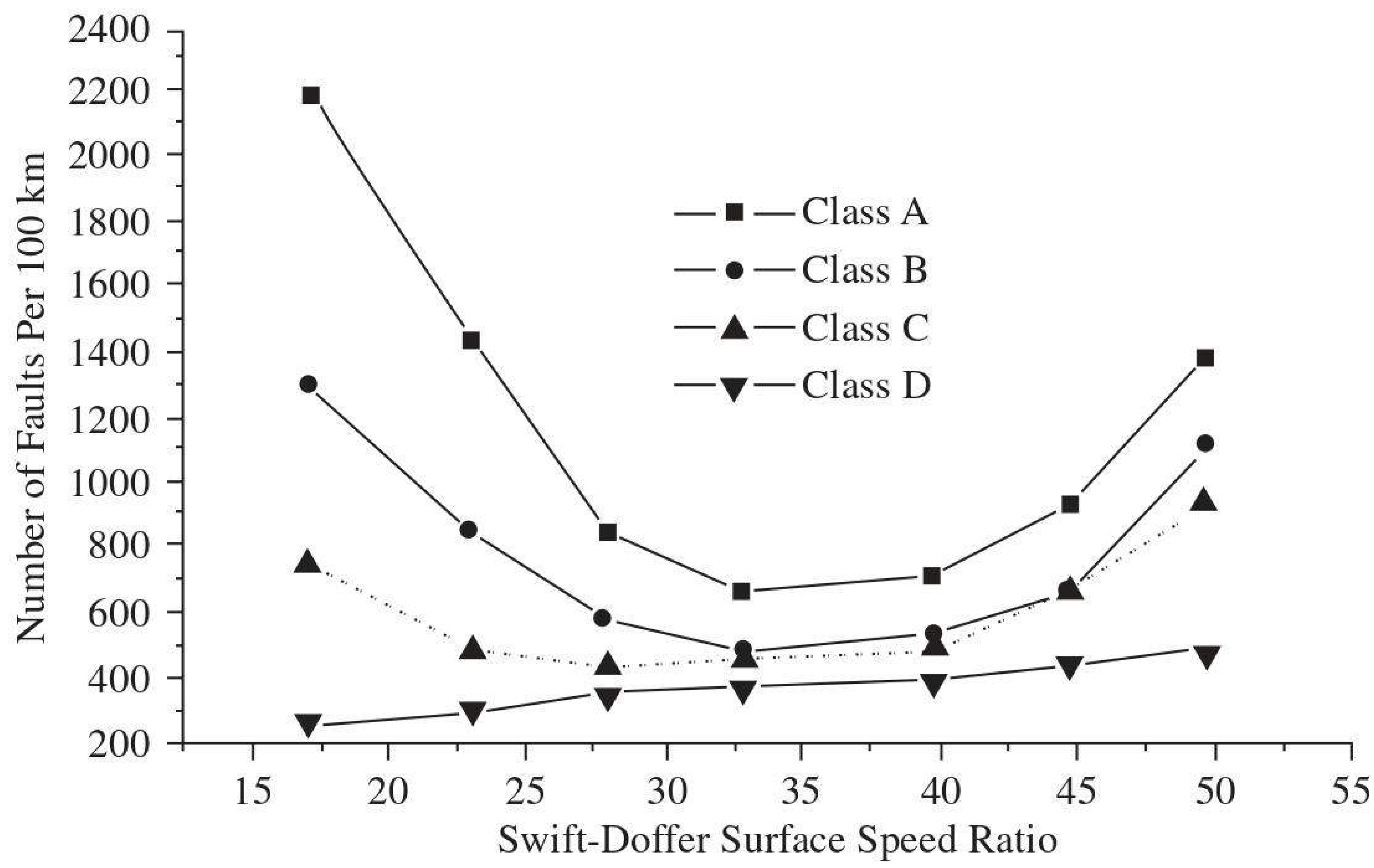


FIGURE 6.99 Effect of swift-doffer surface speed ratio on yarn Classimat values. (Courtesy of Zellweger Uster.)

and therefore the short-term irregularity of a sliver becomes the longer-term irregularity of the spun yarn, which, in practical terms means the variation in the yarn count ($CV\%_{100m}$). It is the short-term irregularity of the yarn that is added by the roller drafting system employed at the spinning stage. In ring spinning processes, where the card sliver is first reduced to a roving and then the roving attenuated in spinning the yarn, there will be two additional increases to the sliver CV% of irregularity. In other words, the roller drafting at the spinning stage will introduce an added CV% of irregularity to that of the roving. Drafts used in attenuating rovings during spinning are much lower than for slivers; therefore, the short-term irregularity of a roving becomes the medium-term irregularity of the yarn.

Anderson and Foster[151] found that the relation between the spinning draft and the added CV% of irregularity is given b:

$$(CV\%_{T-yarn})^2 - (CV\%_{T-input})^2 = A\,(D - 1) \tag{6.47}$$

where $CV\%_{T-yarn}$ = total yarn irregularity
$CV\%_{T-input}$ = irregularity of sliver or roving
D = draft employed at spinning
A = a factor of proportionality

The factor of proportionality, A, has been found by Ratnam[152] to be dependent on fiber properties, the count of the input material, and the proper functioning of the machine (i.e., the good order of the machine). Thus, Equation 6.47 may be rewritten as

$$(CV\%_{T-yarn})^2 - (CV\%_{T-input})^2 = [KT_{input} + z]\,(D - 1) \tag{6.48}$$

where K = constant for a given fiber
T_{input} = count of the input material (sliver or roving)
z = constant for a given spinning machine

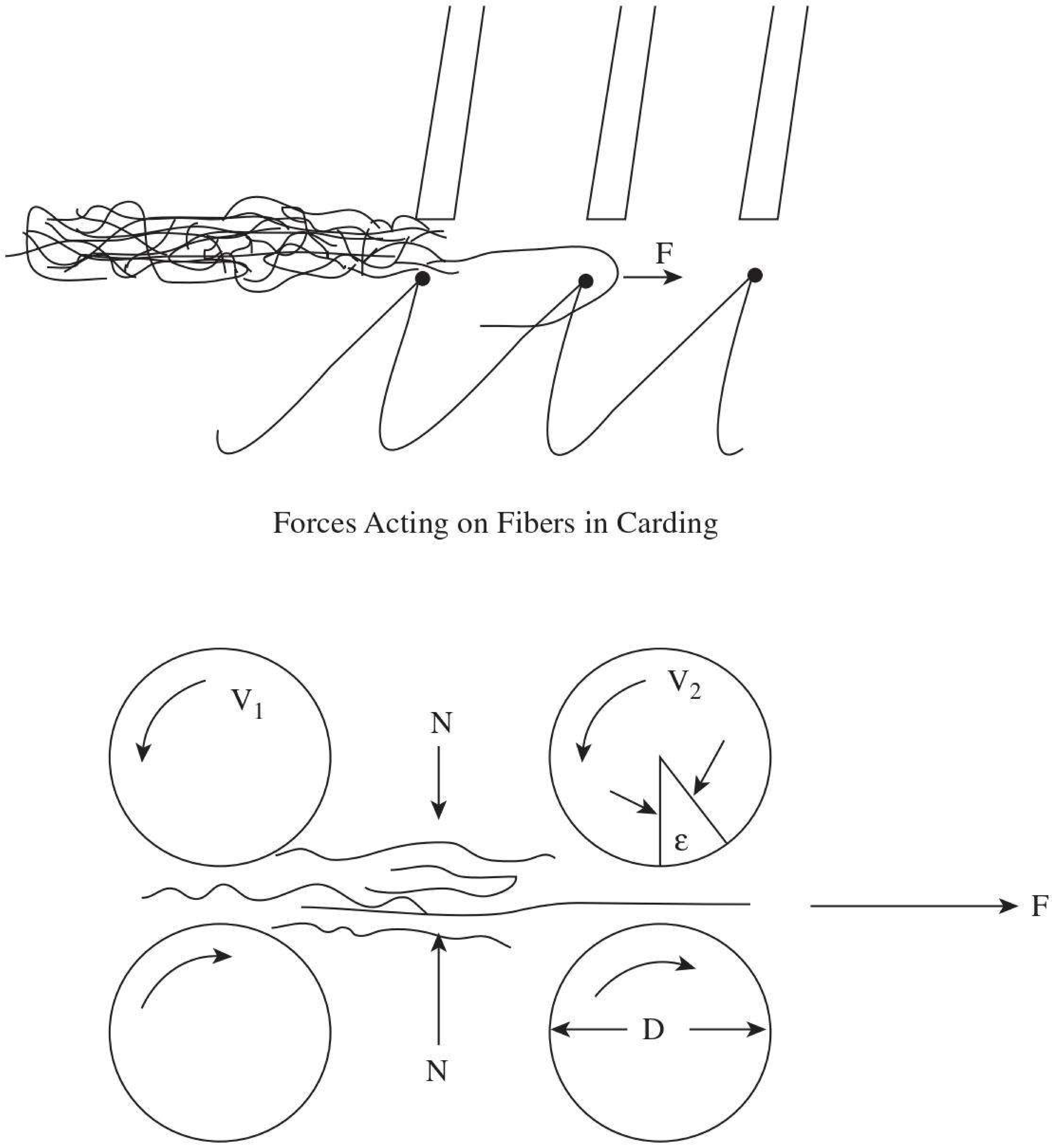


FIGURE 6.100 Forces in carding and roller drafting.

The constant z enlarges the effect of the draft on the yarn irregularity, so its effect is greater as the count of the input material increases. Since fiber control in drafting systems may be expected to be less efficient with heavy input counts, z maybe viewed as a measure of the lack of fiber control by the drafting system, which can be an indication of the proper functioning of the system. In ring spinning, a lack of fiber control may be also caused by increases in the tension on the spinning triangle.[117] This is associated with increased spindle speed and results in an increasing number of thin places with increased speed. As mentioned earlier, twist concentrates in thin places. It not only affects yarn strength variation but also gives, visually, a pronounced difference between the cross-sectional areas of the thick and thin places.[117]

The fiber constant K, is dependent on the fiber state of the input material and the fiber properties, principally the fiber fineness and length. For cottons, $K = 29.4[F/L]$,[2] where F is the ratio of fineness to maturity coefficient and L is the 50% span length. The ratio F/L can be taken as a measure of drafting quality of a given fiber with regard to yarn irregularity. For example, Ratnam[151] found that, with ring-spun yarns produced from Indian cottons, 60% of the yarn irregularity was due to

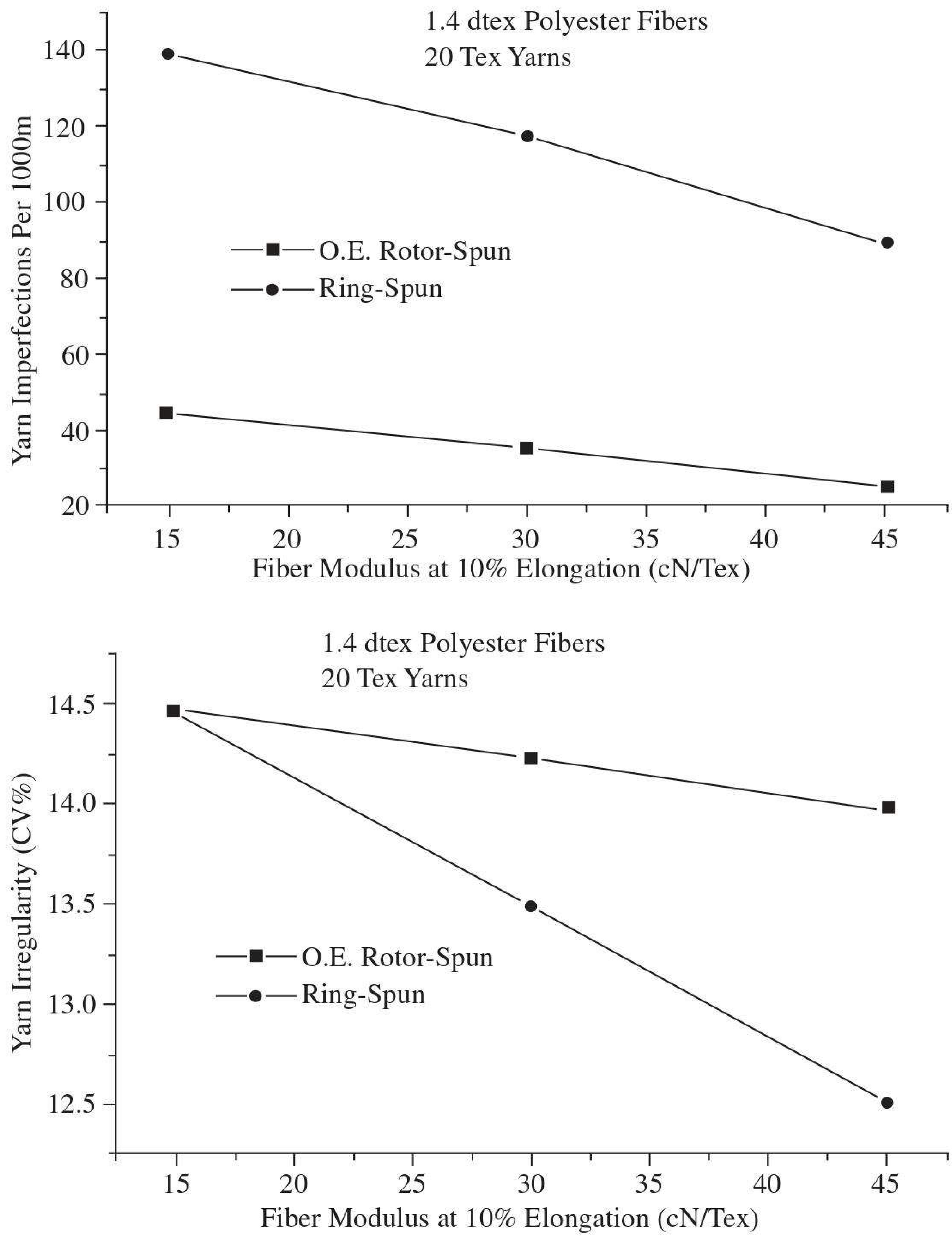


FIGURE 6.101 Effect of fiber modulus on yarn irregularity and imperfections.

cotton quality, 25% the condition of ring frame, and 15% roving irregularity (the latter value having a cotton quality contribution). The 50% span length was found have a larger effect on yarn irregularity than fineness/maturity ratio. The 50% span length by definition is the product of the 2.5% span length and the uniformity ratio (see Chapter 1) and is indicative of the short-fiber content, which is detrimental to effective drafting. Combing is therefore an important preparatory stage for greatly reducing the irregularity and the nep content of the yarn (see Table 6.20) and is essential in spinning fine yarn counts. In short-staple spinning, carded cotton yarns are usually within the count range of 20 to 100 tex, whereas combed cotton yarns are of 5 to 25 tex, the upper limit being one of economics.

From the above discussion, it can be seen that Equation 6.48 could be used as a practical tool to assist in assessing the drafting performance of the spinning process, including material quality. The reason for this is that the equation includes the known factors that influence yarn irregularity.

TABLE 6.20
Example of the Effect of Combing on Yarn Quality

Yarn properties	Combed cotton yarn	Carded cotton yarn	Percent difference
Count (tex)	20	20	
CV% yarn irregularity	12	15.5	–23% (less irregular)
Strength (cN/tex)	18	12.0	+50% (stronger)
CV% (strength)	9	12.5	+28% (fewer weak places)
Percent extension at break	7	7	
Thin places per 100 m	15	100	
Thick places per 100 m	100	500	
Neps per 100 m	80	500	

In theory, opening-roller systems provide the means for drafting the input material at the individual fiber level and thereby circumventing the problem of drafting waves (see Chapter 5). Periodic irregularities, however, will still be present. The effect of the separation of fibers is only a part of the action needed for achieving the required yarn count. As we have seen from the rotor and Dref friction spinning techniques, the separated fibers should be reassembled so as to keep any added irregularity to a minimum.

In Dref friction spinning, the parallel feeding of multiple slivers provides the doubling effect described in Chapter 5, and this reduces the longer-term yarn irregularity caused by the short-term irregularity of the sliver. However, as we may infer from Figures 6.51 and 6.53, the fiber transportation in the airflow and deposition on the friction drums result in a low K_F, and bulked and folded fiber configurations will cause variations in the number of fibers in the cross section along a given yarn length, thereby adding a short-term to longer-term irregularity to increase the CV%.

Rotor spinning has the advantage of cyclic aggregation, which is essentially a doubling effect of the deposited layers accumulating to form the ribbon of fibers within the rotor groove. From the description given in Section 6.2.2.3 of the cyclic aggregation process, it can be seen that the number of doublings, B, is usually very high and can be approximated by

$$B = T\pi D_R - 1 \tag{6.49}$$

where D_R = rotor diameter
T = level of twist

The K_F value for rotor yarns is significantly higher than for Dref-2 friction yarns (see Tables 6.9 and 6.11). Therefore, the factor of fiber configuration is not as severe. Hence, the overall irregularity (the total $CV_{T\text{–}yarn}\%$) of rotor yarns (12.1 to 15.2) is lower than for Dref yarn (13.3 to 19.0), and both are lower than for conventional ring-spun yarns (13.6 to 22.5) of similar counts spun from rovings.[120] The lower irregularity for rotor yarns is dependent on rotor speed, as will be explained below. The fact that the evening out effect of B only involves successive lengths of πD_R indicates that the longer-term irregularity corresponding to the sliver CV% is not effectively reduced in rotor spinning.[153] Hence, CV% of yarn count is lower for Dref yarns (0.1 to 2.2) than for rotor yarns (0.8 to 2.5), but the values for both are much lower than for ring yarns (1.82 to 3.5).[20]

Since configuration of deposited fibers is an important factor with opening-roller drafting systems, it not surprising that many process parameters affect the resulting yarn irregularity. This aspect has been extensively studied for rotor spinning.[134–137] Rotor yarn irregularity decreases with opening roller speed. This is because of the improved fiber separation with increasing speed, but a point can be reached at which the ratio of the airflow and the opening roller linear velocities is too low to give effective stripping of fibers from the opening roller. Also, high opening-roller speed increases the probability of fiber breakage. Increased rotor speed can lead to increased yarn irregularity. In particular, with the use of high rotor speeds for spinning fine rotor yarns, the yarn irregularity can become greater than that for ring-spun yarns. There are two reasons for this.

First, increased rotor speed is usually used to obtain higher production rates, and this means a high feed rate to the opening roller. If the opening-roller speed is not increased, the degree of fiber separation will be lowered, and the yarn may become more irregular, with increases in the number of thick and thin places. Second, increased rotor speed will result in more wrapper fibers per unit length, and, if the degree of separation is lowered, there will be a higher number of fibers wrapping at a given point on the yarn. As stated before, the belt-type wrapper fibers are detected as neps by the more commonly used yarn irregularity testing instruments. Consequently, the nep level of a yarn increases with increased rotor speed, even though actual neps may be removed by the opening roller or become buried within the fiber ribbon and subsequently in the inner zones of the yarn.

The prepared sliver for rotor spinning is a very important factor with respect to the overall quality parameters of rotor yarns, but especially the irregularity parameters. It is self-evident that the more straight and parallel the fibers are within the sliver, the more effective the opening roller is in separating the fibers. Generally, one or two passages of drawing, with autoleveling, are used except when very short fibers (which may be a blend involving comber waste) permit direct spinning from an autoleveled card sliver; drawing in this case would give a high sliver irregularity.

The trash content of the sliver is of a critical importance and has been a well researched topic.[154–170] Trash particles in sliver have been classified as shown in Table 6.21. Neild[154] has reported how dust and microdust particles get into the rotor groove during the deposition of fibers and build up to a level where a ring of these impurities are formed in the rotor groove. During fiber deposition, the majority of the impurities land onto the ribbon of fibers; these particles cannot penetrate the thickness of the ribbon and so are twisted into the yarn structure. Impurities landing at the gap, Y, behind the peel-off point will enter the rotor groove and, as the ribbon of fibers is removed, will build up over time to form sizeable ring of deposit in the grooved circumference of the rotor.

From the various studies cited above, it is known that, as the impurities build up, they prevent the required close packing of fibers within the rotor groove and deteriorate the fiber configuration. The result is a constant decrease in yarn tensile properties and an increase in irregularity, until the yarn strength is too weak to

TABLE 6.21
Classification and Composition of Rotor Deposits

Coarse trash	>500 μ, husk, stalk leaf and seed fragments
Dust particles	<500 μ, fine seed fragments, leaf and fiber fragments
Microdust particles	<50 μ, microscopic fragments of fiber, leaf and seed coat

Courtesy of Heap, S. A., *Some Problems and Opportunities for Cotton Spinners, Technical and Economic Aspects,* Dyson, E., Ed., *Textile Trade Press,* The Textile Institute, Manchester, UK, 1975; and Gilbert, D. K., Chemical Composition of Cotton Dust, *Text. Res. J.*, 50, 96–102, 1980.

withstand the spinning tension, and the yarn breaks. A slow rate of build may occur, in which case the impurities may form one or more clusters well before reaching the level at which the yarn breaks. It may also happen that a sizeable sizable trash particle gets stuck within the groove. Such occurrences would cause periodic spots of twist concentration in the yarn, which become periodic faults with a wavelength of the order of πD_R. This type of periodic fault would have little effect on the $CV_{T\text{–}yarn}\%$ of the yarn but would be seen in the irregularity spectrogram and, if undetected, would produce the fabric fault termed the Moiré effect (see Figure 6.102). A sizeable-length of yarn (20 m or more) may be wound around a card of black background to visually detect this type of yarn fault.

A further detrimental effect of impurities getting into the rotor groove is the wear of the rotor wall and the rotor groove. The high speed of the particles results in a sandblasting effect on the wall, and the twisting action of the yarn length in the groove (i.e., the peripheral twist extent) causes the particulate impurities to grind away at the rotor. Wear on opening roller clothing can also occur. This has led to special wear-resistant coatings being applied to the rotor surfaces and hardening treatments of opening roller clothing.

Modern rotor spinning machines have been automated to periodically stop and clean rotors well before the yarn properties deteriorate to an unacceptable level, and then to restart spinning. However, it is also necessary for the impurity levels in the feed sliver to be as low as possible. In the spinning of fine-count rotor yarns, combing is therefore a necessary part of the sliver preparation.[121–123]

6.2.3.4.3 Yarn Blends

The blending of fibers that have different properties has become an established practice to produce fabrics for diverse applications that are not obtainable by using only one type of fiber. Therefore, the blend irregularity can be as important as the mass irregularity of the yarn. A low blend irregularity is desirable not only for consistency of physical properties of the yarn, but also so that unwanted shade variations do not appear in the finished cloth. Shade variations can arise from the differential dye absorption by different fibers but can be particularly acute in mixtures of spun-dyed fibers or cross-dyed mixtures. Any shade variations along the length of the yarn can cause bars or streaks in the finished cloth. It is thus very important, in processing blends of fibers, to avoid irregularities in the distribution of the component fibers.

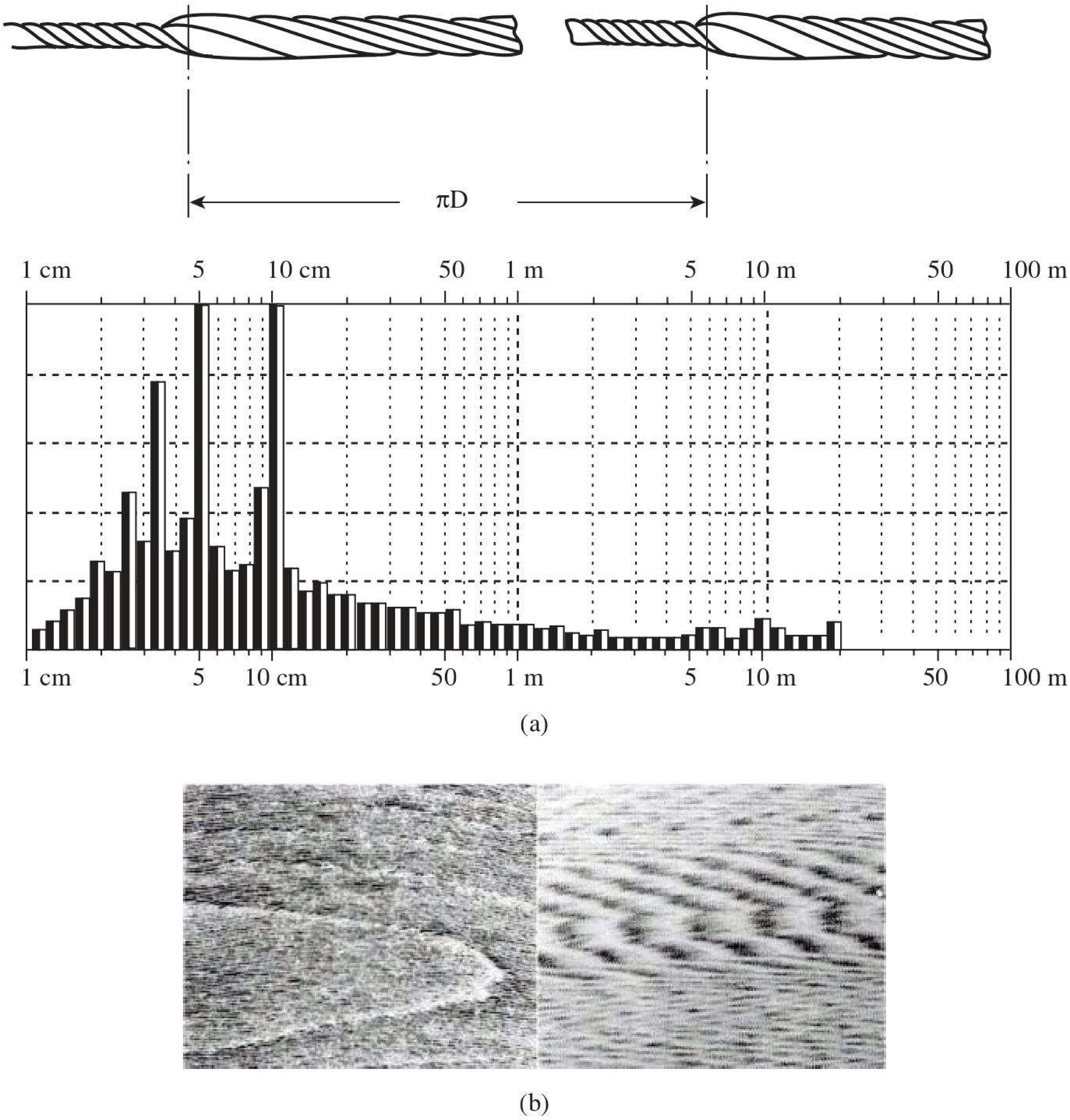


FIGURE 6.102 Effect of rotor deposits. (Courtesy of [a] Lord, P. R., *J. Text. Inst.*, 4, 1980 and [b] *Uster News Bulletin,* 34, February 1987.)

There are three kinds of irregularities that can arise from inadequate blending of, for example, two blend components.[173–82]

1. Irregularity due to an uneven arrangement of blend components in the cross section of the yarn
2. Irregularity caused by variations in the relative numbers of each blend component in the cross section of the yarn (related to the CV% of the short-term linear density of the yarn)
3. Very long-term irregularity

The first kind of irregularity is one in which the distribution of the blend components in the yarn cross section deviates from that referred to as the *perfect cross-sectional blend,* even though the number of each blend component matches the total blend proportions. The second concerns the deviations of blend proportions between yarn cross sections. This is the irregularity of blending along the yarn length. The final irregularity concerns the blend consistency from batch to batch and is just a matter of accurate weighing of the feed to the opening line.

6.2.3.4.4 The Ideal Blend

No process machine as yet can put together, say, black and white fibers in an orderly three-dimensional structure. The best that can be obtained is a random distribution of the single fibers of each component along the axis of a yarn. Apart from changes in the composition of the blend over a long period of time (long-term variation), blend irregularities are mainly concerned with separation of fiber groups of each component into individual fibers and the intermixing of them.

The intimacy of a blend may be obtained by determining, microscopically, the relative distribution of the blend components and the size of the aggregates of each component in representative samples of the yarn cross sections. Based on this approach, the ideal blend or most intimate blend would be one in which single fiber units are distributed at random throughout a yarn cross section.

There are various methods for quantifying the irregularity of a blended yarn.[173–182] One of the simplest and most practical, which will be described here, is that proposed by De Barr.[182] It is based on a general understanding of the widely practiced technique of blending the fiber components in drawing during material preparation (see Chapter 5).

Imagine white and black slivers having the same number of fibers randomly arranged in the sliver cross section. The fiber types are of the same dimensions and properties. The slivers are then mixed or blended together with a total number of N doubling. Assume the yarn is ring spun and is formed by ideal drafting of the sliver to a ribbon, which is then twisted. Consequently, the fibers in any cross section of the yarn are likely to be in black and white groups, the number of groups corresponding to the number of doublings. If a substantial length of the yarn were to be untwisted, the ribbon of fibers would be composed of a number of thinner sub-ribbons corresponding to the number of doublings N. This means that there is no lateral mixing. However, if the doubling, and thereby its associated drafting, is sufficient to reduce each group to a single fiber, the fibers in the cross section would give the appearance of lateral mixing, but the untwisted yarn would reveal a ribbon composed of sequential black and white parallel lines across the ribbon width, each line extending the ribbon length.

If a group of, let's say, white fibers is defined as a set of one or more adjacent white fibers with a black fiber at each side of the set, then if Q is the number of such groups in the yarn cross section and Q_p the average number of individual white fibers that should be in the cross section, the degree of blending may represented by

$$\gamma\% = \left[\frac{Q}{Q_p}\right]100 \tag{6.50}$$

Inadequate blending will give small values of $\gamma\%$, whereas very thorough blending will give values approaching 100%. Only if the fibers are randomly distributed in the cross section will $\gamma\% = 100$.

Q_p can be determined from calculating the number of fibers in the yarn cross section and from knowing the blend proportions. Q is measured from yarn cross sections. Thus, γ% can be used to determine the effect of various process parameters.

Figure 6.103 compares the effect of blend ratio and the number of doubling for 10-tex and 100-tex ring-spun yarn. It can be seen that, irrespective of the blend ratio, the fibers in the cross section approach, at a decreasing rate, the state of completely random distribution as the number of doublings increases. It is also evident that, with fewer fibers in the cross section (i.e., finer counts), fewer doublings are needed to achieve a satisfactory degree of blending. Independent of the blend ratio and yarn count, if the number of doublings exceeds the mean number of fibers in the yarn cross section, the degree of blend will be greater than 95% of an ideal cross-sectional mixing.

The above is applicable to all spinning methods employing roller-drafting systems. Spinning methods utilizing opening-roller drafting have the added benefit that the individual fiber separation facilitates lateral mixing, and the doubling action within rotor spinning is therefore effective in achieving a lower blend irregularity than the other spinning systems.

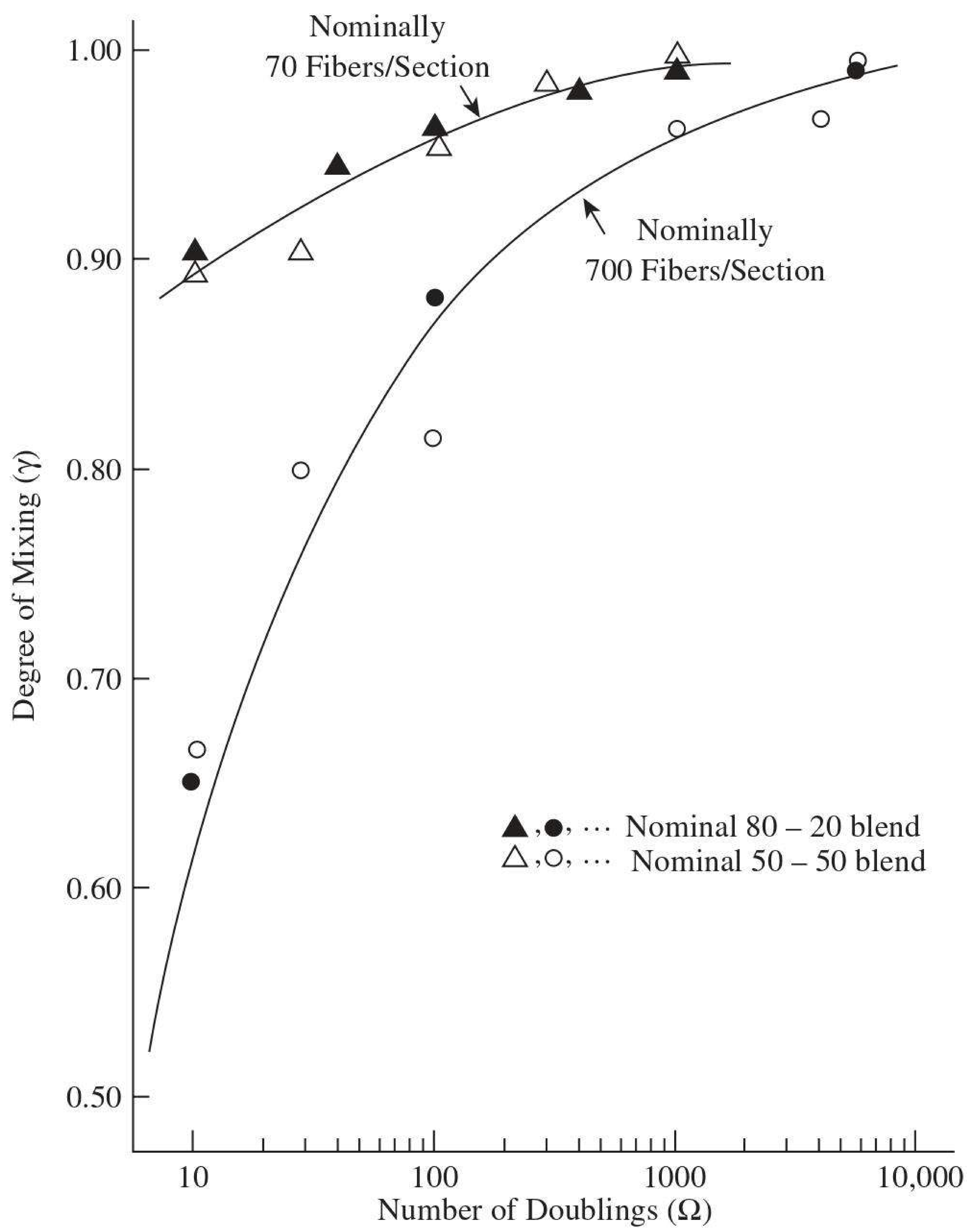


FIGURE 6.103 Relation between the degree of blending, blend ratio, yarn count, and the number of doublings.

With conventional ring-spun yarns, fiber migration can influence the blend intimacy in the yarn. Therefore, factors controlling migration are of importance to blend irregularity. Since tension variation between the component fibers is the principal cause of fiber migration, then significant differences in length or fineness between the blend components will result in the definite tendency for the longer or finer fibers to migrate to the core region of the yarn. This we can call *preferential migration.*

The width of the drafted strand can be used to control the tension differences. A compact strand reduces the tendency of fiber toward preferential migration. An increased width gives pronounced preferential migration, since there are fewer neighboring fibers to hinder migration. However, the level of preferential migration that takes place in a previously well blended feed to the ring frame, although affecting color shades, does not appreciably affect the yarn tensile properties.

For satisfactory blending of fibers that are to appear in different colors in the finished woven fabric, emphasis must be placed on *ideal cross-sectional mixing* because of the fiber arrangement along the yarn length. It is then necessary in such cases to blend before carding. The card intermixes the fibers so as to produce a blend of single fiber elements. With woolen spinning, blending has to be done prior to carding but, for the other processes, blending can be done in drawing. Where the appearance of the blend is not critical, e.g., hosiery or light shade wovens, two or three drawframe or gilling passages are used.

6.2.3.5 Hairiness Profile

There are various techniques for measuring yarn hairiness[183–188] with which the reader may wish to become familiar. However, from Figure 6.104, we can see that, by using a suitable optical arrangement, transmitted light may be employed to measure, per unit length of yarn, the number of fiber lengths projecting beyond set distances from the body of a yarn (e.g., 1 to 10 mm, in 1-mm increments), thereby gaining a useful indication of a yarn's hairiness profile.

In general, all other factors being equal, conventional short-staple ring-spun yarns will have the greatest number of hairs per unit length compared with other yarn structures. Looking at the other structures (Figures 6.36 and 6.41), it can be seen that compact ring-spun yarns, as a result of the very narrow spinning triangle, have the vast majority of surface fibers bound into the twisted structure. Rotor-spun, air-jet spun, and HS yarns have surface fibers or filaments wrapping the remaining fibers that form the bulk of the yarn, thereby restricting the number and the actual projected length of hairs. It is easily appreciated, then, that compact ring-spun, rotor-spun, and wrap-spun yarns have much lower hairiness values than conventional ring-spun yarns. The Dref-2 structure does not have wrapper fibers and, although the structure is highly twisted, the hairiness is comparable to conventional ring-spun yarn of similar coarseness of count. The surface structure of Dref-3 yarns (not shown) is similar in appearance to that of Dref-2.

Although the above is given as the general case, there are fiber and process variables that may be used to greatly alter the hairiness of these structures. For a given yarn count, the longer the fibers, the fewer the number per unit length of a

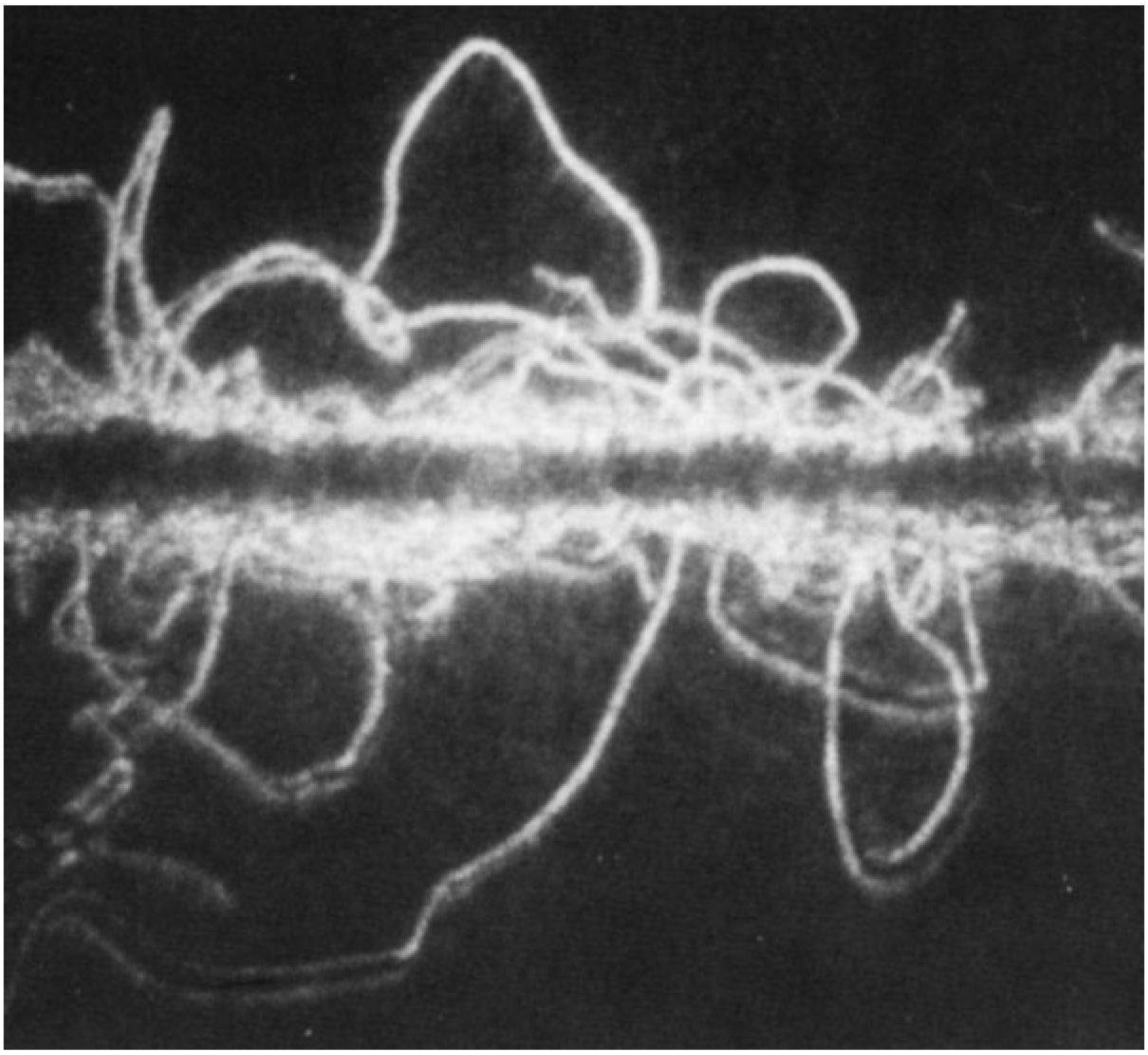


FIGURE 6.104 Yarn structure observed with transmitted light.

given yarn count, and this is reflected in the yarn hairiness. Consequently, the removing of short fibers by combing results in combed yarns being much less hairy than carded yarns of equivalent count. For a similar reason, worsted yarns are significantly less hairy than short-staple ring-spun yarns.

Based on the number of ends per unit length being an important factor, it might be expected that, for the same fiber length, finer fibers should give more hairy yarns. In fact, coarser fibers give the more hairy yarns. The torsional and flexural rigidities of a fiber are directly proportional to the square of the fiber fineness.[187] Therefore, coarser fibers, being more rigid, have a greater resistance to the binding action by the inserted twist, and the fiber ends readily project from the yarn.

The arrangement of the fibers in the material to be twisted also has a strong effect on yarn hairiness. In woolen slubbings, fiber lengths are hooked and disorderly, similar to the card web from which they are formed. Consequently, the resulting woolen ring-spun yarns are hairier than, say, the equivalent count semi-worsted yarn, where the fibers would have been given a much more orderly arrangement by gilling and apron drafting prior to being twisted to form the yarn.

For particular end uses, e.g., filtration cartridges, a yarn may be required to be hairy, but the hairiness may need to be reduced for most applications. In the case of conventional ring-spun cotton yarns, singeing, also referred to as *gassing,* can be employed. In this process, a flame or heated element is used to remove the unwanted projecting fiber lengths. The singed (or gassed) yarn has approximately a 10% reduction in hairiness. This order of reduction is relatively moderate; therefore, it is of interest to identify the spinning parameters, as well as the fiber properties, that influence yarn hairiness.

An important problem attributed to yarn hairiness is the tendency for yarns to shed fly (i.e., the propensity for fibers to be released from the yarn during post spinning processes, particularly in weft knitting.)[190] Much has been reported[188,191–194] on the effect of fiber properties and spinning variables on fly generation. Although reported results are mainly for studies involving conventional ring-spun yarns, they are applicable to the other yarn structures and therefore are of general interest.

Table 6.22 summarizes the findings by using what is termed the *mean logarithmic fly decrement,* FD,[195] calculated for each variable, to rank the order of importance of primary spinning variables. Negative values of FD indicate a reduction in the amount of fly for changes in a particular variable; the positive values refer to an increases in fly.

TABLE 6.22
Ranked Order of Fiber and Spinning Variables on Fly Generation

Variable of influence	FD
Mean fiber length	–0.36
Yarn twist	–0.29
Yarn linear density	+0.04
Yarn moisture content (cotton)	–0.03
Yarn tension	+0.03
Yarn coefficient of friction	+0.02

$$FD = \frac{[\log F_1 - \log F_o]/\log K}{[P_1 - P_o]/P}$$

where $F_1 - F_o$ = change in the amount of fly corresponding to the change fly from the minimum (P_o) to the maximum (P_1) value of a particular variable

K = constant = 1 g/kg for short-staple yarns[194]

P = mean value of fly for changes in the particular variable

The importance of increased fiber length was previously explained. Twist level is important, because fiber lengths become more tightly bound to the yarn. Most studies have concluded that increasing twist reduces yarn hairiness.[190] However, increased twist means reduced production speed and causes changes to other yarn properties, not all of which are desirable with respect to fabric properties. Since coarser count yarns contain more fiber ends per unit yarn length, it can be appreciated that hairiness and fly generation will increase with yarn count. The effect of the remaining variables concerns the locking of fibers within the yarn structure. For an explanation of this, we must first consider the ways by which fly is generated.

The fibers constituting fly may be pulled out from the yarn or fragments of the fiber length sheared from the yarn as the yarn runs at high speed (>100 m/min) over metal or ceramic guide surfaces of a machine. In the weft knitting of cotton yarns, rupture of hair lengths resulting from shear is a very significant factor, since up to 90% of the fly collected are shorter than 10 mm. With hydrophilic fiber, moisture results in fiber swelling, which in turn gives a higher frictional contact between fibers to resist pullout of that part of a fiber length caught within the yarn body. Increased mean fiber length and twist also contribute to increased interfiber frictional contact. Reduced surface friction reduces the pullout force and shear rupture of the projecting fiber lengths. A wax coating applied to the yarn surface (see Chapter 7) can reduce the yarn coefficient of friction by up to 44% and fly generation by 11%. Increased twist is also effective in reducing friction. As the yarn twist increases, the surface fibers, because of their helical orientation to the yarn axis, act as a series of ridges inclined at an increasing angle of steepness to the principal direction of movement of the yarn over the machine surfaces. The yarn is in effect supported by these ridges and hence has only a small area of contact with the machine surfaces. This reduces the friction forces acting at the interface of yarn and machine surfaces and, consequently, reduces fly generation. It can be reasoned from this that a surface structure that has wrapper fibers, as well as reducing yarn hairiness, should also be effective in preventing fiber pullout and shear fracture. An example of this is that, for the same count and twist level, rotor yarns tend to shed up to 20% less fly than ring-spun yarns. However, it should be noted that groove doffing tube navels significantly increase the hairiness of rotor yarns.[184]

6.2.3.6 Moisture Transport

An important factor in clothing comfort is the translocation of moisture caused by perspiration, as this prevents the sensation of *clamminess*.[196] The spontaneous movement of a liquid though a porous structure such as a yarn, by surface tension forces, is a phenomenon referred to as *wicking*, and it is generally interpreted as hydrodynamic flow through capillaries.[197–199]

To initiate wicking, it is important to have a wettable surface. When there is contact between water and any solid surface, an attraction between the two takes place. However, the difference between a wettable and nonwettable or hydrophobic surface is that the former causes water to spread over it in a continuous film whereas, with the latter, the water stands in a droplet covering only a small area of the surface (see Figure 6.105). With the droplet, there is a common boundary line between the liquid, solid, and surrounding air. From any point on this boundary line, the tangent to the curved surface of the liquid makes angle, θ, known as the *contact angle*. It has a specific value for different solid-liquid combinations. If the contact angle were to be $\theta = 0°$, the surface would be completely wetted. It would be nonwettable if

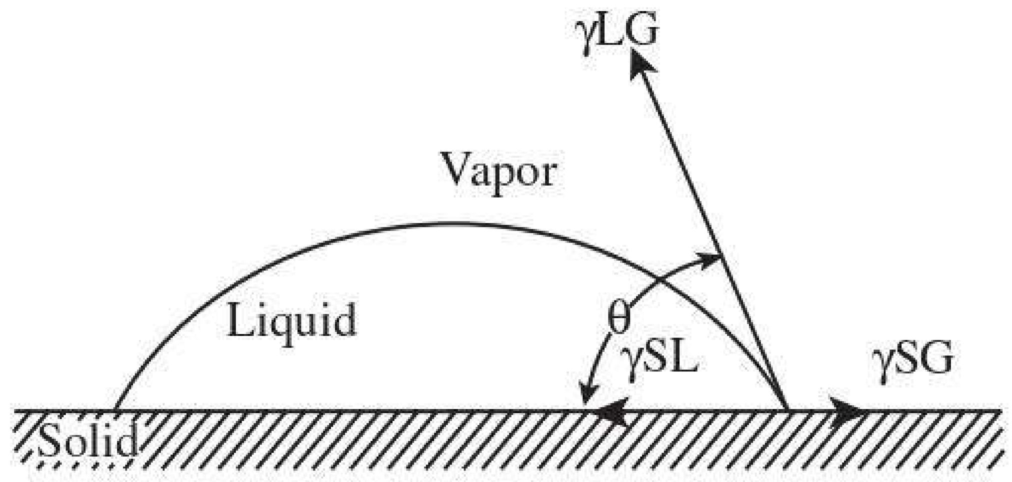


FIGURE 6.105 Interfacial forces at solid, liquid, gas boundaries.

$\theta = 180°$. With contact angles between $\theta = 0$ and $180°$ the surface will be partially wetted, with the degree of wettability decreasing as θ increases.

Wettability occurs when the attraction between solid and liquid is at least as great as the liquid-liquid attraction. In elementary physics, the surface free energy of the liquid (γ LG), the solid (γ SG), and the interfacial free energy (γ SL) are known to have the relationship defined by Young's equation,

$$\gamma\,SG - \gamma SL = \gamma\,LG \cos\theta \tag{6.51}$$

If the surface of the solid is textured, then a surface area factor, ξ, can be defined as

$$\xi = \frac{\text{Actual surface area}}{\text{Nominal surface area}}$$

With the textured surface, there will be an apparent contact, φ, so that

$$\xi(\gamma\,SG - \gamma\,SL) = \gamma\,LG \cos\varphi \tag{6.52}$$

and

$$\cos\varphi = \xi\cos\theta \tag{6.53}$$

Thus, the texture of the surface has increased the contact angle. The textured surface of a yarn will be its hairiness. Assuming that the surface of the fibers constituting the yarn are not treated to be hydrophobic, then, for a liquid to enter the yarn structure spontaneously, the apparent contact angle, φ, of the yarn must be less than 90°.

From the laws of hydrodynamic flow through capillaries formed by fibers of a yarn structure, it can be shown that[197,198]

$$S^2 = \gamma\,\cos\varphi\; r_e\,\frac{t}{2\eta} = kt \tag{6.54}$$

where S = advanced by the liquid
γ = liquid surface tension
η = liquid viscosity
t = time
r_e = the effective capillary radius
k = wicking rate

From our early consideration of yarn structure, it is evident that filament yarns would have low ξ factors. At the other end of the scale, conventional ring-spun yarns have higher ξ with respect to yarn hairiness. As a result, a rotor yarn (which has a dense core, an open outer area, and the wrapper fibers surface structure) wets and wicks more quickly than a conventional ring-spun yarn. Twist and fiber crimp, however, play an important part in the wicking mechanism. Table 6.23 shows apparent angles for a range of fibers and their corresponding ring-spun yarns. All fibers have contact angles of <90°; however, wool yarn, because of the level of crimp, has a fairly hairy surface and discontinuities in the interfiber capillary channels, resulting in an apparent contact angle of >90° for the yarn. Figure 6.106 shows effect of twist on wicking rate for 100% nylon, 70% wool/30% nylon, and 100% wool ring-spun yarns. The curves demonstrate again the effect of the capillary discontinuity caused by the wool fiber crimp giving low wicking rates.

TABLE 6.23
Comparison of Fiber and Yarn Contact Angles

Material	Form	Apparent contact angle, θ°
Polyethylene	Fiber	86
	Yarn	25
Nylon	Fiber	83
	Yarn	55
Wool	Fiber	85
	Yarn	108
Cotton	Fiber	33
	Yarn	33

Courtesy of Booth, J. E., *Principles of Textile Testing*, Heywood-Temple Press Books, Ltd., l964, 444–450.

The trend of the curves is for the wicking rates to increase with increasing twist, reaching a maximum before declining with further twist. There is a critical interfiber spacing (approximately 0.1 to 0.2 times the fiber diameter) below which the capillary forces will cause liquid to flow along an interfiber channel. At low twist levels, and therefore lower packing densities, the distribution of the interfiber distances will contain a small percentage below the critical value. This number increases with twist until twist choking of the capillaries occurs to reduce the liquid transport rate.

Moisture migration in fabric is dependent on several mechanisms, in particular the holding capacity of a fabric and speed of liquid transport through the fabric structure. For many applications, the former factor is given prominence, since it is mostly required that the liquid be distributed over as wide as possible an area of the fabric. However, in the early stages, it is the latter that dominates, and this is largely dependent on yarn structure.

6.2.3.7 Friction

Yarn friction is an important property with respect to the running behavior of a yarn in post-spinning processes and in the effect of yarn surface structure on fabric properties. It was explained earlier that yarn friction influences the mechanical properties of fabrics through the factor of fabric assistance.[200] The surface friction is also related to the tactile character of a fabric.[201] From both perspectives, rotor-spun yarns and air-jet yarns give a crisp fabric handle as compared with the other

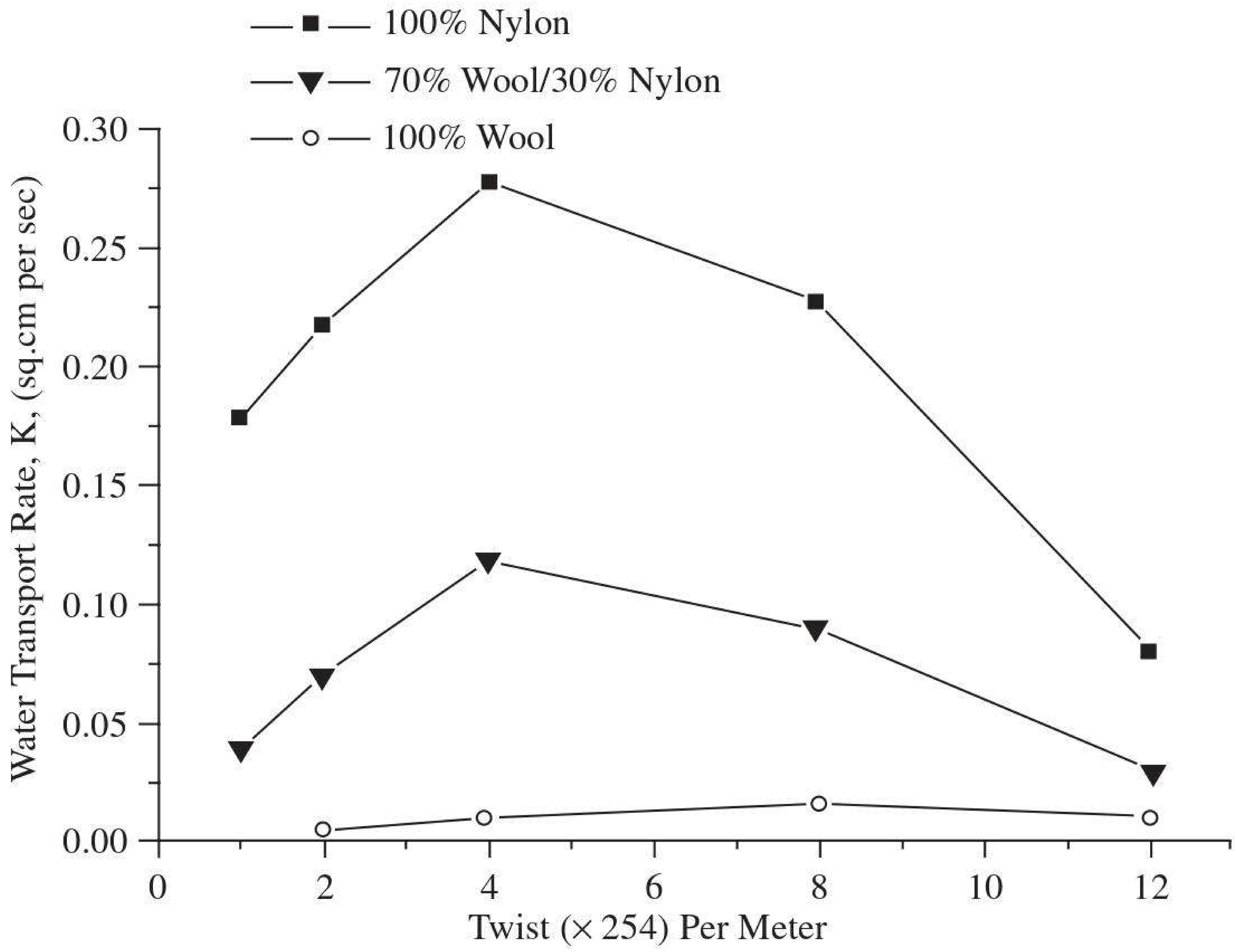


FIGURE 6.106 Effect of twist on wicking rate of yarns.

structures. This comparison does not include the Dref-2 yarn, as it is rarely used for general garments.

With respect to the performance of a running threadline, the static and kinetic yarn frictions are usually measured for a particular reference surface — often ceramic or steel.[202]

Figure 6.107 shows the general pattern observed in friction/yarn speed plots for ring and rotor-spun yarns produced from the same cotton and of similar counts.

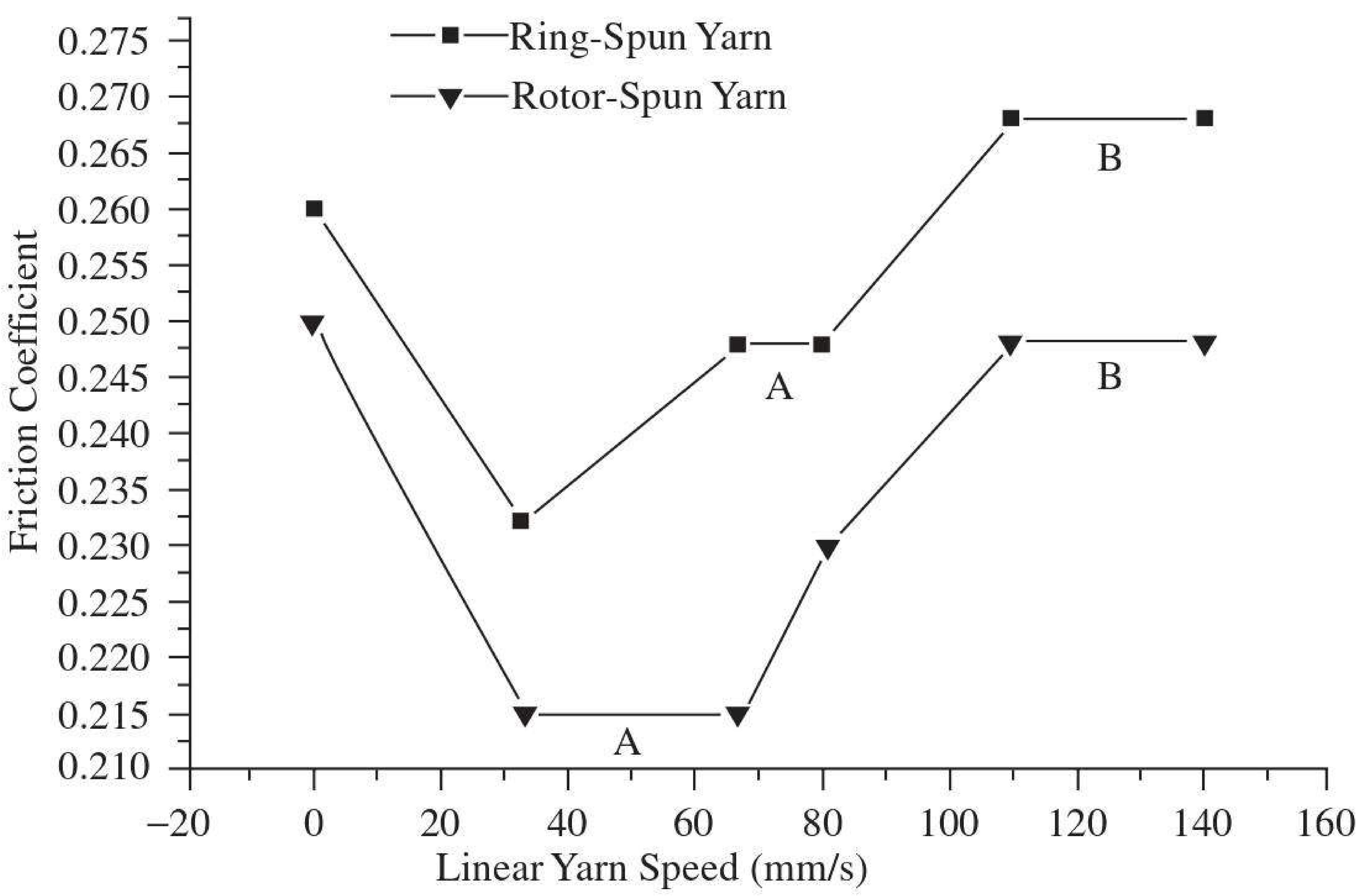


FIGURE 6.107 Friction profile of ring- and rotor-spun yarns.

Initially, as the thread line speed increases, the friction decreases because the protruding yarn hairs prevent full contact between yarn and metal surface. With ring-spun yarns, stick slip is observed at low speed. The first flat region, A, of the curve, seen as the speed increases, is caused by the resilience of longer surface hairs. Rotor yarns are less hairy, but the wrapper fibers prevent the yarn from flattening and spreading, and they more effectively separate the body of the yarn from full contact with the metal surface. The curve for the rotor yarn is therefore much lower, irrespective of speed.

At higher speeds, shear forces bend the hairs down, increasing the area of contact and thereby the friction. At still higher speeds, the shorter hairs come into effect, giving the second flat region, B.

The friction values of the curves will increase with linear density because of the increased area of contact, initially because of the increased number of hairs and subsequently owing to the actual contact area of the yarn. Spun-yarn/metal friction values will depend on yarn lubrication. As would be expected, waxing reduces friction, but only for low speeds. The friction pattern changes in that there is no initial decrease with speed; instead, the second phase of the curve occurs, starting at a lower friction value and increasing with speed, reaching a friction value equal to that of a nonwaxed yarn. Different types of lubricant give different initial friction values but similar trends.

6.3 QUALITY CRITERIA

The quality criteria of a spun yarn are the specified properties of the yarn that indicate its ability to be efficiently converted into, say, a woven or knitted fabric. They enable the resulting finished cloth to be imparted with the visual and tactile aesthetics required by the customer, i.e., *customer acceptability.* This means that there two aspects to yarn quality requirements: post-process performance and fabric quality.

6.3.1 Post-Process Performance Criteria

6.3.1.1 Knitting

A yarn's *knittability* first depends on how well it unwinds from the yarn package (see Chapter 7) and second on its frictional properties (i.e., yarn-yarn friction and yarn metal friction with regard to the knitting needles and generation of fly). For knitting yarns, a strength of approximately 10 cN/tex and as high as possible a breaking extension are normally required.[123] These factors, along with the bending and elastic moduli, affect the yarn tension during knitting. When a yarn contacts the needle, it takes up a large curvature. The bending moment is therefore of importance.

6.3.1.2 Weaving

In weaving preparation, beaming machines operate at high draw-off speeds of more than 1000 m/min. The end breaks in beaming are often used as an indication of yarn quality. With cotton yarns, for instance, end breaks greater than one per million meters of running yarn are viewed as indicating a poor-quality yarn. The tensile strength (cN/tex), variation in strength [CV% (strength)], the breaking strain (ε%) are the important properties in weaving; less strength is required for weft (9 to 12 cN/tex) than for warp (12 to 16cN/tex), and the minimum extension should be around 6.5 to 8.0%.

The weaving performance of a yarn is judged in terms of weaving costs, particularly as a result of downtime. On average, 20 to 30% of stoppages in cotton weaving result from yarn breaks, 30 to 40% are due to faults during warping sizing, and 30 to 40% are loom related.[202] With short-staple yarns, the processing behavior of the sized warp yarns is critically dependent on the properties of the sizing agent and the degree of sizing. However, the yarn structure is also a key factor, and loom types have specific requirements regarding the characteristic profile of warp yarns.

Over the years, weaving rates (picks per minute or meters per minute) have significantly increased with continuous improvement in shuttle-less looms. The efficiency in weaving is now highly dependent on downtimes for beam changes and tying in new warps, repair time delays, and, importantly, downtimes caused by short stops caused by warp or weft breaks. The short stops constitute a very important quality factor since, in many instances, greater than two per 100 km of yarn would be seen as below average.

The number of warp stoppages is highly dependent on the abrasion resistance of the warp yarn and a low level of hairiness, since hairs can cause adjacent yarns in a warp to cling together (snag) and hinder the passage of the weft yarn through the shed. Warps for air-jet looms generally need to have high abrasion resistance. A low degree of hairiness is particularly important in air-jet weaving. For projectile and rapier looms, warp yarns are subject to less abrasion during weaving, but the important requirement is a reduced snagging tendency (i.e., a low force needed to separate the threads during shedding). In rapier looms, hairy weft yarns can prevent the efficient transfer of a yarn between grippers. Generally, ring-spun yarns have higher snagging tendency and lower abrasion than rotor yarns.

There is a direct relationship between yarn tension during weaving and weft insertion rates. Hence, for weft insertion rates above 1200 m/min, the CV% of yarn strength is an important quality factor. Particularly important for a weaving yarn is the number of "weak places." These are the short lengths usually identified by the Uster Classimat system and are of the order of 50 cm with breaking strengths less than 30% of the mean yarn strength. When these weak places are placed under peak tension in the warp or weft, they break.

6.3.1.3 Fabric Quality

The count variation or $CV\%_{100m}$ affects fabric appearance. For woven fabric, depending on weave structure, variations in count within and between weft packages can cause stripiness that is discernible to the human eye. With knitted fabrics, the quality characteristics that are particularly important in the evaluation of yarns are elongation at break, Classimat values, and the Uster CV. As seen in Figure 6.95, a high Uster CV% will give knitted fabrics a patchy appearance.

The ideal yarn has been defined as "being the one that is spun from the finest fiber with the least twist, the fullest volume, the best evenness, and the most consistent strength."[203] Although the perfect yarn will always be the quest of textile technologists, agreements have to be reached between the yarn manufacturer and customer on quality criteria, and these are best based on "as good as necessary" quality specifications rather than "as good as possible." Whatever the agreed specifications, the yarn manufacturer has to take steps to ensure that every wound package delivered to the customer conforms to the specified requirements, i.e., quality must be assured.

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