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# 1 Fundamentals of Yarns and Yarn Production

## 1.1 EARLY HISTORY AND DEVELOPMENTS

Although it has yet to be discovered precisely when man first began spinning fibers into yarns, there is much archaeological evidence to show that the skill was well practiced at least 8000 years ago. Certainly, the weaving of spun yarns was developed around 6000 B.C., when Neolithic man began to settle in permanent dwellings and to farm and domesticate animals. Both skills are known to predate pottery, which is traceable to circa 5000 B.C.

Man's cultural history goes back about 10,000 to 12,000 years, when some tribes changed from being nomadic forager-hunters, who followed the natural migration of wild herds, to early farmers, domesticating animals and cultivating plants. It is very likely that wool was one of the first fibers to be spun, since archaeologists believe that sheep existed before *Homo sapiens* evolved. Sheep have been dated back to the early Pleistocene period, around 1 million years ago. The Scotch black-face and the Navajo sheep are present breeds thought to most closely resemble the primitive types. Domesticated sheep and goats date from circa 9000 B.C., grazing the uplands of north Iraq at Zam Chem Shanidar; from circa 7000 B.C., at Jarmo, in the Zagros Mountains of northwest Iran; and in Palestine and south Turkey from the seventh and sixth millennia B.C. Sheep were also kept at Bougras, in Syria, from circa 6000 B.C.

We can speculate that early man would have twisted a few fibers from a lock of wool into short lengths of yarn and then tied them together to make longer lengths. We call these staple-spun yarns, because the fibers used are generally referred to as staple fibers. Probably the yarn production would have been done by two people working together, one cleaning and spinning the wool, the other winding the yarn into a ball. As the various textile skills developed, the impetus for spinning continuous knotless lengths would have led to a stick being used, maybe first for winding up the yarn and then to twist and wind up longer lengths, thereby replacing the making of short lengths tied together and needing only one operative. This method of spinning a yarn using a dangling spindle or whorl was widely practiced for processing both animal and plant fibers. Seeds of domesticated flax (*Linum usitatissimum*) and spindle

whorls dating back to circa 6000 B.C. were found at Ramad, northern Syria, and also in Samarran villages (Tel-es Swan and Choga Mami) in north Iraq (dated circa 5000 B.C.). In Egypt, at Neolithic Kom, in Fayum, stone and pottery whorls of about 6000 B.C. have been discovered, while at the predynastic sites of Omari, near Cairo, and Abydos, both circa 5500 B.C., flax seeds, whorls, bone needles, cloth, and matting have been found.

Flax was probably the most common ancient plant fiber made into yarns, though hemp was also used. Although flax thread is mentioned in the Biblical records of Genesis and Exodus, its antiquity is even more ancient than the Bible. A burial couch found at Gorigion in ancient Phrygia and dated to be late eighth century B.C. contained twenty layers of linen and wool cloth, and fragments of hemp and mohair. Cotton, native to India, was utilized about 5000 years ago. Remnants of cotton fabric and string dating back to 3000 B.C. were found at archaeological sites in Indus in Sind (India). Many of these fibers were spun into yarns much finer than today's modern machinery can produce. Egyptian mummy cloth was discovered that had 540 threads per inch in the width of the cloth. Fine-spun yarns, plied threads, and plain-weave tabby cloths and dyed garments, some showing darns, were also found in the Neolithic village of Catal Huyuk in southern Turkey.

The simple spindle continued as the only method of making yarns until around A.D. 1300, when the first spinning wheel was invented and was developed in Europe into "the great wheel" or "one-thread wheel." The actual mechanization of spinning took place over the period 1738 to 1825 to meet the major rise in the demand for spun yarn resulting from the then-spectacular increase in weaving production rates with the invention of the flying shuttle (John Kay, 1733). Pairs of rollers were introduced to thin the fiber mass into a ribbon for twisting (Lewis Paul, 1738); spindles were grouped together to be operated by a single power source—the "water frame" (Richard Arkwright, 1769), the "spinning jenny" (James Hargreaves, 1764–1770) and the "mule" (Samuel Crompton) followed by the "self-acting mule" by Roberts (1825). In 1830, a new method of inserting twist, known as *cap spinning*, was invented in the U.S. by Danforth. In the early 1960s, this was superseded by the ring and traveler, or *ring spinning*, which, despite other subsequent later inventions, has remained the main commercial method and is now an almost fully automated process.

Today, yarn production is a highly advanced technology that facilitates the engineering of different yarn structures having specific properties for particular applications. End uses include not only garments for everyday use and household textiles and carpets but also sports clothing and fabrics for automotive interiors, aerospace, and medical and healthcare applications. A detailed understanding of how fiber properties and machine variables are employed to obtain yarn structures of appropriate properties is, therefore, an important objective in the study of spinning technology. In this chapter, we shall consider the basics for developing an understanding of the process details described in the remaining chapters.

## 1.2 YARN CLASSIFICATION AND STRUCTURE

A good start to our study of staple-yarn manufacture is to consider the question, "What is a staple-spun yarn?"

There are three ways of constructing an answer to this question:

- To present a classification of yarns
- To look at the importance of yarns in fabrics
- To analyze various yarn structures and identify their most common features

### 1.2.1 CLASSIFICATION OF YARNS

Table 1.1 shows that yarns may be classified into four main groups: continuous filament, staple spun, composite, and plied yarns.

**TABLE 1.1**  
**Yarn Classification**

<b>Group</b>	<b>Sub-group</b>	<b>Examples</b>	
Continuous filament yarns	Untextured (flat)	Twisted Interlaced Tape	
	Textured	False twisted Stuffer box crimped Bi-component Air-jet	
Staple spun yarns	Noneffect/plain (conventional)	Carded ring spun Combed ring spun Worsted Semi-worsted Woolen	
		Noneffect/plain (unconventional)	Rotor spun Compact-ring spun Air-jet spun Friction spun Hollow-spindle wrap spun Repco
		Fiber blend	Blend of two or more fiber types comprising noneffect yarns
	Effect/fancy	Fancy twisted Hollow-spindle fancy yarn Spun effects	
Composite yarns	Filament core Staple core	Core spun (filament or staple fibers forming the core) and staple fibers as the sheath of a noneffect staple yarn	
Folded/plied/doubled	Filament staple	Two or more yarns twisted together	

These groups may be further subdivided, with the final column giving the commonly used names for particular yarns, and are based largely on the method or technique used to produce the yarn. Generally, a particular technique produces a yarn structure that differs from those of other techniques.

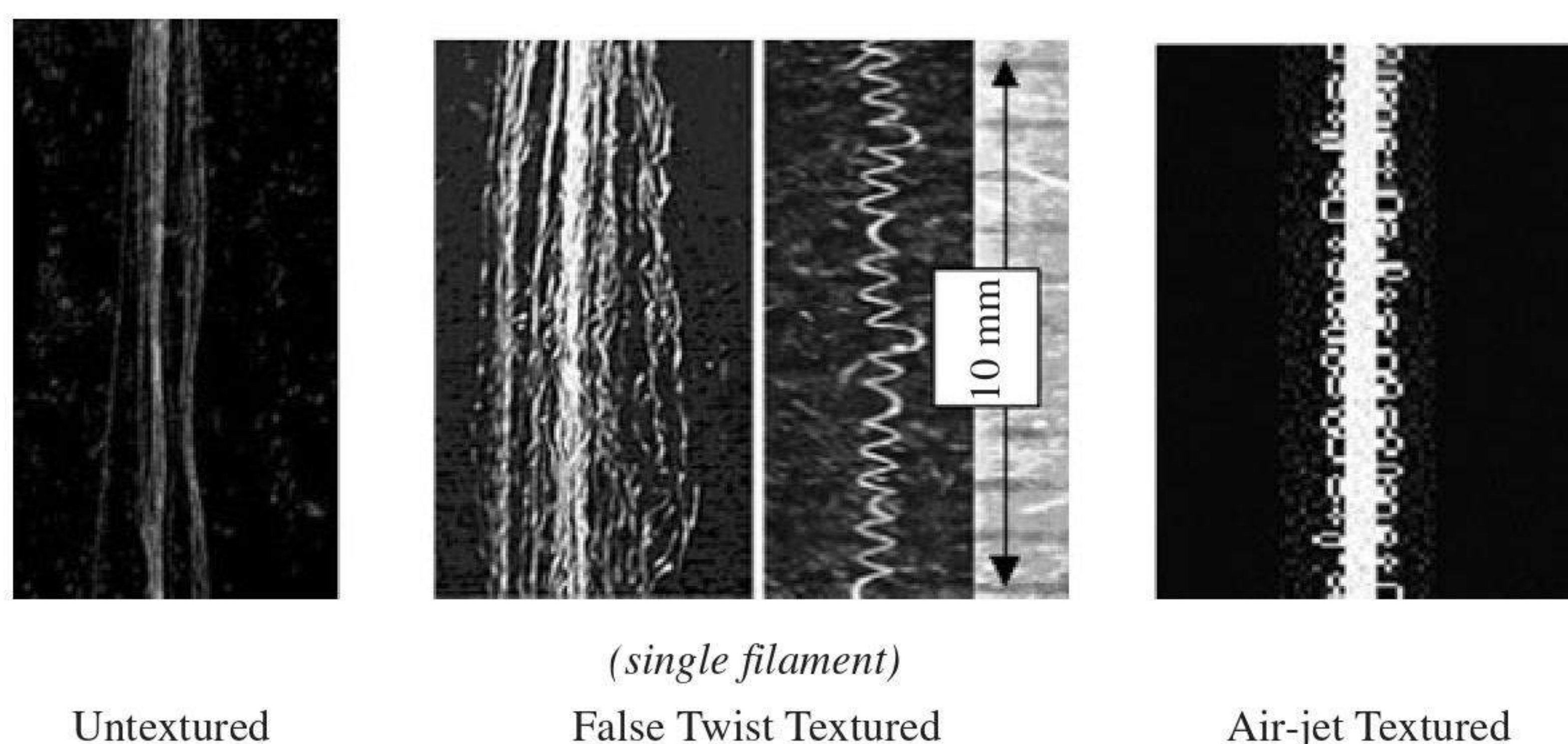
Continuous filament (CF) yarns are basically unbroken lengths of filaments, which include natural silk and filaments extruded from synthetic polymers (e.g., polyester, nylon, polypropylene, acrylics) and from modified natural polymers (e.g., viscose rayon). Such filaments are twisted or entangled to produce a CF yarn.

CF yarns can be subdivided into untextured (i.e., flat) and textured yarns. As [Table 1.1](#) shows, CF textured yarns may be further separated into several types; the more commonly used are false-twist textured and air-jet textured yarns. For the former, extruded filaments are stretched, then simultaneously heated, twisted, and untwisted, and subsequently cooled to give each filament constituting the yarn a crimped shape and thereby a greater volume or bulk to the yarn (see [Figure 1.1](#)). Alternatively, groups of filaments forming the yarn can be fed at different speeds into a compressed-air stream (i.e., an air-jet), producing a profusion of entangled loops at the surface and along the yarn length. These processes are known as texturing or texturizing<sup>1,2</sup> and form an area of technology that is outside the context of this book, so they will not be given further consideration. The actual principle of false-twisting is used in other processes and is explained in a later section.

Continuous filaments can be chopped into discrete lengths, comparable to the lengths of natural plant and animal fibers. Both manufactured fibers and natural fibers can be assembled and twisted together to form staple-spun yarns. [Table 1.1](#) shows that this category of yarn can be subdivided into plain and fancy yarns. In terms of the quantity used, plain yarns are of more technological importance, and the chart indicates the wide range of differing types (i.e., structures) of plain yarn, and thus spinning techniques used to produce them. In the later chapters, we shall consider the production of both plain and fancy yarns. For the moment, we will confine our attention to plain yarns.

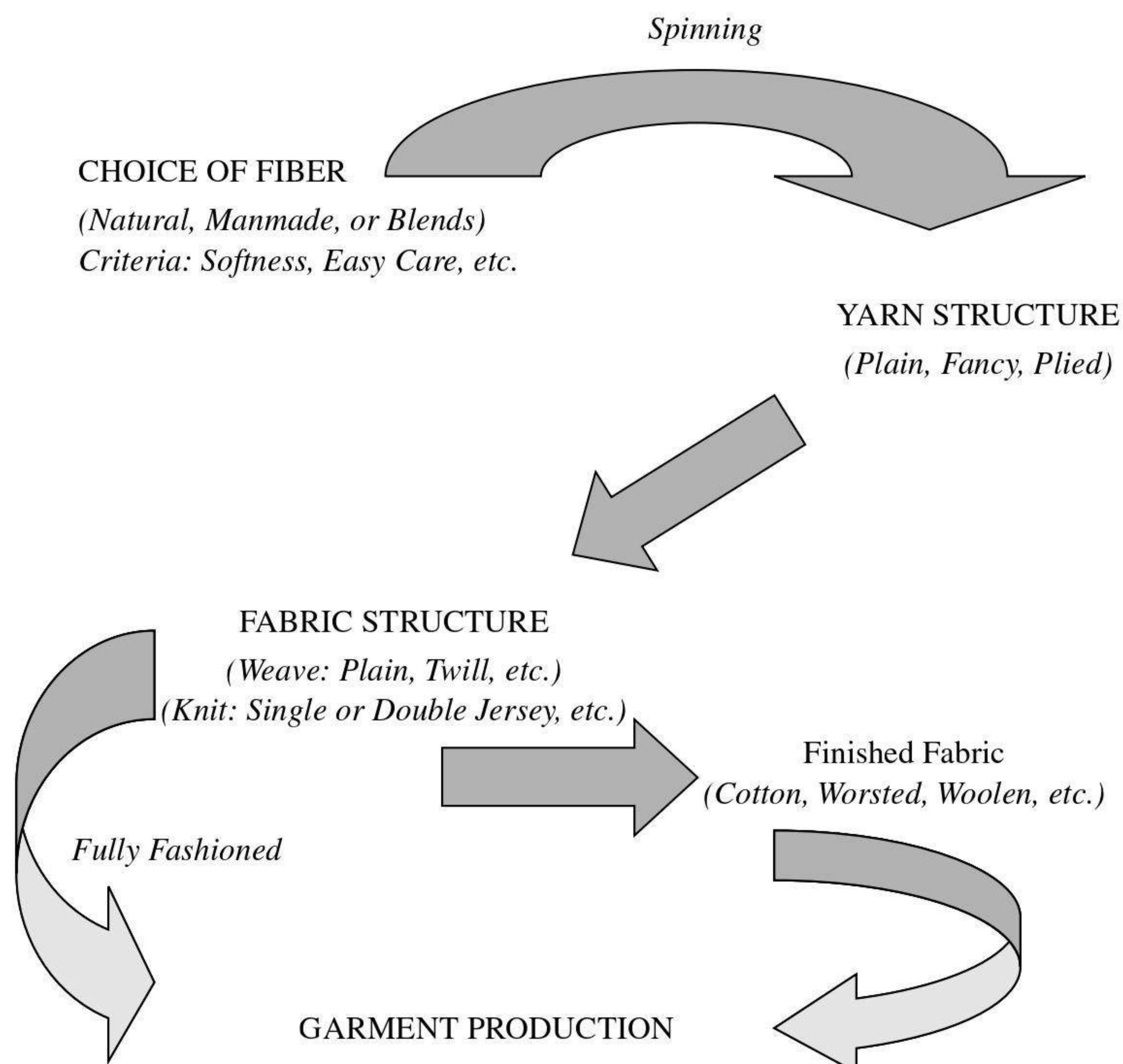
### 1.2.2 THE IMPORTANCE OF YARNS IN FABRICS

Textile fabrics cover a vast range of consumer and industrial products made from natural and synthetic fibers. [Figure 1.2](#) illustrates that, to produce a fabric for a particular end use, the fiber type has first to be chosen and then spun into a yarn



**FIGURE 1.1** Continuous filament yarns.

## BASIC SEQUENCE TO GARMENTS



**FIGURE 1.2** Production chain.

structure of specified properties so that the subsequent woven or knitted structure give the desired fabric aesthetics and/or technical performance.

Textile fabrics are also made by means other than knitting and weaving, which may just involve bonding fibers or filaments together without the need of converting them into yarns. Although such *nonwoven fabrics* are an important area of textile manufacturing, especially for technical and industrial end uses, they have limited application in the consumer sector. It is reasonable, then, to say that, second only to fibers from which yarns are made, yarns are the basic building blocks of most textile fabrics. Many required fabric properties will, in addition to the fiber properties and the fabric structure, depend on the structure and properties of the constituent yarns. Therefore, in the study of yarn manufacture, we need to determine not only how yarns are made but also how to get the required properties for particular end uses. To achieve these two goals, we must first establish the factors that characterize a yarn.

### 1.2.3 A SIMPLE ANALYSIS OF YARN STRUCTURE

In [Chapter 6](#), we will consider in detail the various yarn structures. Here, a simple analysis is given so as to answer our question, “What is a staple-spun yarn?”

Figure 1.3 shows highly magnified photographic images of a twisted filament yarn structure and a typical staple-spun yarn structure (ring-spun yarn).

The following three characteristics are evident:

1. A linear assembly of fibers. The assembly could be of any thickness
2. The fibers are held together by twist. However, other means may be used to achieve cohesion
3. There is a tendency for fibers to lie in parallel along the twist spiral.

From these three characteristics, we can now answer the question, “What is a staple-spun yarn?” with the following definition:

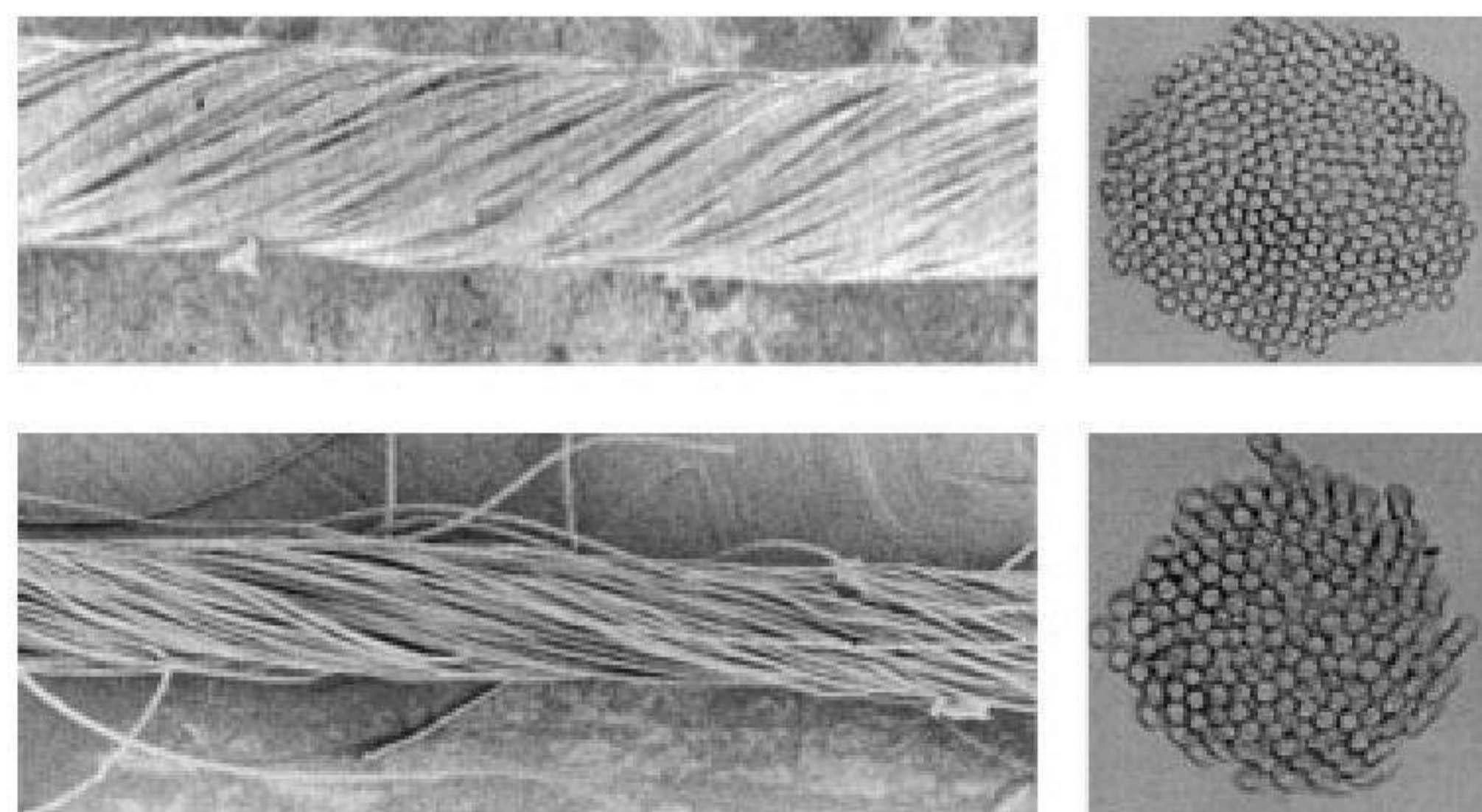
*A staple-spun yarn is a linear assembly of fibers, held together, usually by the insertion of twist, to form a continuous strand, small in cross section but of any specified length; it is used for interlacing in processes such as knitting, weaving, and sewing.*

The reader should note that there are several other definitions,<sup>3,4</sup> but these are more general, covering filament as well as staple-spun yarns.

### 1.2.3.1 The Simple Helix Model

Based on the three common characteristics, a simplified model can be constructed to represent yarns in which filaments or fibers are held together by twist, i.e., twisted yarns. [Table 1.2](#) lists the assumptions that are made to construct the model.

The manner in which fibers are packed together in the yarn cross section is important to the effect of frictional contact between fibers on yarn properties. If fibers are loosely packed so that they can move about in the interstitial space, the yarn will appear bulkier and with a larger diameter than if fibers are closely packed. Two types of packing have therefore been proposed:<sup>5</sup> *close packing*, which gives a hexagonal arrangement of the fibers in the yarn cross section, and *open packing*, where the fibers are considered to be arranged in concentric circles of increasing radii. The basic helix model assumes an open packing configuration. [Figure 1.4](#) depicts the geometry of the model, and the equations in [Table 1.2](#) give the relations between the model parameters.



**FIGURE 1.3** Scanning electron micrograph of continuous filament and ring spun yarn structure: polyester continuous filament yarn (above) and ring spun yarn (below).

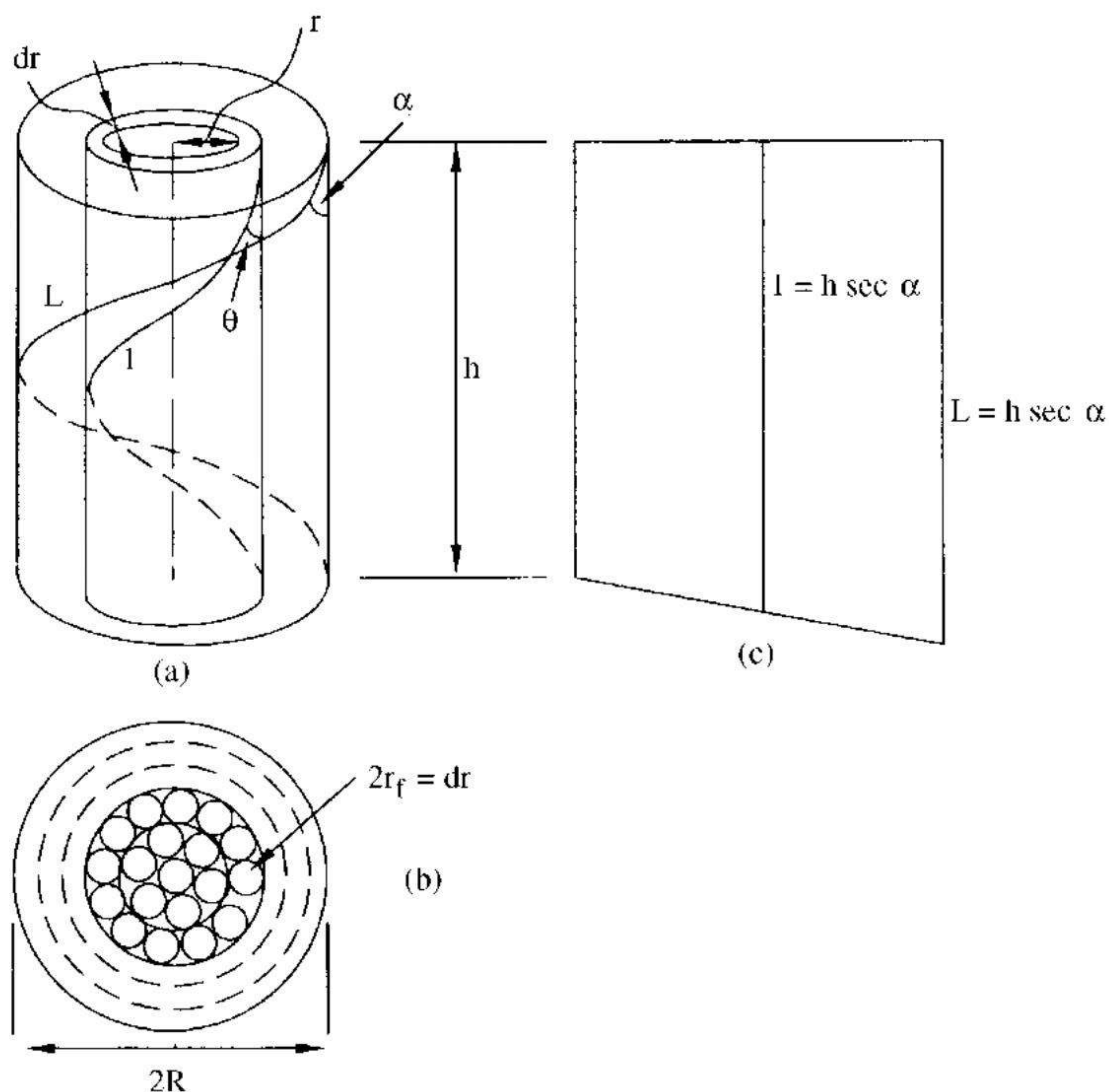
**TABLE 1.2**

**Assumptions and Geometrical Relations for Helix Yarn Model**

Assumptions for helical structure with open packing of constituent fibers	Geometrical equations defining the helix model
• Yarn composed of a large number of fibers	$h = t^{-1}$ (1.1)
• The yarn structure consists of a central fiber lying straight along the yarn axis and surrounded by successive, concentric cylindrical layers of fibers of increasing radii.	$I^2 = h^2 + 4\pi r^2$ (1.2)
• The fibers in each layer are helically twisted around preceding layers.	$L^2 = h^2 + 4\pi R^2$ (1.3)
• The helix angle of twist gradually increases with radius from 0deg. for the central fiber to $\alpha$ for the surface fibers.	$\tan \theta = \frac{2\pi r}{h}$ (1.4)
• All fibers in a given layer have the same helix angle of twist	$\tan \alpha = \frac{2\pi R}{h}$ (1.5)
• By convention the yarn twist angle is $\alpha$	$R = (2n - 1)r_f$ (1.6)
• The turns per unit length is constant throughout yarn	$m = \frac{180}{\sin^{-1}\left[\frac{1}{2(n-1)}\right]}$ (1.7)
• The fiber packing density is constant throughout the yarn	
• A 90-degree cross section to the yarn axis shows the yarn and fibers to be circular and the fiber cross sections lying in filled concentric circular layers.	where $n = nth$ fiber layer, $m =$ the number of fibers in the $nth$ layer, and the remaining parameters are defined by Fig. 1.4

We must consider several important limitations to the basic model.

- Many fibers do not have circular cross sections. Furthermore, when fibers of circular cross sections are inclined at a helix angle of twist, they appear elliptical in the yarn cross section 90° to the yarn axis. Thus, only the circular fiber on the yarn axis strictly meets this assumption. Nevertheless, fiber diameters are sufficiently small, and generally tend sufficiently toward circular, for the model to remain useful.
- In the yarn cross section, the concentric circular layers are filled with fibers in contact with each other. Therefore, if there are  $N$  layers comprising the yarn, then the arithmetic sum of the number,  $m$ , of fibers in each layer should equal the total amount of fibers in the yarn cross section. This, however, is not always so, and the outer layer then becomes partially filled. The result is that the yarn radius,  $R$ , is ill defined. In practice, there are many fibers in the cross sections of yarns and correspondingly many circular layers, each only the thickness of one fiber — a few microns in diameter. Thus, a partially filled outer layer may not give too great an error.
- The model does not take into account the projection of fiber ends from the yarn surface (termed yarn *hairiness*) or the relative positions of fiber ends within the body of a spun yarn. The projection of fiber ends from the yarn surface suggests that fiber lengths must move across layers for their ends to become hairs. Fibers at the yarn surface must have part of their lengths within the body of the yarn; otherwise, the yarn would not



**FIGURE 1.4** Simple helix model of a yarn with open packing fiber arrangement.

hold together. The fibers of a yarn are therefore interlaced. The interlacing of fibers is called *migration* and is further described in [Chapter 6](#). Migration enables the frictional contact between fibers to resist fiber ends slipping past each other. When compared with [Figure 1.3](#), the model is clearly more appropriate for continuous filament yarns. It can be assumed, however, that, under applied axial loads, where overlapping fiber ends have sufficient frictional contact because of migration and twist, such sections of a staple yarn will approximate the behavior of a continuous filament yarn, and, where insufficient, the ends will slip past each other. Hence, by introducing the idea of slippage of overlapping fiber ends, the model can be used to interpret the effect on yarn properties of important geometrical parameters such as twist.

## 1.3 YARN COUNT SYSTEMS

### 1.3.1 DIMENSIONS OF A YARN

Let us now consider in more detail the three common characteristics deduced from [Figure 1.4](#). First, the idea of a linear assembly of fibers raises the question of how



the dimensions of yarns are expressed. In specifying the thickness of a yarn, we could refer to its diameter or radius as in the above model. This, however, is not a straightforward parameter to measure. Clearly, we would need to assume that the yarn is circular. Then, if it were to be measured on a linear scale, we can see from [Figure 1.3](#) that consideration must be given to whether yarn hairiness is included in the measurement.

Straightening the yarn length to measure the diameter involves tensioning the yarn, which also narrows the cross section by bringing fibers into closer contact and increasing the packing density. Although there are test methods<sup>6</sup> for yarn diameter measurements that attempt to circumvent these difficulties, they are not appropriate for use in the commercial production of yarns. Also, in spinning yarns, there is no direct relationship between spinning variables and yarn diameter, so it is not the practice to set up a spinning machine to produce a specified yarn diameter. A more useful and practical measure that indirectly gives an indication of yarn thickness is a parameter that is termed the *yarn count* or *yarn number*.

The yarn count is a number giving a measure of the yarn linear density. The linear density is defined as the mass per unit length. In *Système International (SI)* units, the mass is in grams, and the unit length is meters. In textiles, a longer length is used for greater meaningful measurements, since this would average the small, random, mass variations along the length that are characteristic of spun yarns. There are two systems by which the count is expressed, as described below.

- *Direct system.* This expresses the count as the mass of a standard length. The mass is measured in grams, and the specific length is either 1 km or 9 km.
- *Indirect system.* This gives the length that weighs a standard mass. The standard mass is either 1 kg or 1 lb, and the associated length is, respectively, in meters or yards.

Usually, thousands of meters of a yarn are required to weigh 1 kg and, similarly, thousands of yards to weigh 1 lb. This makes measurements and calculations cumbersome. To circumvent any such awkwardness, a standard length is used. The standard length can be 1 km, 840 yd, 560 yd, or 250 yd. The standard lengths in yards are commonly called *hanks*, or some cases *skeins*. Thus, we can now say that the indirect system gives the number of kilometers that weigh a kilogram (metric units) or the number of hanks that weigh one pound (English Imperial units). The type of hank being referred to depends on the type of yarn or, more correctly, the manufacturing route used to produce the yarn. For carded and combed ring spun yarns, an 840-yd hank is used; a 560-yd hank is associated with worsted and semi-worsted yarns, and a 256-yd hank with woolen yarns. Generally, cotton fibers are made by the carded and combed ring spun yarn routes, and synthetic fibers of similar lengths to cotton are made by the carded ring spun route, whereas wool and similar lengths synthetics are processed by the worsted, semi-worsted and woolen routes. With respect to the unconventional processes, if a fiber type spun by any of these systems can be also spun by one of the conventional systems, the hank associated with that conventional route is used. For example, the production of rotor spun yarns

is usually from cotton and synthetic fibers of cotton lengths, and the 840-yd hank is therefore used. Recco yarns can be made of wool or synthetic fibers of wool lengths, and the 560-yd hank is the applicable standard length.

Table 1.3 summarizes the most commonly used units of count for the direct and indirect systems. A more comprehensive list can be found in a publication by The Textile Institute, "Textile Terms and Definitions,"<sup>4</sup> and a number of the references cited at the end of this chapter give a brief account of the historical origins of several units of the indirect system.

**TABLE 1.3**  
**Systems for Yarn Count**

Unit of count	Symbol	Abbreviation for unit	Standard mass unit	Standard length unit	Equivalent tex
<b>Direct System</b>					
Tex	$T_t$	tex	gram	1 km	1
Decitex		dtex	gram	10 km	0.1
Millitex		mtex	gram	1000 km	0.001
Kilotex		ktex	gram	1 m	1000
Denier		den	gram	9 km	0.1111
<b>Indirect System</b>					
Cotton (English)	$N_{e_c}$	cc (cotton count)	1 lb	840 yd (1 hank)	590.5
Metric	$N_m$		1 kg	1 km	1000
Worsted (English)	$N_{e_w}$		1 lb	560 yd	885.8
Woolen (Yorkshire, UK)	$N_y$		1 lb	256 yd (1 skein)	1938

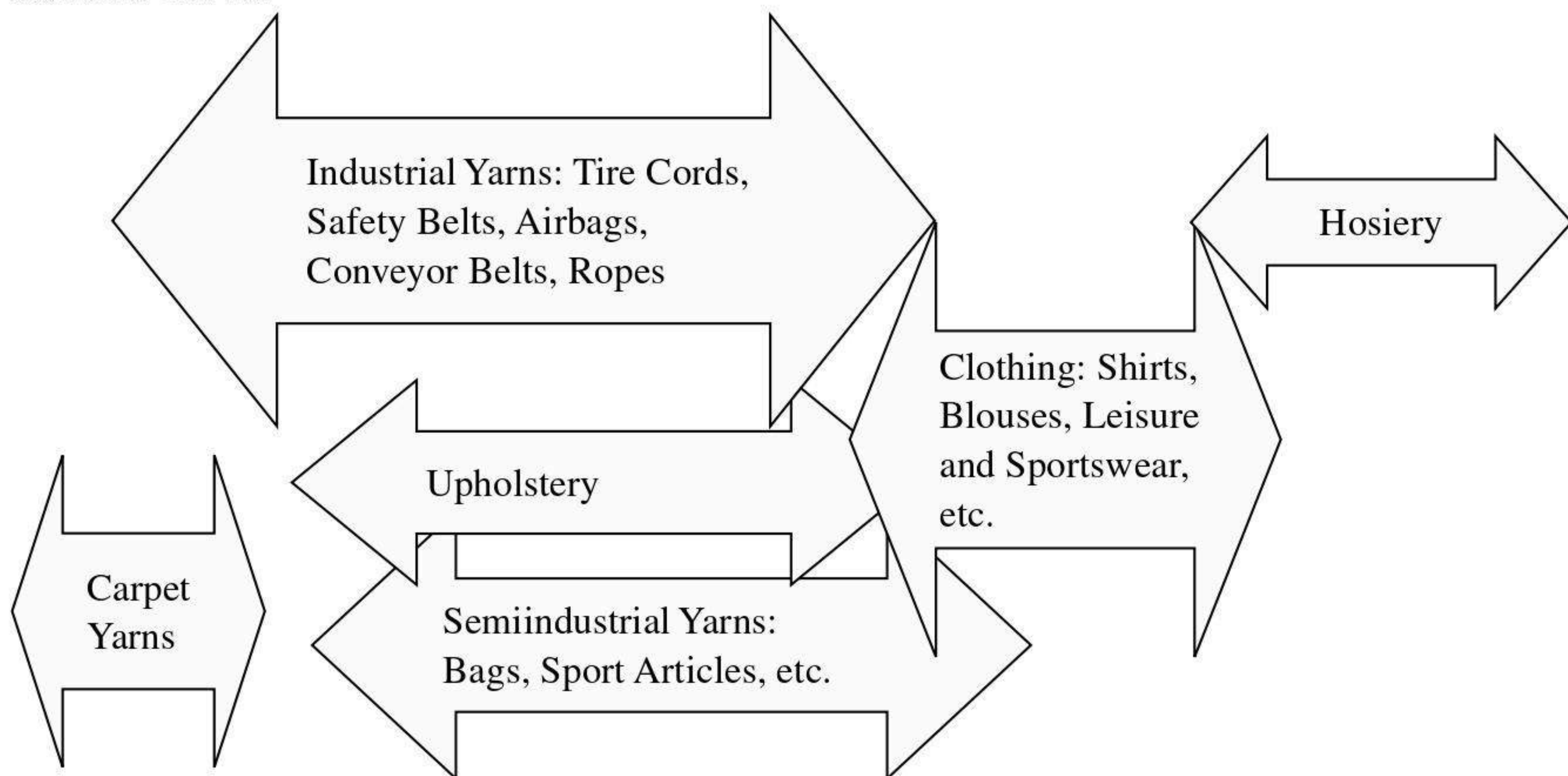
Although all the units of count in Table 1.3 are used in practice, we shall use only the tex throughout the remaining chapters of this book. The table gives the conversion factors in relation to tex. A clear advantage of the tex is that we can refer to multiples and decimal fractions of the tex in terms of the base 10 scale. Thus, 1000 tex = 1 kilotex (ktex), 0.1 tex = decitex (dtex), and 0.001 tex = millitex (mtex). In this way, the tex unit can be used for fibers and yarns. Hence, if we have a yarn of 100 tex spun from fiber of 1 dtex (0.1 tex), we can estimate the number of fibers in the yarn cross section to be 1000. A 50-tex yarn should be half the size of a 100-tex, requiring only 500 fibers in its cross section. It is the practice to refer to the dtex of a fiber as the *fiber fineness*; the denier (den) is also used to express fiber fineness. A fiber fineness of 1.5 den is therefore equivalent to 1.7 dtex.

Two or more yarns may be twisted together to make a coarser yarn. Using the tex unit of count, the resultant yarn count would be the sum of the individual counts or, if yarns of the same count are twisted together, the product of the number yarns and the count. The process of twisting yarns together is generally known as *plying*, *folding*, or simply *twisting*, and the resulting yarns as *plied* or *folded* yarns. The term *doubling* is also used when two yarns of the same count are plied, and the

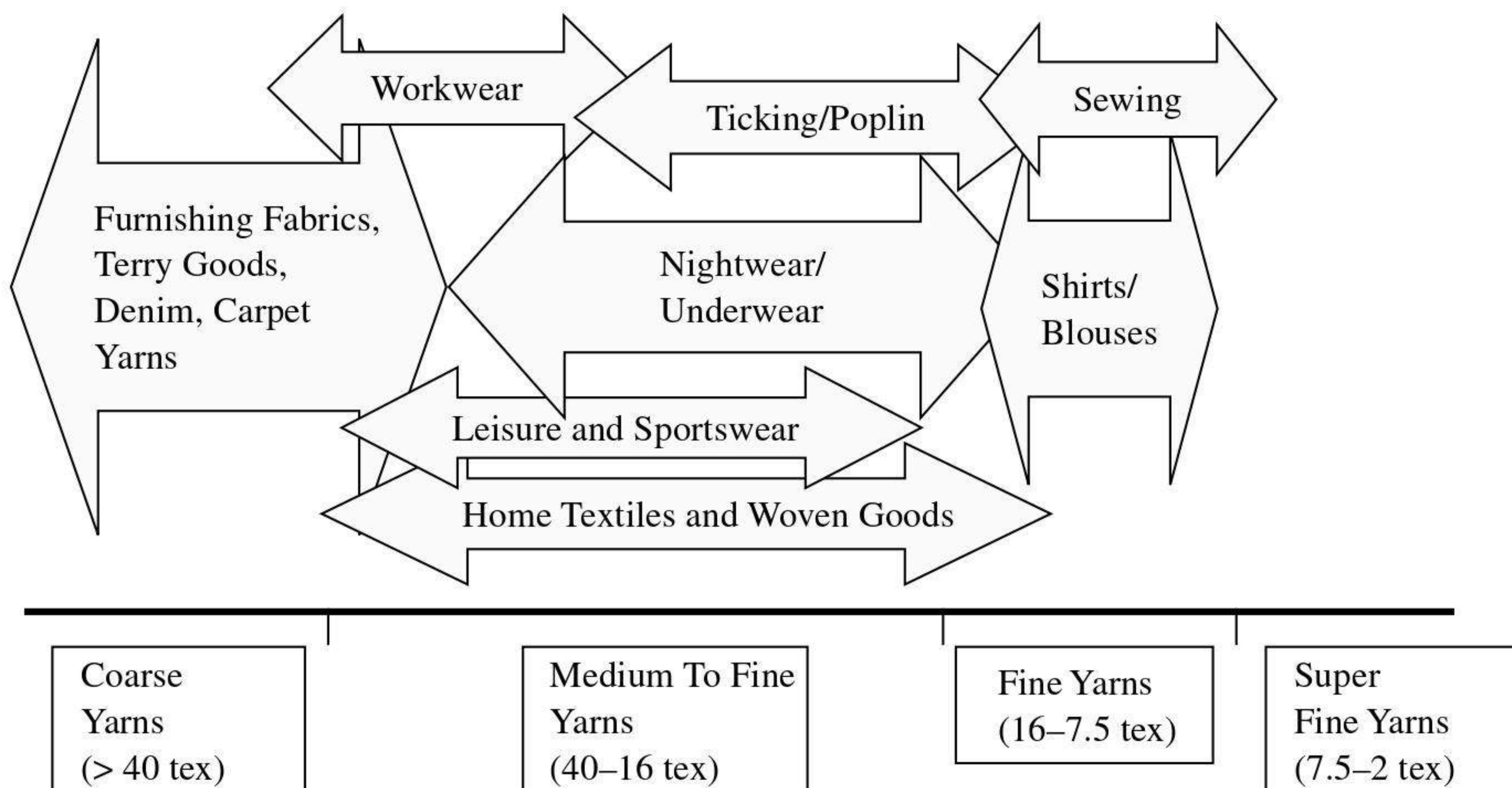
plied yarn is then called a *doubled yarn*. Assume that two 50-tex yarns are doubled; the resultant yarn count would be 100-tex yarn. However, the doubled yarn (i.e., the *two-ply yarn* or *twofold yarn*) may be written as  $R100/2$  tex or just  $2/50$  tex — meaning a two-50 tex plied yarn. The  $R$  denotes resultant count, and the  $/2$  signifies twofold. If we let  $N$  yarns of the same count,  $X$ , be plied, then the plied yarn would be written as  $N/X$  tex and termed an  $N$  ply.

Figure 1.5 illustrates the wide count range for the various end uses of filament and staple yarns. Besides the very fine yarn count range of 2 to 7.5 tex for hosiery, staple fiber and continuous filament yarns have quite similar market areas, where the fine to medium yarn counts, 7.5 to 40 tex, are largely used to make textiles for

### Filament Yarns



### Staple Spun Yarns



**FIGURE 1.5** Count range of product areas for continuous filament and staple spun yarns.

apparel. Spun staple yarns hold a principal position in the market for shirts, blouses, home textiles, bed linen, trousers, suits, and so on. Filament yarns are highly competitive in the carpet-yarn and sportswear sectors and in the industrial yarn area for technical textiles.

When yarn is sold to a weaver or knitter, one of the buyer's fundamental concerns is the length of yarn that gives a specified number of grams per square meter ( $\text{g/m}^2$ ). The count system enables the meterage of yarns wound onto bobbins to be sold in terms of the yarn mass of the formed package.

After giving some thought to the tex unit, the reader should see that the use of count as an indication of yarn thickness does not take account of the issue of differing fiber densities when comparing the size of yarns spun from different fiber types. At times, the bulkiness (i.e., voluminosity) of the yarn is of interest, and then yarn diameter can either be measured or the equivalent diameter,  $d_y$ , can be calculated.

With reference to the yarn helix model, the yarn diameter is related to the count as follows:

$$T_t = \frac{1000\pi d_y^2}{4\delta_y} \quad (1.8)$$

where  $\delta_y$  = the specific volume in  $\text{g/m}^3$

$T_t$  and  $\delta_y$  can be measured,<sup>7</sup> and  $d_y$  can be calculated.

## 1.4 TWIST AND TWIST FACTOR

Let us now consider the second of the three identified common characteristics, that of twist. The following four parameters are of importance when discussing twist in yarns:

1. Direction of twist
2. Twist angle
3. Twist level (degree of twist)
4. Twist multiplier

The terms *real twist* and *false twist* need also to be explained.

### 1.4.1 DIRECTION AND ANGLE OF TWIST

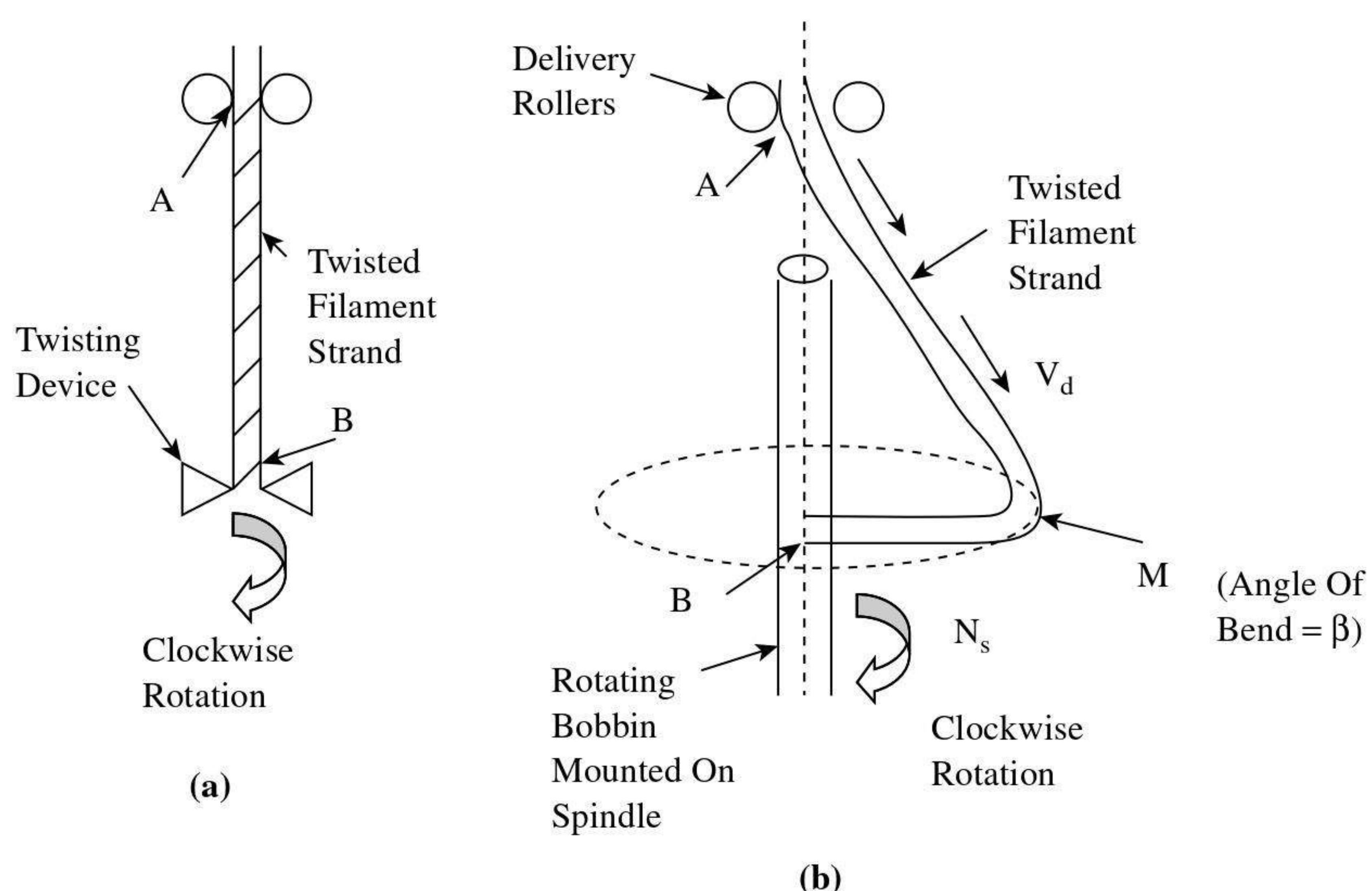
From the simple geometrical model of a yarn, the spiral direction and angle of the surface helix, representing the yarn surface fibers, are by convention the direction and twist angle of the yarn. In [Figure 1.4](#), the yarn twist angle is  $\alpha$ . Looking along the axis of the model, the helix has a clockwise direction. The spiral direction of a helix may be made counterclockwise. The diagonal of the clockwise spiral conforms to the diagonal of the letter Z, and an counterclockwise spiral to the letter S. Thus, the directions of twist are referred to as either Z or S. When making microscopic

observations of yarns. Matching the inclination of the surface fibers to the center portions of the letters Z and S will determine if the yarn is S-twisted or Z-twisted, and the angle of inclination to the yarn axis would be the twist angle  $\alpha$ . In [Figure 1.3](#), the CF yarn is S-twisted with a twist angle  $\alpha = 30^\circ$ , whereas the ring-spun yarn is Z twisted and  $\alpha = 20^\circ$ .

## 1.4.2 TWIST INSERTION, REAL TWIST, TWIST LEVEL, AND FALSE TWIST

### 1.4.2.1 Insertion of Real Twist

The simplest way to insert twist into a strand of fibers (or filaments) is to hold one end (or part) of the strand while the strand length (or the length of the remaining part) is made to rotate on its axis. Figure 1.6a illustrates this. The strand is nipped at point A between a pair of stationary rollers while the end, B, is turned to cause rotation of the strand on its own axis. The first rotation of the strand will cause the fibers (or filaments) to adopt a helical form, and each subsequent rotation will increase the number of spirals of the helical form and the helix angle, i.e., the number of turns of twist and the twist angle. Figure 1.6b shows an alternative situation in which B is now attached to a bobbin placed on a rotating spindle, and A is still nipped by the rollers, but the length AB is made to bend through the angle  $\beta$  at M. The nipped point A is in line with the spindle axis of rotation. As the spindle rotates, the length BM is made to rotate with the spindle, and M circulates the spindle axis. Each rotation (circulation) of M will cause the strand to also rotate on its own axis, thereby inserting twist. The twist will initially appear in AM and, if unrestricted at M, propagate through to B. In both situations, the twist inserted



**FIGURE 1.6** Real twist insertion.

will remain in the strand and is therefore called *real twist*. If  $Y$  is the number of rotations of  $M$ , then the twist per unit length inserted into the strand would be equal to  $Y$  divided by  $AB$ . Thus, if  $Y = 100$  and  $AB = 10$  cm, the twist inserted would be 10 turns per centimeter.

Consider now the dynamic situation of [Figure 1.6b](#), when the rollers are delivering the strand to the twisting zone at a *delivery speed*,  $V_d$ , of, say, 20 m/min. In this situation, if the bend  $M$  is made to circulate the spindle axis at a rotational speed,  $N_s$ , then the twist inserted would be given by the general formula,

$$t = N_s/V_d$$

where  $t =$  inserted twist (tpm)  
 $N_s =$  rotational speed of the twisting device (rpm)  
 $V_d =$  yarn delivery speed (m/min)

If the speed of  $M$  is 10,000 rpm, the twist inserted into the strand would be 500 turns per meter or 5 turns per centimeter. If  $V_d$  were to be increased to 40 m/min and the twist per unit length kept constant, then the *twisting rate* would have been doubled, i.e.,  $N_s$  increased to 20,000 rpm.

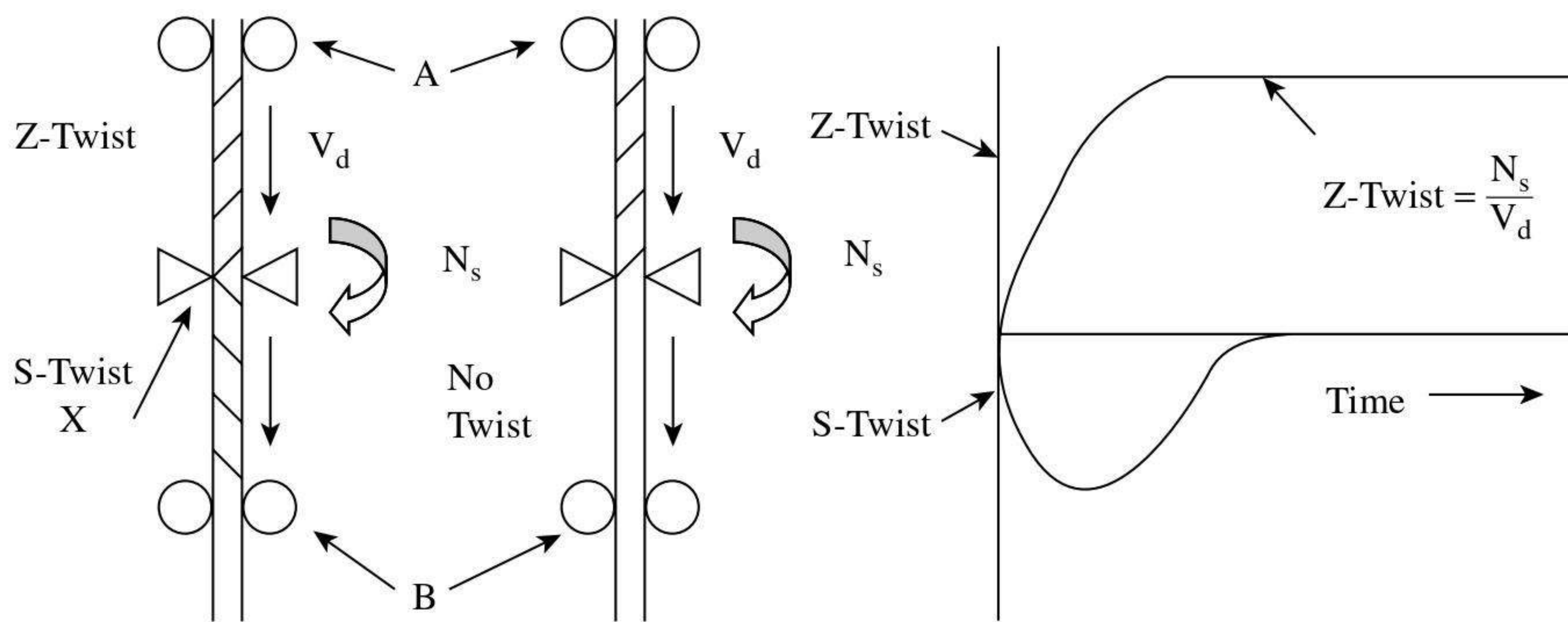
The rotation speed of  $M$  should actually be slightly lower than that of the spindle so that the filament strand can be wound onto the bobbin at the delivery speed  $V_d$ . Some means would be also needed to make the yarn traverse up and down the length of the bobbin on the spindle during winding. This method of twist insertion combined with winding is used in a commercial process known as *ring spinning*, which is described in detail in [Chapter 6](#).

### 1.4.2.2 Twist Level

The twist level (or degree of twist) in a yarn is the number of turns of twist per unit length. In Imperial units, we refer to the turns per inch (tpi), whereas, in metric and SI units, we speak of turns per meter (tpm), although turns per centimeter (tpcm) is also used. Turns per meter will be used throughout the remaining chapters.

### 1.4.2.3 Insertion of False Twist

[Figure 1.7](#) shows a situation where a strand of filaments, nipped by two pairs of rollers at  $A$  and  $B$ , is driven at a linear speed of  $V_d$  m/min while being twisted at a rate of  $N_s$  rpm at some point  $X$  along the length spanning the distance between the two sets of rollers. If the twisting device is rotating in the direction shown, it will appear to be turning clockwise when viewed along the length  $AX$ , and counterclockwise when viewed along  $BX$ . Thus, at the start of twisting, Z-twist will be inserted in the strand as it passes through the  $AX$  zone, and S-twist is inserted as it moves through the  $XB$  zone. As time passes, the Z-twist in the strand length passing through the  $AX$  zone will increase to a constant value of  $N_s/V_d$ . In zone  $XB$ , S-twist initially will be present in the yarn length passing through the zone; it will increase to a



**FIGURE 1.7** False-twist insertion.

maximum value and then decrease to zero. This is because each length of strand moving from zone AX into zone XB will become untwisted by the counterclockwise torque that is present as it enters zone XB. A derivation of the equations for Z and S twist as function of time is given in [Appendix 1A](#).

The time over which the Z-twist builds up to its constant value and the S-twist increases and then decreases to zero may be termed the *transient period*. At the end of this period, the system is said to be in dynamic equilibrium. Z-twist will be observed in the AX zone and no twist will be seen the XB zone. This twisting action is called *false-twisting* because, under dynamic equilibrium, the strand, although being twisted, has no twist when it leaves the twisting device. A number of spinning systems employ the false-twisting action for producing yarns, and these are also described in [Chapter 6](#).

### 1.4.3 TWIST MULTIPLIER/TWIST FACTOR

The twist angle  $\alpha$  has an important influence on yarn properties, as is explained in Chapter 6. It can be seen from the equations defining the yarn helix model that the twist angle is related to the twist level,  $t$ , according to

$$\tan \alpha = \pi dt \quad (1.9)$$

Substituting for  $d$  from Equation 1.8,

$$\tan \alpha = t \left( \frac{\pi T_t 4 \delta_y}{1000} \right)^{\frac{1}{2}}$$

Rearranging,

$$TM = t T_t^{\frac{1}{2}} \quad (1.10)$$

where

$$TM = \frac{\tan \alpha}{[(\pi 4 \delta_y / 1000)]^{1/2}}$$

and is called the *twist multiple (TM)*, expressed in turns  $\text{m}^{-1} \text{tex}^{1/2}$ .

With regard to the indirect system of count, Table 1.4 gives the corresponding equations for the Imperial and metric units. Note that, with the former, we refer to the twist factor (*TF*) and, for the latter, alpha metric ( $\alpha_M$ ).

**TABLE 1.4**  
**Twist Multiples/Twist Factors**

System	Equation
English Imperial (twist factor, <i>TF</i> )	$TF = t / \sqrt{N_{e_c}}$ , where <i>t</i> is the twist in turns per inch (tpi)
Metric (alpha metric, $\alpha_M$ )	$\alpha_M = t / \sqrt{N_m}$ , where <i>t</i> is the twist in turns per meter (tpm)

If there is a change of count but the twist angle, and therefore the twist multiple, is to remain unchanged, then Equation 1.10 would be used to calculate the required new level of twist. For example, with a 25-tex yarn spun at a twist multiplier of 4000  $\text{m}^{-1} \text{tex}^{1/2}$ , the twist inserted would be 800 tpm. Spinning 16-tex and 64-tex yarns with the same TM would require 1000 tpm and 500 tpm, respectively. In practice, different ranges of twist multiples are used in spinning yarns for particular end uses, and Table 1.5 gives examples of the TM range of yarns for knitting and weaving.

**TABLE 1.5**  
**TM, TF, and  $\alpha_M$  Values for Knitting and Weaving**

Spinning system	End use	Twist multiple (TM)
Cottons (staple length < 25mm)	Weaving, <sup>a</sup> warp yarns	3800–4800
Blends with man-made fibers	Weaving, weft yarns	3170–3650
Cottons (staple length > 25 mm)	Weaving, warp yarns	2400–2860
Blends with man-made fibers	Hosiery	2050–2550
Wool and blends with man-made fibers	Weaving, warp yarns	2050–2400
	Weaving, weft yarns	1750–2050
	Hosiery <sup>b</sup>	1420–1750

a. Warp yarns run the length of woven cloth; weft yarns run across the warp.

b. Knitted fabrics and goods made up of them.

As indicated in the table, short fibers require a greater level of twist than longer fibers so as to hold together to form a yarn of useful strength. The level of twist in



a yarn has a strong influence on the yarn properties — in particular, strength, hairiness, and bulk. In weaving, warp yarns require more twist than weft yarns, because they need to be of a higher strength and lower hairiness to withstand the tensions and frictional forces of shedding. The lower twist gives weft yarns greater bulk, which is imparted to the fabric. Knitted fabrics are generally required to have good bulk and softness; consequently, hosiery yarns have the lowest twist levels. A yarn with a high twist level is often referred to as *lean* and is not suitable for knitwear.

#### 1.4.4 TWIST CONTRACTION/RETRACTION

The insertion of twist gives a small increase in count, referred to as *twist contraction*. In Figure 1.4, the simple helix model, if we compared fiber lengths within a yarn length having one turn of twist, we would find that all but the fiber length on the central axis would be longer than the yarn length. That is to say, from the figure,  $L > l > h$ . This can be viewed as contraction of the fiber lengths, where  $h$  is the contracted length compared with  $L$  and  $l$ . If we imagine cutting a length  $h$  from the yarn and then untwisting it to straighten all the fibers, then  $L$  and  $l$  would be the untwisted length. It should be clear that the count of the untwisted length will be lower than the twisted length; hence, twist contraction. As the straightened fiber lengths will vary, increasing from  $h$  at the yarn axis to  $L$  at the surface, the untwisted yarn length is taken as the mean of the straightened fiber lengths.<sup>5</sup>

Letting  $L_m$  be the mean untwisted length, we can define the magnitude of length change in two ways.

1. Contraction,

$$C_y = \frac{\text{Mean untwisted length}}{\text{Twisted yarn length}} = \frac{L_m}{h}$$

2. Retraction,

$$R_y = \frac{\text{Mean untwisted length} - \text{Twisted yarn length}}{\text{Twisted yarn length}} = \frac{L_m - h}{h}$$

$$L_m = \frac{1}{2}h[\sec \alpha + 1]$$

Substituting for  $L_m$ ,

$$C_y = \frac{1}{2}[\sec \alpha + 1] \quad \text{and} \quad R_y = \frac{(\sec \alpha - 1)}{(\sec \alpha + 1)}$$

Thus, by determining the twist angle, the level of twist contraction can be calculated.

## 1.5 FIBER PARALLELISM

The third common structural feature of yarns is the tendency for fibers to lie in a parallel manner. When twist is present in the yarn, the fiber parallelism is along the twist direction (see [Figure 1.3](#)). We will see, in [Chapters 5](#) and [6](#), that this orderly arrangement of fibers and therefore the level or degree of fiber parallelism varies between yarn types, some showing some significant randomness. Important to the degree of fiber parallelism is fiber shape or configuration within the yarn. Where almost all the fibers have their full lengths following the twist helix, as depicted in the [Figure 1.3](#), there is a high degree of parallelism. The presence of looped, hooked, and folded fiber configurations and of fibers lying at different twist angles within a fiber layer would significantly reduce the degree of parallelism.

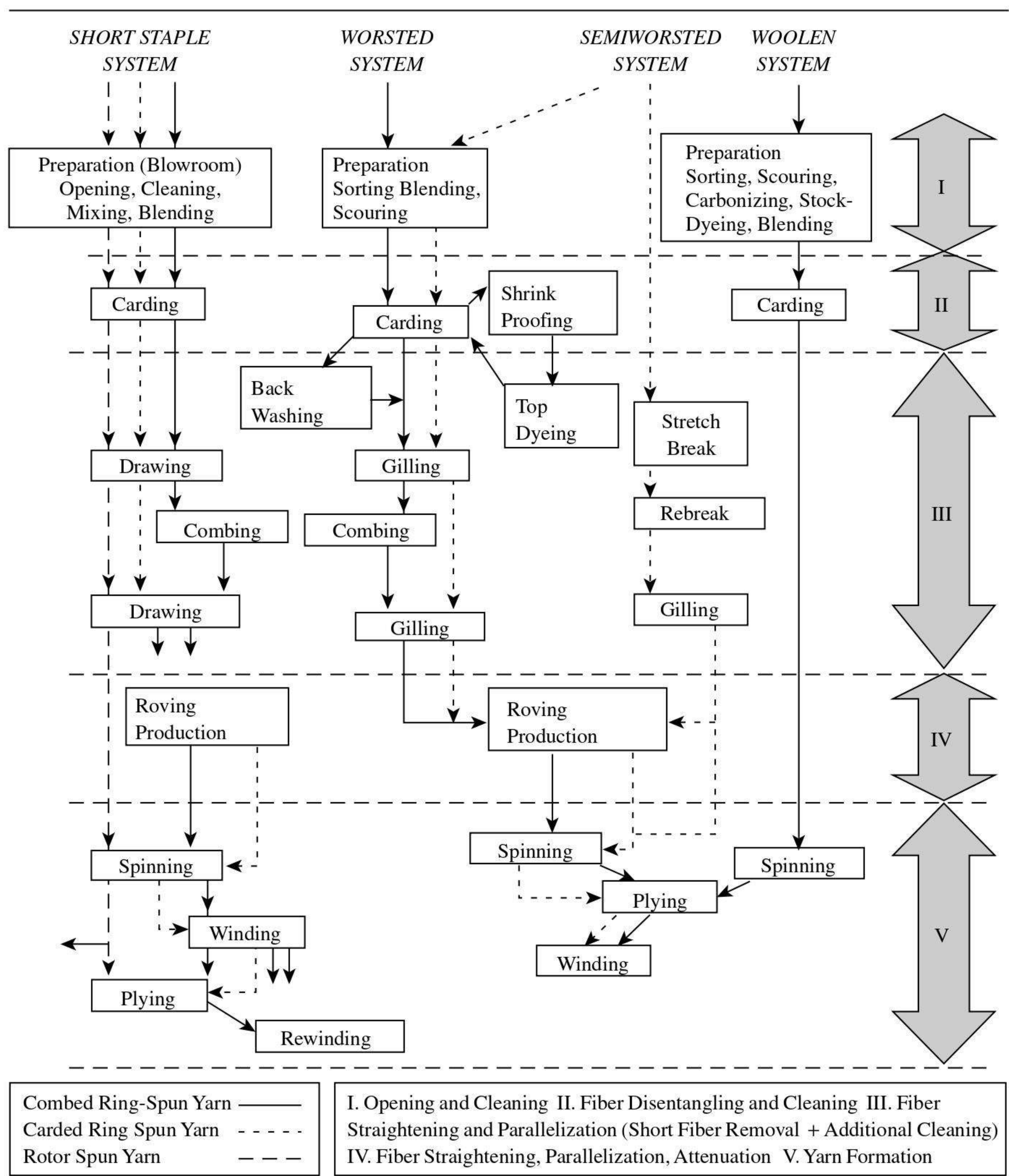
The orderly arrangement of fibers in a yarn strongly influences yarn properties and, for the majority of yarns, is dependent on the mechanical actions utilized in processing the fibers up to the point of inserting twist to form the yarn structure. It is therefore appropriate to now describe these basic mechanical actions and their influence on parallelism prior to considering, in the following chapters, the detailed operating principles of the machinery used.

## 1.6 PRINCIPLES OF YARN PRODUCTION

It can be reasoned that to obtain a high degree of fiber parallelism in a yarn, the fibers must be already straight and parallel in the fiber assembly presented for consolidation by twist or some other means. [Figure 1.8](#) shows the process sequence for the manufacture of the more common types of staple-spun yarn.

When fibers are first purchased for conversion to yarns, they are usually obtained in large fiber bales. At this stage, the fibrous mass is referred to as the *raw material*; some raw material may be waste for recycling. In the raw material state, fibers have no definite orientation or configuration. A high proportion will be entangled and, in the case of natural fibers like cotton and wool, dirt and vegetable particles and other impurities (e.t., grease) will be present. The first stage in a yarn production process is therefore the cleaning and disentangling of the raw material. Where grease has to be removed, the material is scoured. The disentangling of the fiber mass occurs progressively using pin or saw-tooth wire-covered rollers. The earlier stages are collectively referred to as *opening* and *cleaning*, since, as the compressed fiber mass is opened up, solid impurities are released to become waste. The final stage of disentanglement is called *carding*, where the fiber mass is separated into individual fibers that are collected together to form a twistless rope termed a *card sliver*. Because of the carding process, the fiber orientation is very close to the sliver axis; therefore, carding may be considered as the start of the parallel arrangement of fibers. However, only very few fibers in a card sliver have a straightened shape.

To straighten hooked and folded fibers, and greatly improve fiber alignment along the sliver axis, the sliver is thinned by stretching; the mechanical action is called *drafting*, and the amount by which it is stretched is the *draft*. Clearly, the count of the sliver will decrease, so drafting is an attenuating action, and the draft is equal to the factor by which the sliver count is reduced. Thus, if a 6-ktex sliver

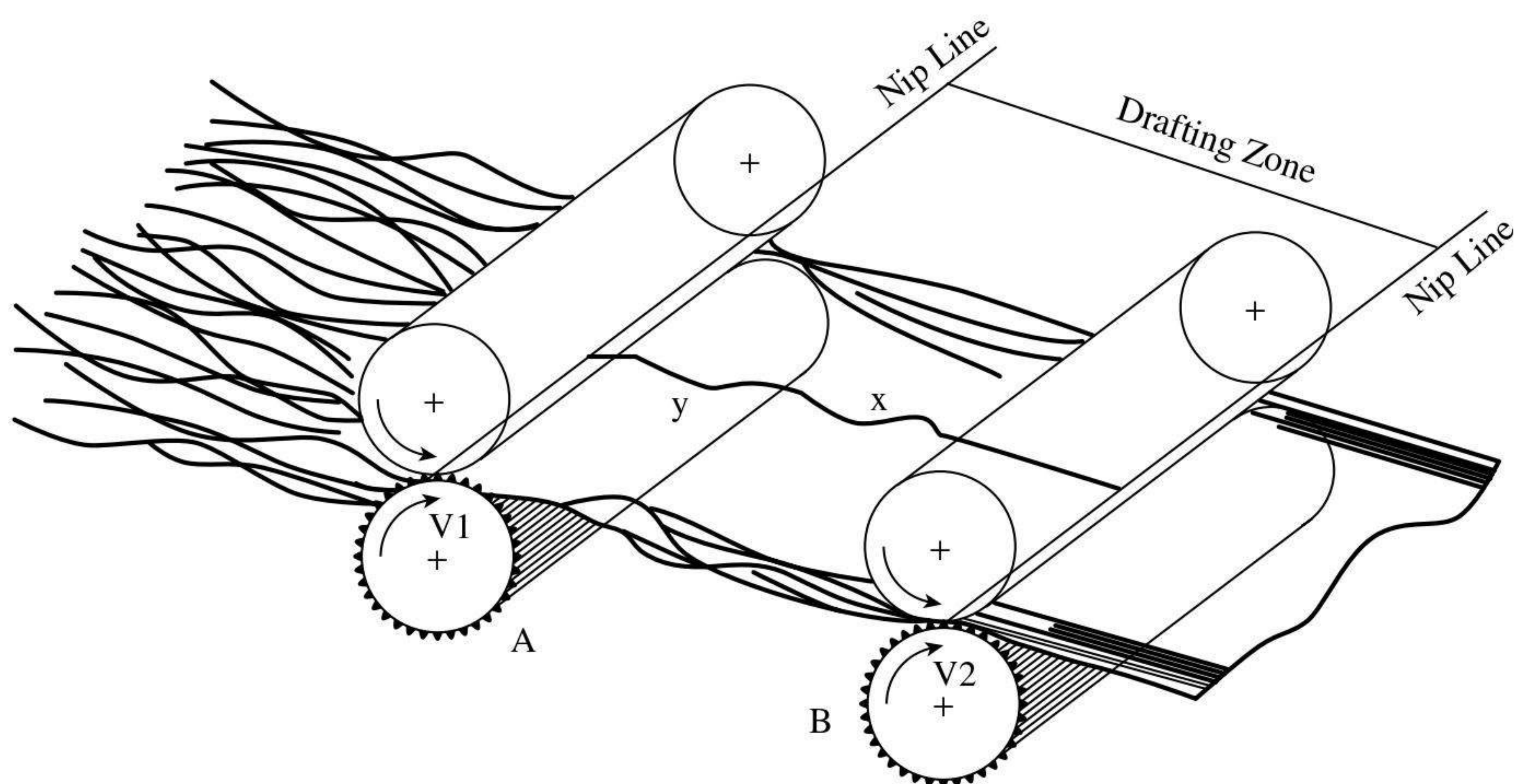


**FIGURE 1.8** Yarn production process sequence.

is reduced by a draft of 3, a 1-m length would be stretched to 3 m, and the resulting sliver count would be 2 ktex. This means that

$$\text{Draft} = \frac{\text{stretched length}}{\text{initial length}} = \frac{\text{initial count (tex)}}{\text{final count (tex)}} \quad (1.11)$$

The drafting of the sliver gives rise to shear within the fiber mass; fibers slide past each other as the sliver is stretched, giving the permanent extension or elongation. The friction contact between fibers during the sliding motion straightens and aligns fibers along the sliver axis. [Figure 1.9](#) shows the situation where two pairs



**FIGURE 1.9** Single-zone roller drafting.

of rollers are used for drafting. The bottom rollers are fluted metal rollers that are driven through a set of gears by an electric motor. The flutes may be straight, as illustrated in Figure 1.9, or given a slight spiral. The top rollers are synthetic-rubber-covered rollers and are pressured down onto the bottom rollers (termed *weighted down*) and driven through frictional contact. The compression, referred to as the *hardness*, of the synthetic rubber cover can be varied to suit the fiber frictional properties. The flutes of the bottom rollers and the resilience of the top rollers are important for the nipping of fibers during drafting.

The diagram illustrates what is called a *single drafting zone arrangement*, and the method of drafting is termed *roller drafting*. There are other methods of drafting, and these are described in the later chapters wherein we consider the processes in which they are used. The basic idea of drafting is explained here, using roller drafting as an example.

The drafting zone in which the material is stretched and attenuated is the horizontal area between the nip lines of the two pairs of rollers. The material is fed into the zone at the surface speed,  $V_1$ , of rollers A and pulled out of the zone by rollers B at speed  $V_2$ . Thus, Equation 1.11 can be rewritten,

$$\text{Draft} = \frac{V_2}{V_1} = \frac{\text{stretched length}}{\text{initial length}} = \frac{\text{initial count (tex)}}{\text{final count (tex)}} \quad (1.12)$$

Ideally, where two fibers, x and y, are in frictional contact with the leading end of x nipped by rollers B while its trailing end is free, and the converse is true for y with roller A, then the sliding of x past y will be effective in straightening and aligning the fibers along the sliver axis. Even if we were to assume that fibers forming the card sliver were of equal lengths, there will be differing fiber shapes (i.e., configurations) giving different extents and orientations to the sliver axis. Conse-

quently, on the first pass of the sliver through the drafting zone, there would be fibers that are not nipped effectively to be straightened and aligned. The use of more than one drafting zone and the passing of the material through the drafting process several times therefore would be beneficial. In practice, the process stage after carding, known as *drawing*, involves six or eight card slivers of the same count being drafted to the count of one sliver, and the drawing passage repeated with six or eight of the first drawn sliver. Up to three drawing passages can be used. [Chapter 5](#) describes in more detail the drawing processes used in the production of staple yarns.

In bringing six or eight slivers together, termed a doubling of six or eight, and applying to them a draft of six or eight, the resulting sliver will comprise a sixth or an eighth of the count (and also of the number of fibers in the cross section) of each original sliver. Repeating the process further reduces the proportion to 1/36 or 1/64. There is, in effect, a blending of the original slivers, and the greater the number of drawing passages, the better the blending. This blending by doubling of slivers improves the uniformity of the final slivers and, ultimately, that of the spun yarn. Drawing is, therefore, an important stage in the sequence of preparatory processes when producing yarns from either one fiber type or a blend of two or more fiber types.

It should be evident that important factors in roller drafting are

- The distance between the nip lines (termed the *roller setting*) in relation to the distribution of fiber lengths within the sliver
- The applied draft (i.e., the relative roller speeds)
- The number of fibers (or the input count) fed into the drafting zone

Chapter 5 gives an account of drafting theory and considers these factors in more detail.

Where the raw material has a broad distribution of fiber lengths, it is sometimes necessary, after the first passage of drawing, to remove from slivers some fibers that are much shorter than the mean length of the distribution. The process for doing so is known as *combing*, and, as the name implies, a pin surface is used to comb through the fiber mass of first-passage drawn slivers, removing fibers of preselected short lengths. Combing also has the added benefit of contributing to the straightening and alignment of fibers and of removing residual impurities present in the material after the opening, cleaning, and carding stages. Combed ring-spun yarns and worsted yarns are produced from combed material, making them of the highest quality in terms of yarn properties, and enabling such yarns to cover the finer end of yarn count range. Chapter 5 describes the principles of combing.

Following the final passage of drawing, the sliver produced has to be attenuated to give the required yarn count. The most common approach is to attenuate the sliver into a roving and then to attenuate the roving during spinning prior to twist insertion, or other means, to form the yarn structure. Roving production is then the last of the preparatory stages to spinning. However, the total required attenuation can be achieved directly from sliver, either with high-draft, roller drafting systems or by pin and saw-tooth-covered rollers, known as opening rollers, used in rotor and friction spinning. In Chapter 5, a detailed description is given of the roving produc-

tion process, and [Chapter 6](#) explains the operating principles of opening-roller systems.

The carding process also involves attenuation of the fiber mass to obtain the required sliver count but, as mentioned, few fibers in the card sliver are straight. This indicates that drafting during carding is not suitable for fiber straightening. From a yarn structure perspective, low fiber straightness and parallelism will significantly reduce certain important properties (e.g., strength) but increase yarn bulkiness. This yarn characteristic is a requirement for some fabrics and other more technical end uses (e.g., water filtration packs), and a compromise is then reached between yarn strength and bulk. The woolen spinning process makes use of the fiber randomness at the card to achieve yarn bulk. In this case, the web of carded fibers is split into thin strands and consolidated to form slubbings, which are subsequently spun into yarns. High-bulked yarns are also produced by differential shrinkage of fibers that are obtained by stretch-breaking filaments. [Chapter 5](#) describes the stretch-breaking process.

Following the ring spinning and any plying processes, yarns are usually rewound into large-size packages; these usually take the form of a *parallel-sided cheese shape* or a *cone shape*, suitable for use in fabric production and the process of producing such packages is known as *winding*. Winding is important, because it provides the opportunity for removing imperfections (faults) from the yarn and thereby assists the efficiency of the subsequent processes and improve fabric quality. Yarns can also be waxed during winding to improve knitting efficiency. The point of importance, however, is that a rewind package is along continuous length of yarn, which enables a long running time of fabric production. The principles of winding are described in [Chapter 7](#). Several spinning systems are, however, able to produce large-size waxed- and unwaxed-yarn packages of the above types, and rewinding then is not practiced.

## 1.7 RAW MATERIALS

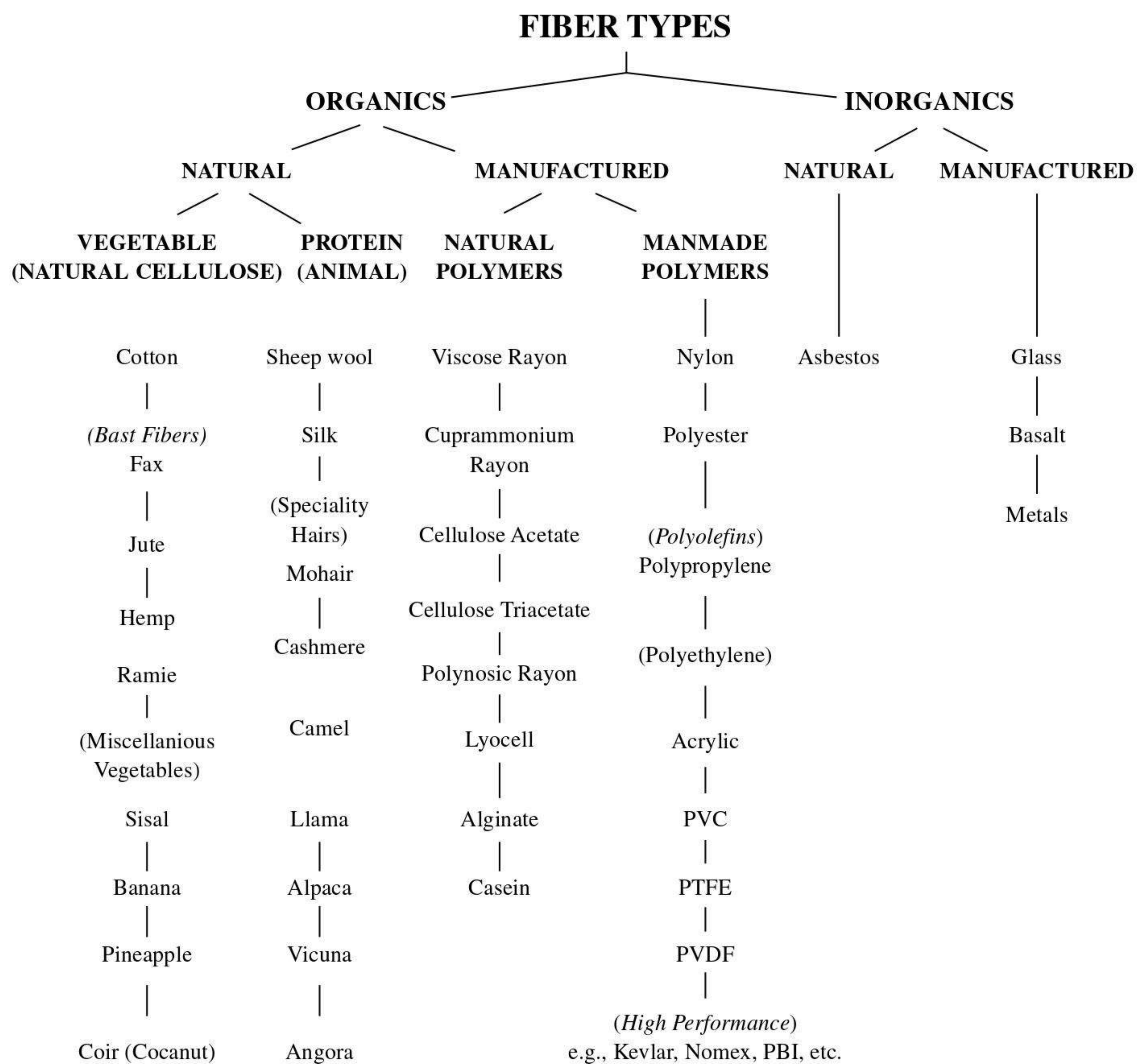
The old adage among some yarn spinners, “If it has two ends, it can be spun,” is not strictly true, but it is indicative of the wide range of fiber types and lengths that are today converted into yarns. [Figure 1.10](#) charts the broad variety of fiber types that may be converted into yarns. It is not the intention to describe the production processes or the detailed chemical properties of these fibers, since the subject of fiber technology would form a textbook in its own right, and indeed many books and scientific papers are readily available for the interested reader; several are cited at the end of this chapter.<sup>8–10</sup> It is, however, appropriate to consider certain aspects of fiber properties relevant to the production of staple yarns involving those fibers that are used in large tonnages.

### 1.7.1 THE GLOBAL FIBER MARKET

The statistics for organic fiber production are regularly reported by Fibre Organon,<sup>11</sup> ICAC,\* and CIRFS†.<sup>12–13</sup> The reader may wish, in the future, to keep an updated

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\* International Cotton Advisory Committee, [www.icac.org](http://www.icac.org).

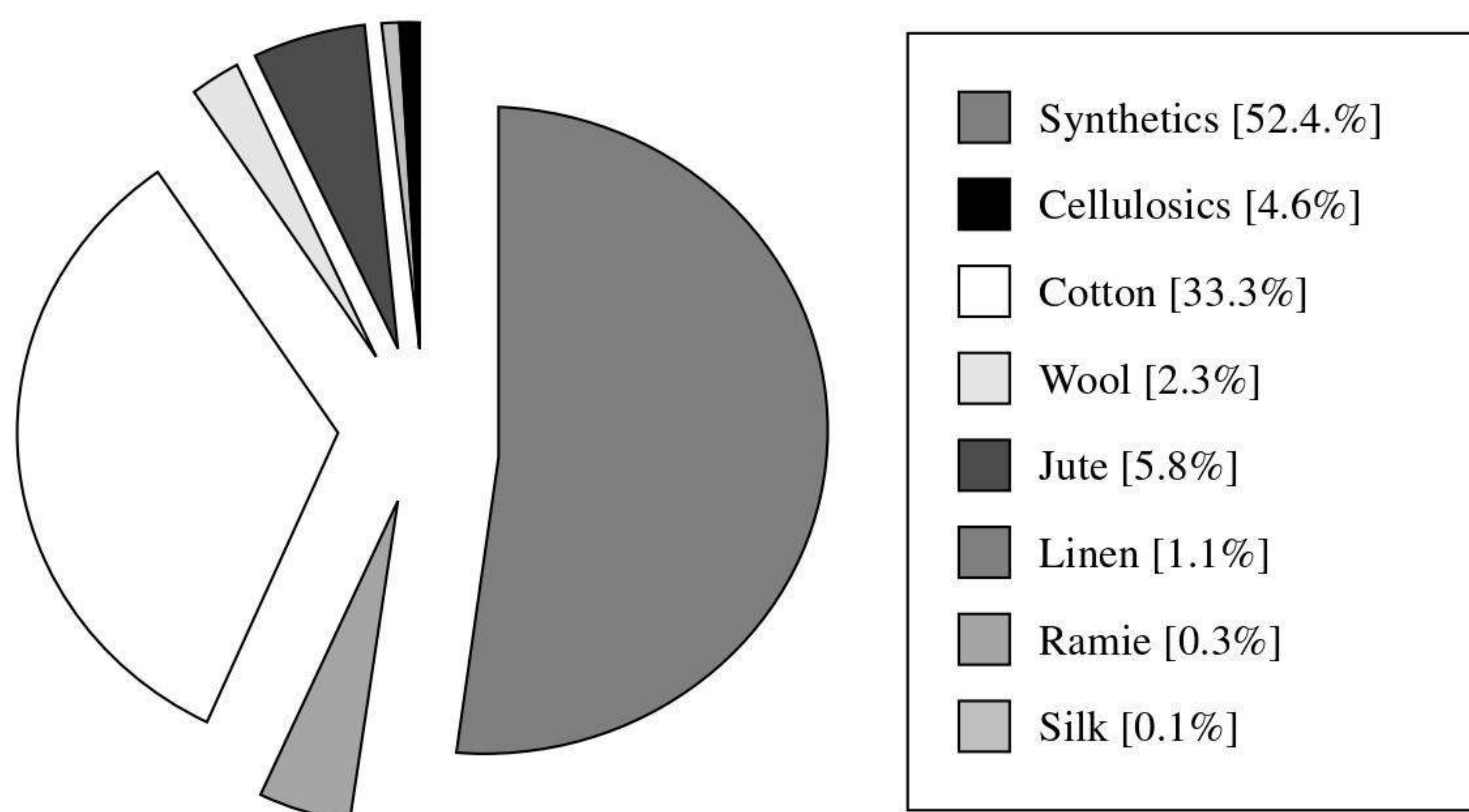


**FIGURE 1.10** Examples of the range of fiber types.

check of the production statistics from these sources. The latest figures (published in 2001) at the time of writing this book showed that textile fiber production had reached 57.2 million tons. [Figure 1.11](#) illustrates the breakdown of the production tonnage by fiber type, and [Table 1.6](#) lists the main producing countries, Asia and Oceania being the dominant geographical regions.

Approximately 90% of world fiber consumption is processed into yarns, 7% into nonwovens, and the remainder used for fillings, cigarette filters, etc. Since circa the 1960s, there has been a general growth in world population and an increase in disposable income in the developed economies. As a result, consumer demand for easy-care, comfortable fabrics has led to manufactured fibers, largely synthetics, assuming a significantly increased share of world fiber production, accounting for 57% of production, while natural fibers have declined to 43%. Of the synthetic fibers,

† Comité International de la Rayonne et des Fibres Synthétiques (International Rayon and Synthetic Fibres Committee), [www.cirfs.org](http://www.cirfs.org).



**FIGURE 1.11** World production of textile fibers (57 million tons).

**TABLE 1.6**  
**Principal Producing Countries**

Country	Synthetics <sup>a</sup> (× 1000 tons) <sup>d</sup>	Cotton <sup>b</sup> (× 1000 tons)	Wool <sup>c</sup> (× 1000 tons)
Australia	–	700	673
Brazil	–	569	–
China	6,156	3,900	290
Germany	880	–	–
Greece	–	390	–
India	1,430 <sup>e</sup>	2,800	–
Indonesia	1,026 <sup>e</sup>	–	–
Japan	1,460	–	–
Korea	2,687	–	–
Mexico	638	–	–
New Zealand	–	–	252
Pakistan	–	1,800	–
Syria	–	325	–
Taiwan	3,066	–	–
Turkey	936	850	–
USA	4,583	3,690	–
Uzbekistan	–	1,160	–
Others	7,112	3,066	1,141
World totals	29,974	19,250	2,356

<sup>a</sup>Courtesy of Fibre Organon, June 2000.

<sup>b</sup>Courtesy of ICAC Washington, August–July 1999/2000.

<sup>c</sup>Courtesy of *Wool Statistics*, Greasy Wools 1999/2000, Brussels, Belgium, International Wool Textile Organization.

<sup>d</sup>1999 production.

<sup>e</sup>Excluding polypropylene.



polyester accounts for the largest tonnage (59.3%), followed by the polyolefins {polypropylene + polyethylene} (18.4%), polyamide (13.1%), and acrylic (8.5%).

Manufactured cellulosic fibers have an 8% share of global production. Cotton has been the most widely used natural fiber for over 5000 years<sup>14</sup> and is still a very popular material among consumers for many items of textiles and apparel. Cotton accounts for around 33% of total fiber production. Wool has only a 2.3% market share but, like cotton, is still an important fiber with respect to spinning technology, since many machinery developments have been directed at the worsted and woolen spinning sector. The remaining natural organic fibers, except for jute, have comparatively much lower tonnage. Other than the bast fibers, these remaining organic fibers can be spun on either (a) the short-staple, worsted, woolen or (b) the unconventional spinning systems described in this book. The bast fibers have specific process technologies for yarn production, which are more specialized areas and are described elsewhere.<sup>3,15</sup>

Only very small quantities of inorganic fibers are spun into staple yarns. Asbestos is used very little because of well reported associated health problems;<sup>16–18</sup> glass, basalt, and metal fibers are used largely in filament form or as nonwovens, but small amounts of staple yarns are made from metal fibers on conventional spinning systems and find applications in the areas of conductive fabrics and some protective clothing.<sup>19,20</sup>

Although the inorganic fibers and the lower-tonnage organic fibers have less significance in yarn technology as compared with, say, polyester, acrylic, cotton, the regenerated cellulose, and wool, they are of much importance with respect to textiles for medical and industrial applications, i.e., technical textiles<sup>21,22</sup> and, in the case of silk and speciality hairs, luxury fabrics.<sup>23</sup> The luxury fabrics market, being more exotic, will always remain relatively small, but the technical textiles sector is seen to have major growth potential.

The market drivers that influence growth in yarn production are population and general economic growth, and increasing consumer purchasing power. The world population is above 6 billion people and is predicted to grow at approximately 1.7% per annum. Around 16% of the world population currently has a per capita fiber consumption of greater than 10 kg, with the richer countries having 20 to 40 kg per capita. The remaining 84% of world population has between 3 to 10 kg per capita fiber consumption. It is reasoned that by the mid twenty-first century, the average annual per capita fiber consumption will exceed 12 kg, of which 60% will be consumption of synthetic fibers. The effect of population growth alone will provide only 40% of this projected increase; the remaining 60% is ascribed to anticipated economic growth and a rise in disposable income. This projection is equivalent to a 2.8% per annum growth rate in world fiber consumption; approximately 62% will be converted into spun yarns and 30% into filaments, and the greatest demand is likely to be for polyester fibers.

### **1.7.2 THE IMPORTANT FIBER CHARACTERISTICS AND PROPERTIES FOR YARN PRODUCTION**

If we consider the points made earlier about what constitutes a yarn, we can make reasonable deductions as to what fiber characteristics and properties are important

in yarn production. The process sequence of [Figure 1.8](#) is a useful starting point. The actions involved in stages I and II indicate that most materials have to be cleaned and disentangled. The level of cleaning is important because, the more work done to clean the material, the greater the chances of damaging fibers. Thus, cleanliness of the material prior to its processing is an important parameter; this is mainly applicable to natural organic fibers. The processes in stages III, IV, and V involve attenuation and, as indicated in [Figure 1.9](#), this may involve drafting zones where rollers are placed a specified distance apart. As explained in [Chapter 5](#), this distance depends on fiber length.

With any type of natural fiber, there are different lengths of fibers in a fibrous mass. Since drafting zones must be set to avoid the breaking of the longer fibers during attenuation, very short fibers at times will be between the two drafting rollers and are not properly attenuated. Thus, as we will see in [Chapters 5 and 6](#), very short fibers tend to cause irregularities in the drafted material and ultimately in the yarn. It is therefore important to establish the fiber length distribution of the raw material to be processed so that, where necessary, the short fibers can be removed during processing. It is also important to minimize fiber breakage in processing; therefore, the fiber strength-extension characteristic, which is indicative of the fiber toughness, can play a major role in the limitations placed on parameters of the operating machine — in particular rotational speed and the set closeness of component parts.

Fiber length, fineness, strength, and extension are also important material parameters to the spinning process of stage V. All contribute significantly to the yarn tensile property and thereby enable the forming yarn to withstand the mean tension and the peak values of tension fluctuations during spinning and in subsequent processing. The strength of a yarn depends on how well its constituent fibers can equally share the tension induced by the load applied to the yarn. The finer the fiber, the greater is the number of fibers in a particular count of yarn to share the applied load; finer fibers therefore tend to give stronger yarns. The distribution and transfer of tension among fibers in a yarn depend on the length and frictional contact of the overlap of their ends. Longer fibers tend to give longer overlaps. The frictional contact is largely governed by the level of twist; the higher the twist, the higher the frictional contact. Also, the greater the number of fibers present, the greater is the number of frictional contact points. Thus, for adequate frictional contact, a yarn composed of fine, longer fibers will require less twist than one composed of short, coarser fibers. Fine-count yarns have fewer fibers in the yarn cross section and are therefore made from fine, longer fibers.

Fiber rigidity and cohesion are important properties in twist insertion. The intrinsic rigidity of fibers is the property that determines resistance to the twist insertion. Although there are experimental ways<sup>6</sup> of measuring intrinsic rigidity, they are impractical commercially. An intuitive understanding is gained from the elastic modulus of the load-elongation fiber characteristics and from the general knowledge that, the finer the fiber, the easier it should be to twist. The rigidity can be strongly affected by the moisture absorbency of the fiber; the rigidity of dry wool fibers is about 15 times greater than that of wool fibers saturated with water. Thus, the moisture regain of fibers, which can be easily measured,<sup>7</sup> is also important to spinning.

Cohesion is a fiber property that aids spinning, since it is essentially the ability of fibers to hold together in a mass. Cohesion is related to the relative fiber rigidity as well as its ability to blend or mix with other fibers, and it is influenced by the surface characteristics of fibers or by the frictional resistance of fibers. Fiber friction is again a very difficult property to measure, but simple nonstandard tests can be used for evaluating fiber friction.<sup>6</sup>

For fibers to be processed without difficulty through stages I and II, they must have what is termed *crimp*; this is a waviness along the fiber length. Crimp enables the cohesion of fibers during carding, combing, and the drawing stages. However, a high level of crimp can be counterproductive, causing particular difficulties in disentangling the raw fiber mass.

Natural organic fibers usually retain small amounts of wax or grease on their surfaces after cleaning, which is an aid to the disentangling and the drafting actions of the subsequent processes. They also have significant moisture regain. Most fibers exposed to the atmosphere pick up some moisture; the quantity will depend on the relative humidity and temperature of the atmosphere and on the fiber chemistry.<sup>10</sup> The percentage of moisture present, calculated on the oven-dry weight, is the moisture regain of the fiber.<sup>7</sup> The moisture regain of natural fibers assists in dissipating electrostatic charges generated during processing. Electrostatic charges can cause processing difficulties such as fibers sticking to and wrapping around components, and static can also cause a lack of fiber cohesion resulting from the action of repulsion of electrostatic forces. Synthetic fibers have low moisture regain and no natural surface lubricants, so fiber manufacturers apply special surface chemicals as processing aids, commonly referred to as *surface finishes*.

The reader should be aware that, even with a given fiber type (such as the diverse cotton varieties and wool breeds) there are variations, and with man-made fibers, variations occur between different manufacturers' polyester, polypropylene, etc. The sourcing of raw materials that will give the required yarn properties and process satisfactorily on the particular machines making up a process line is essential. Raw materials usually account for 50% or more of production cost and, being a major factor in processing efficiency, strongly influences the remaining 50%, referred to as *conversion costs*. Having outlined, in a general way, the fiber characteristics important to yarn production processes, it is useful to consider these in more detail for cotton, wool, and the manufactured fibers that are processed in sizable tonnages.

### 1.7.2.1 Cotton Fibers<sup>3</sup>

Although cotton is grown in more than 80 countries worldwide,<sup>24</sup> botanically, there are three principal groups of cotton that are of commercial significance.

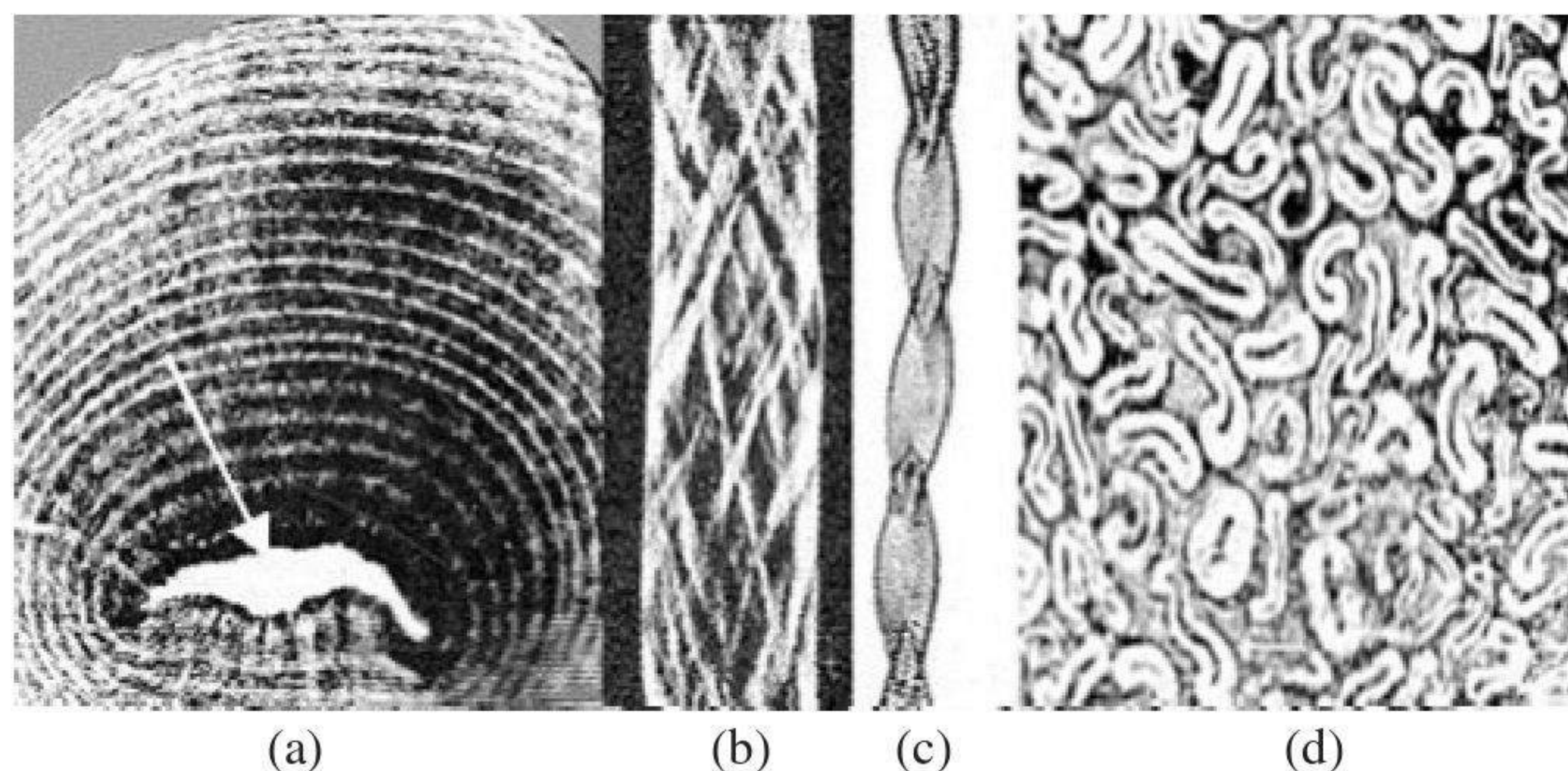
1. *Gossypium hirsutum*. This first group is native to Mexico and Central America and varies in length from about 22 to 24 mm (7/8 to 1 5/16 in.). It accounts for more than 95 percent of U.S. production is commonly called American upland cotton.
2. *Gossypium barbadense*. This second botanical group is of early South American origin and varies in length from 32 to 40 mm (1 1/4 to

1 9/16 in.). It makes up the remainder of U.S. production and is referred to as American pima, or extra-long-staple (ELS) cotton.

3. *Gossypium herbaceum* and *Gossypium arboreum* form the third group, which covers cottons of shorter lengths, 13 to 25 mm (1/2 to 1 in.), that are native to India and Eastern Asia.

A cotton fiber grows in two stages from the surface of the seed coat. During the first stage of its growth, ten days from flowering, the fiber elongates to its full length as a thin-walled tube. As it matures, during a further 35 days after flowering, the fiber wall is thickened by deposits of cellulose inside the tube, leaving a hollow area in the center. These deposits have the form of concentric layers, and each layer is made up of fibrils arranged in a helical manner (which can be seen only microscopically). When the growth period ends and the cotton crop is harvested, the fiber collapses and twists about its own axis. Figures 1.12a through 1.12c depict the cross section of a cotton fiber, where the collapsed central hollow is evident, as are the fibrillar structure and the typical collapsed and twisted longitudinal appearance. As illustrated, the cotton fiber may be divided into four parts. The cuticle is composed of wax and pectic substances. The primary wall consists of very small threads or fibrils of cellulose, and the secondary wall is made up of the concentric cellulosic layers. The collapsed central hollow forms the lumen. It is evident from the fiber cross sections in Figure 1.12d that the thickness of the secondary wall varies from fiber to fiber. There are fibers with thick walls and others with very thin walls. The latter are referred to as *immature fibers*, and there are various soil and climatic reasons for immature growth.<sup>14</sup> Clearly, the mature fibers are stronger.

From the above descriptions, we can reason that the quality of cottons will depend on the fiber length distribution, degree of maturity, fineness, and strength. However, a number of other factors have also to be taken into account. The natural color of cottons is a light to dark cream, depending on the variety and weather and



- (a) 4 parts: –Cuticle; primary wall; secondary wall of concentric cellulosic layers; lumen (arrows).
- (b) –Fibrillar structure
- (c) –Collapsed and twisted longitudinal appearance
- (d) –Fibers of different degrees of maturity

**FIGURE 1.12** Cotton fiber morphology.

soil conditions. However, climatic changes and poor farming practices can result in color discoloration [e.g., brown spots (*spotted cotton*), extensive brown discoloration (*tinged cotton*), or a mottled tan appearance (*yellow-stained cotton*)], which would deteriorate the final shade of a dyed yarn or fabric. Color is therefore an important factor in the cotton quality assessment.

Foreign particles, inevitably, get into the harvested crop and, although the cotton is removed from the cotton seed by saw gins for intensive cleaning, the result can be finer particle contaminants remaining in the cotton mass (referred to as *lint*) that is baled and sold for yarn production. The types of particle contaminant are leaf and seed fragments, sand, dirt, and dust. With intensive cleaning, fibers can be damaged, thereby increasing the amount of very short fibers present in the cleaned mass (the lint).

Batches of cotton can become sticky during processing. Such cottons may reduce processing efficiency, lower yarn quality, cause excessive wear and increased maintenance of machinery, and (in severe instances) mill shutdown, with a thorough cleanup being required. Stickiness occurs when excessive sugars present on fibers are transferred to machinery surfaces. Cotton fibers are largely cellulose formed from sugars synthesized by the cotton plant. Sugars are therefore always present in lint, but they usually occur at levels that pose no processing difficulties. The excess sugars may be insect or plant derived. Honeydew is the main source of excess sugars that can result in sticky lint. Common cotton pests such as aphids and whiteflies ingest sucrose and then transform and excrete it as honeydew. Another source of stickiness is free plant sugars sometimes found in immature fibers. Dry, mature cotton fibers contain little free sugar, while immature cotton contains glucose, fructose, sucrose, and other sugars. Trash content and excess sugar or stickiness therefore are also factors affecting cotton quality.

When considering the quality of cottons, the practice is to refer to cotton classification standards, primarily as established for the above-described three principal groups by the United States Department of Agriculture (USDA). The USDA classification<sup>25</sup> for cottons is based on specific test methods and standardized procedures for measuring the physical characteristics of raw cotton that affect the manufacturing efficiency and/or quality of the finished product. In the past, these qualities were classified by hand-and-eye inspections by experienced classers.<sup>26</sup> Since 1991, classification has been based on objective measurements using precision instruments called high volume instrumentation (HVI),<sup>27</sup> the purpose being to test sizeable quantities as representative samples of a batch of cotton. Currently, cottons are graded by HVI measurements on the following parameters:

- fiber length
- length uniformity
- strength
- micronaire
- color
- preparation
- leaf
- extraneous matter

### *Fiber Length (UHM)*

There are two well known methods of assessing fiber length: the staple diagram and the fibrograph (or fibrogram). Appendix 1B gives a brief description each. The fiber length is determined from the fibrograph and is the average length of the longer half of the fiber span length distribution (i.e., the upper half mean length, or UHM length).<sup>7</sup>

### *Length Uniformity Index (LUI)*

Length uniformity is the ratio of the mean length and the UHM length of the fibrograph and is expressed as a percentage.<sup>7</sup> If the fibers in a bale were all of equal length, the mean length and the UHM would be equal and would give a uniformity index of 100. However, because there are variations in length among cotton fibers, the length uniformity will always be less than 100. The LUI gives an indication of short fiber content, since cottons of low length uniformity index are likely to contain a high percentage of short fibers and would be difficult to process and would produce lower yarn quality. Thus, the length uniformity index is important to yarn production efficiency as well as yarn strength and evenness. The following table illustrates the classification.

<b>Degree of uniformity</b>	<b>HVI length uniformity index (percent)</b>
Very high	>85
High	83–85
Intermediate	80–82
Low	77–79
Very low	<77

### *Fiber Strength*

Strength measurements are made on the same beards of cotton that are used for measuring fiber length. The beard is clamped in two sets of jaws, 12.5 mm (1/8 in.) apart, and the amount of force required to break the fibers is determined. Strength measurements are reported in terms of grams per tex (g/tex). Therefore, the reported strength is the force in grams required to break a bundle of fibers one tex in count. The classification of strength values is as follows:

<b>Degree of strength</b>	<b>HVI strength (g/tex)</b>
Very strong	>30
Strong	29–30
Average	26–28
Intermediate	24–25
Weak	<24

There is a high correlation between fiber strength and yarn strength. Also, cottons of high fiber strengths are less likely to get broken during the manufacturing processes.

### *Micronaire*

This is a measure of fiber fineness and maturity. The micronaire of a cotton is determined by measuring the resistance to airflow of a sample of fibers of a specified mass compressed to a fixed volume.<sup>7</sup> Low micronaire values indicate fine and/or

immature fibers; high values indicate coarse and/or mature fibers. The table below can be used as a guide in interpreting micronaire measurements.

<b>Cotton range</b>	<b>Micronaire reading</b>
Premium	3.7–4.2
Base range	4.3–4.9
Discount	>5.0

Fiber fineness affects processing performance and the quality of the end product in several ways. In the opening, cleaning, and carding processes, low-micronaire, or fine-fiber, cottons require slower processing speeds to prevent damage to the fibers. Yarns made from finer fiber result in more fibers per cross section, which in turn produces stronger yarns, although immature fibers have a negative effect. Dye absorbency and retention vary with the maturity of the fibers. The greater the maturity, the better the absorbency and retention.

Although the micronaire test enables sizable samples to be evaluated, it does not give precise indication of fiber maturity and fineness. The development of better high-volume methods is a requirement, and there is ongoing research into improved test methods.

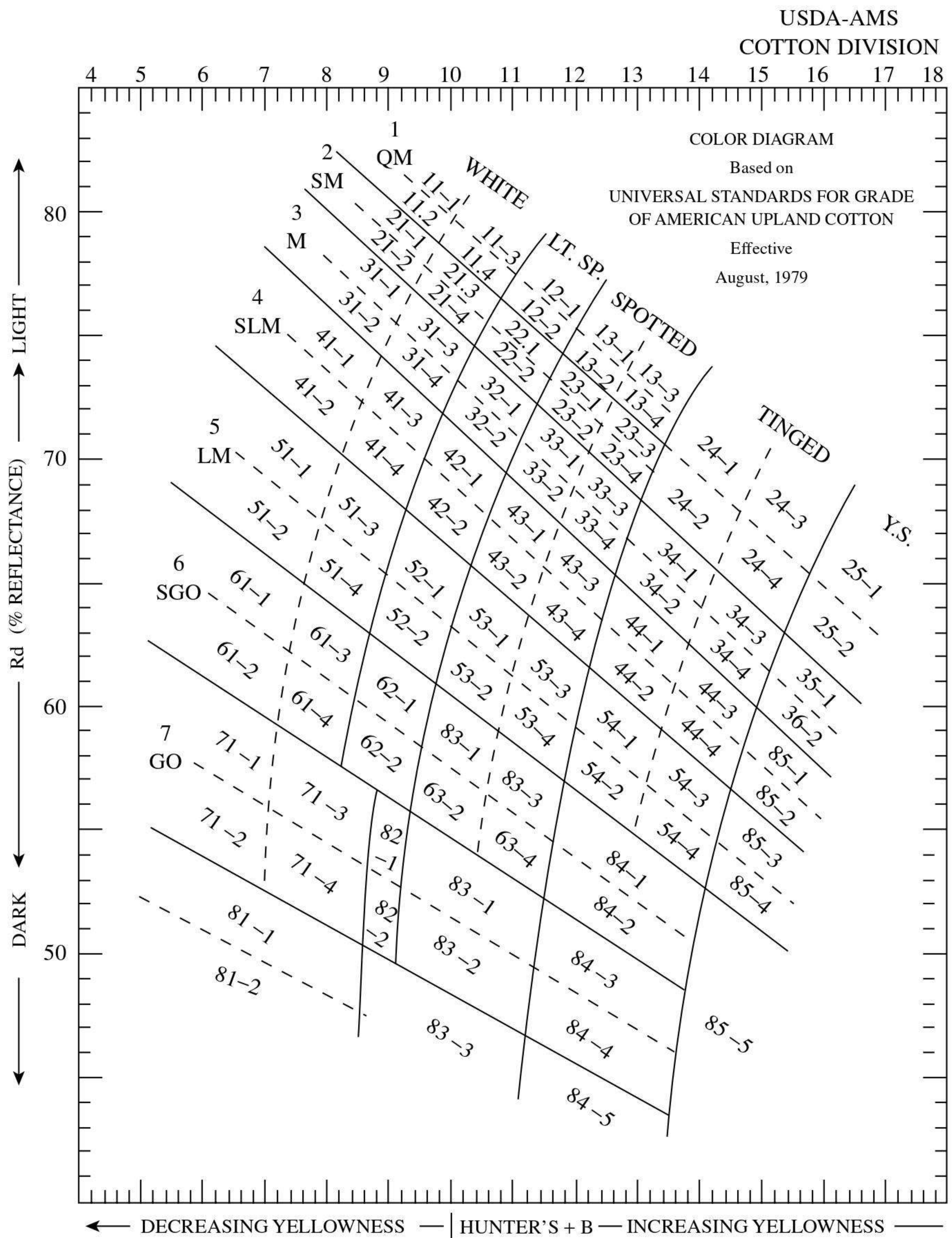
### *Color*

The color of cotton samples is determined from two parameters: degree of reflectance (Rd) and yellowness (+b). Degree of reflectance indicates the brightness or dullness (degree of greyness) of the sample, and +b the pigmentation level in the fibers. There are five recognized groups of color: white, grey, spotted, tinge, and yellow-stained. A three-digit color code is used. The color code is determined by locating the point at which the Rd and +b values intersect on the Nickerson-Hunter cotton colorimeter diagram for cotton variety (see [Figure 1.13](#)).

Even though USDA provides instrument measurements of color, the traditional classer's method of color determination is still used in the industry and is included as part of the official USDA classification. For Upland cotton, there are 25 official color grades plus five categories of below-grade color, as shown in the following table. USDA maintains measured standards for 15 of the color grades. The others are descriptive standards.

<b>Color Grade: Upland Cotton (1993)</b>					
	White	Light Spotted	Spotted	Tinged	Yellow Stained
Good middling	11*	12	13	—	—
Strict middling	21*	22	23*	24	25
Middling	31*	32	33	35*	35
Strict low middling	41*	42	43*	44*	—
Low middling	51*	52	53*	54*	—
Strict good ordinary	61*	62	63*	—	—
Good ordinary	71*	—	—	—	—
Below grade	81	82	83	84	85

\*Physical standards; others are descriptive.



**FIGURE 1.13** USDA color classification.

Small quantities of cottons with intrinsic basic colors of brown, red, and green<sup>27</sup> are commercially available. These fibers are regarded as speciality fibers and are not part of the classification.

*Preparation*

*Preparation* is a term used by classers as an indication of fiber processability in terms of how easily the cotton was ginned, i.e., smoothness or roughness. Various



methods of harvesting, handling, and ginning cotton produce differences in roughness or smoothness of preparation.

#### *Leaf and Extraneous Matter (Trash)*

Trash is a measure of the amount of nonlint material in the cotton, such as leaf and bark from the cotton plant. With HVI evaluation, the surface of the cotton sample is scanned by a video camera, and the percentage of the surface area occupied by trash particles is calculated. The image area is divided by 59,520 pixels or  $248 \times 240$  frame lines, and areas 30% darker than cotton mass are counted as trash particles. This method, however, does not detect seed coat fragments or dust particles. Although there are other long-established methods for measuring trash by weight in the cotton mass,<sup>28,31</sup> the HVI method is preferred for classification because of the speed of measurement. The limitation is somewhat circumvented by relating HVI classification to the traditional classer's leaf grade as indicated below.

The classer's leaf grade is a visual estimate of the preponderance of leaf particles in the cotton. There are seven leaf grades, designated "1" to "7." Extraneous matter is any substance in the cotton mass other than fiber or leaf; for example, bark, grass, spindle twist, seedcoat fragments, dust, and oil are extraneous matter. The kind of extraneous matter and an indication of the amount (light or heavy) are noted by the classer on the classification document. From a yarn production viewpoint, leaf content and extraneous matter are waste, and there is a cost factor associated with their removal. Also, small particles cannot always be removed, and these particles may detract from the quality of the yarn and the finished fabric.

#### **Relationship of HVI Trash Measurement to Classer's Leaf Grade**

Trash measurement (% area)	Classer's leaf grade
0.12	1
0.20	2
0.33	3
0.53	4
0.68	5
0.92	6
1.21	7

Although the above HVI-measurable characteristics form a baseline for raw material specification, there are three further parameters that are of major importance to yarn production efficiency and yarn quality, namely *stickiness*, *nep content*, and *short fiber content*.

#### *Stickiness*

Stickiness is the tendency for the cotton mass to adhere to process machinery. The severity of a stickiness problem will depend on the type of sugar (chemically), on the amount of sugar present, and on the ambient conditions (especially humidity) during processing. Stickiness is consequently a difficult cotton characteristic to

measure. The chemical identity of sugars that are correlated with stickiness may be measured in several ways, each with differing usefulness. Reducing-sugar tests, based on reduction of the cupric ion, are relatively quick and inexpensive, and they may be used to screen cottons for high levels of plant sugar contamination. Using potassium ferricyanide (KFeCN) for the screen test,<sup>29</sup> cottons with reducing sugar levels less than 0.3% usually process without difficulty. Insect sugars are nonreducing sugars. High performance liquid chromatography (HPLC) can be used to measure both reducing and nonreducing sugars.<sup>29</sup> The main insect sugars [honeydew, trehalulose (from whiteflies) and melezitose (from aphids)] and plant sugars (glucose, fructose, and sucrose) are easily identifiable by this test. HPLC is, however, a relatively slow test and does not indicate how a sugar-contaminated cotton may actually perform during processing.

There are three commercially available performance test instruments,<sup>30,31</sup> the minicard (MC), the high-speed stickiness detector (H2SD), and the fiber contamination tester (FCT). With the MC device, a web of fibers is passed between stainless steel rollers, and the degree of stickiness is rated on a scale of 0 to 3, where 0 is no stickiness and 3 is the severe level. The test is carried out under a controlled environment of 24°C and 55%RH. The test has the major disadvantage of being slow. In addition, the rating is a subjective assessment (i.e., operative dependent), and it is unable to assess cottons usefully with high plant sugar evenly distributed along the fibers. The H2SD uses image processing to measure the number of sticking points and the point size distribution on aluminum plates between which a cotton sample has been pressed. The measurements are made for heated (54°C for 30 s) and unheated pressings. The FCT also measures sticking points, but on pressure rollers after a thin web has passed between them, and in a conditioned environment of 65% RH. A laser beam is used to scan the contaminated rollers to allow the sticking points to be counted. The H2SD and FCT are fairly rapid tests, taking 30 and 45 s per test, respectively.\*

### *Nep Content*

There are various definitions of a nep,<sup>32,33</sup> but the following is the most informative: *A nep is a small, tangled knot of fiber often caused by processing fibers.* It is informative because it indicates that nep is not a fiber property but may result from passing fibers through process machinery. Thus, in ginning, neps are readily formed and are an unwanted part of the cotton mass characteristic. There is a high association between neps in the ginned cotton and neps in the resulting yarn. Neps in yarns result in spottiness of dyed or printed fabrics, which lowers the market value of the end product. Neps, consequently, not only need to be removed during yarn production processes, thereby adding to the waste, but also should be prevented from forming by these processes as is explained in [Chapter 3](#). The *neppiness* of the raw

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\* Only the H2SD method is approved by the International Committee for Cotton Test Methods (ICCTM), but more research is required to minimize inter-laboratory variations. The purpose of the ICCTM is to establish suitable harmonized test methods for cotton. The H2SD was developed by CIRAD (Centre de Coopération Internationale en Recherche Agronomique pour le Développement) in Montpellier, France, and is sold by SDL International Ltd., in Manchester, UK, and SDL America Inc., in Charlotte, NC.

cotton, following ginning, may be seen as indicative of the nepping potential of the cotton batch.

Research<sup>34</sup> into the relationship between nep potential and fiber properties has shown that fine fibers and immature fibers have a tendency to become neps. There is a linear correlation between micronaire and the neppiness of processed fibers; the neppiness decreased with increased micronaire values, and it was observed that neppiness in yarns was significantly correlated with the amount of immature fibers in the lint.

The recommended method<sup>30,31</sup> for nep measurement is with the Zellweger Uster Advanced Fiber Information System (AFIS). The AFIS nep tester gives the average number of neps per gram in the fiber mass and the average nep size in millimeters.

### *Short Fiber Content (SFC)*

Like nep content, SFC is usually the result of mechanical processing of the cotton lint. There are, however, a number of factors that influence the resulting amount of short fibers. Clearly, the strength of a fiber is related to its ability to withstand mechanical stresses during processing. Growing conditions affect the cotton maturity and therefore its strength, but the factors most influential to SFC are harvesting and ginning.<sup>35</sup>

Picking and stripping are the two major mechanical methods of harvesting cotton. With picking, revolving spindles are used to twist the locks of cotton from the open bolls, whereas strippers employ fingers or brushes to remove all the cotton bolls from the stalk — both mature and immature bolls. The immature cotton bolls are either not opened or only partly opened, and the picker cannot pull cottons from such bolls. Thus, harvesting with strippers results in more immature and weaker fibers, and stripped cotton contains more foreign particles. Despite these disadvantages, stripping has become the preferred process because of its production efficiency, and because the market system gives a premium for clean cotton. Since grading of cotton does not include SFC, farmers tend to promote intensive ginning. This practice results in significant levels of SFC in the ginned lint. SFC has a negative effect on the yarn production process and on the yarn quality, and therefore quantifying SFC is of commercial importance.

There are various methods for determining SFC, and all have one or more shortcomings with respect to variability, reliability, sample volume, and rapidity of test procedure. However, the aligned comb sorting techniques such as the Baer, Shirley, and Suter Webb, which manually produce fiber length distributions by either counting or weighing the measured lengths of the fibers in a sample, are the ones that give the best estimate of SFC.

In determining the amount of short fibers present in a batch of cotton, the absolute and the relative SFC are often considered. The latter is calculated as defined by Lord<sup>28</sup> from a fiber length distribution (i.e., staple diagram). (See Appendix 1C.) The absolute SFC is defined as the proportion of fibers shorter than a specified length. The specified length can vary from one geographical region to another but is within the range of 6 to 25 mm (~1/4 to ~1 in.).<sup>36</sup> In the U.S., all fibers shorter than 12.7 mm (~1/2 in.) are defined as short fibers; countries employing metric units set 12 mm as the specified length.

With the need for high-volume rapid sampling for commercial practicality, there is much interest in the use of automated systems. Sanderson<sup>37</sup> and Muller<sup>38</sup> report results of comparisons of HVI, the Almeter AL-100, and Suter Webb. It was found that, for a specified length of 17 mm, both automated test devices gave results that showed good correlations with Suter Webb values, but the Almeter had the best correlation. Other researchers<sup>37</sup> have reported the following equations relating SFC to span length (SL) measurements:

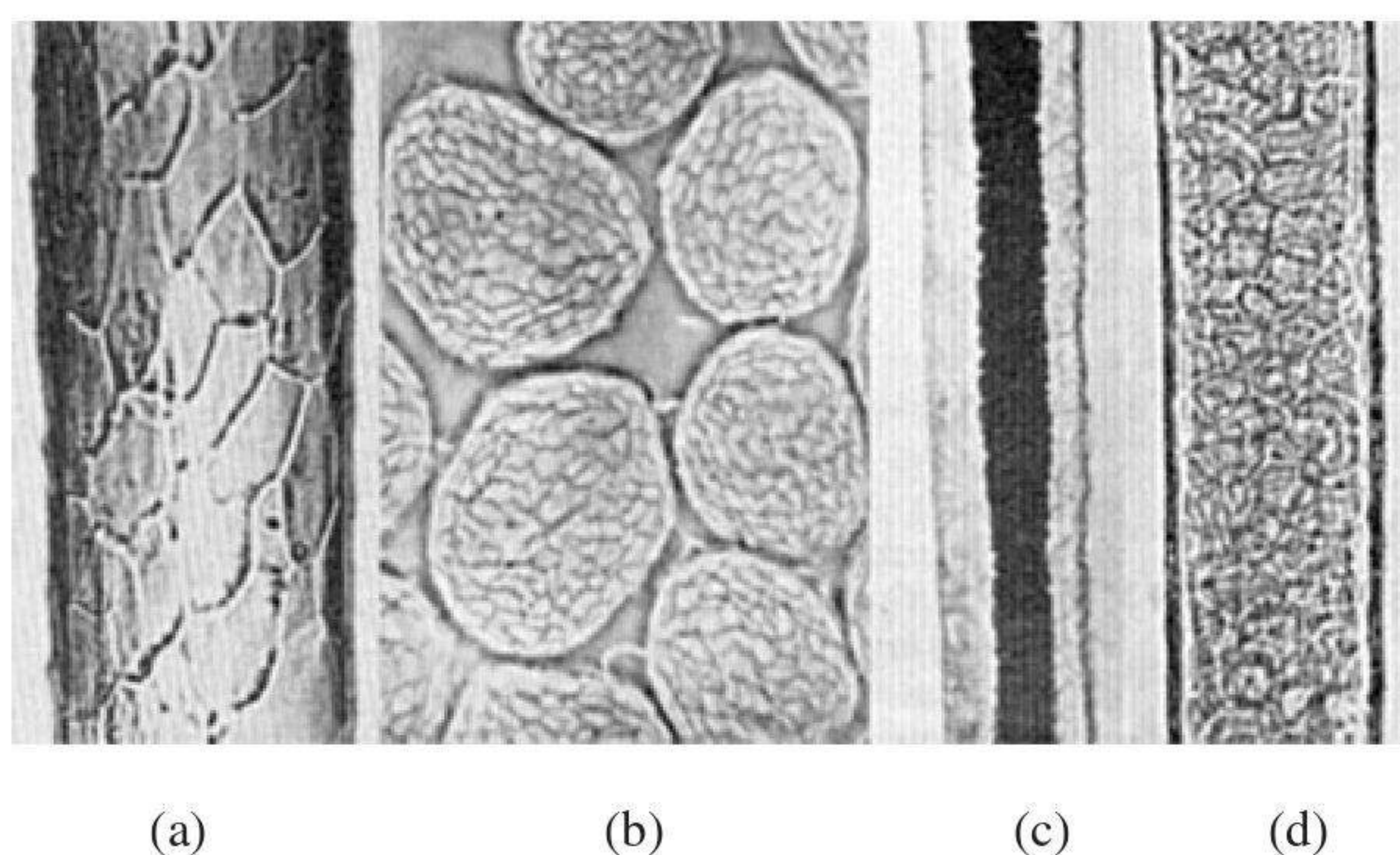
$$\text{(Preysch formula) } \text{SFC} = 39.4 + (1.3 \times 2.5\% \text{ SL}) - (4.5 \times 50\% \text{ SL})$$

$$\text{(Ahmad and Kahn) } \text{SFC} = 4.17 (12.5\% \text{ SL}) - 9.1(50\% \text{ SL}) + 41$$

### 1.7.2.2 Wool Fibers

Wool is an animal hair fiber that, chemically, is made of a naturally occurring protein called keratin. This is a general definition that would include the body hairs of many animals but, in common parlance, the word is used for the body hair of sheep.

Wool is a complex layered structure, as shown in Figure 1.14, largely comprising a sheath of protective overlapping scales called *cuticle* (or *epidermis*) cells; within the sheath is the bulk of the fiber, called the *cortex*. The cuticle cells make up 10% of the fiber, and their overlaps are always away from the fiber end nearest the skin (the base) and toward the opposite end (the tip), causing the fiber surface to have a serrated surface appearance. In the loose state during processing, the scales on fibers can catch in one another and give considerable frictional resistance. The cortex



- (a) –Overlapping scales of cuticle or epidermis cells giving serrated surface appearance
- (b) –Fiber cross sections showing cortex
- (c) –Longitudinal cross section showing hollow medulla
- (d) –Longitudinal cross section showing medulla lattice

**FIGURE 1.14** Wool fiber morphology.

consists of many long, spindle shaped cells — cortical cells — that microscopically are made up of microfibrils held together by strong natural binding materials known as the *para* and *orthocortex*, each with slightly differing properties that give wool fibers their characteristic *crimp*, or small curls. The cortex constitutes 90% of the fiber and determines the physical properties of the fiber. In particular, it is highly moisture absorbent and is able to carry water equivalent to 30% of its dry weight before feeling damp. When wet, the proteins in the wool fibers also release heat, all of which make it a suitable fiber for garments worn next to skin. The hydrophilic core of the fiber takes up heat given off from the human body in the form of water vapor; it has a good capacity to absorb body perspiration. Static electricity in garments can cause discomfort, but, in wool fabrics, the moisture absorbency of wool reduces static charge buildup.

With some wool, usually medium and coarse wools of around 70 to 200  $\mu\text{m}$  diameter, there is a central layer — a cellular marrow or medulla that forms an air-filled honeycomb-lattice-like structure within the cortical layer.

Kempy fibers are short, wavy, very coarse, and brittle, and they taper along their length toward each end. They are of a ribbon-like cross section, strongly medullated, smooth and opaque in appearance, and mainly present in mixed wools such as carpet wools.

The density of wool is one of its fundamental characteristics, which, for practical purposes, seems to be fairly constant in all varieties of the fiber. (Measurement in benzene gives a value of 1.304  $\text{g}/\text{cm}^3$ ; solid keratin is 1.31  $\text{g}/\text{cm}^3$ ). Medulla wools tend to have lower density — particularly kempy wool.

Wool of some variety can be found in most countries of the world, but the commercially significant wools (the parlance used is *wool clips*) are from Australia and New Zealand. South Africa, Uruguay, China, the former Soviet Union, Turkey, and the UK are also sizeable producers, the former two of fine wools the latter three mainly of coarser wool. (The UK is the largest producer in Europe.)

Australia dominates the world market for fine wool fiber suitable for worsted processing (mainly in the region of 17 to 25  $\mu\text{m}$  diameter), having over 30% of the world's production and around 50% of the total exported volume of greasy wool. The wool comes from Merino sheep that represent around 75% of Australia's sheep numbers. New Zealand wools are crossbreds (crossbred sheep result from crossing Merino sheep with other types, mainly the Romney breed),<sup>39,40</sup> accounting for 10% of world production and 20% of wool exports. This breed produces wool that is stronger, longer, and coarser than Merino wool, but it is much less crimped and bulky. About 70% of the New Zealand wool clip is greater than 32  $\mu\text{m}$  diameter (typically 33 to 35  $\mu\text{m}$ ) and is processed into yarns mainly by the woollen spinning route; end uses include carpets, blankets, furnishings, Shetland-style knitwear, and hand-knitted yarns.

As regarding the trade classification of wool, the available types are broadly classified as

1. Merino
2. Crossbreds (fine, medium, and coarse)
3. Carpet-wool types

But there are many grades of wool within these groups. Generally, merino fibers have the finest diameter and shorter lengths than carpet wools, which are known to be long and coarse.

Usually, wool is obtained by shearing the fleece off the sheep's back once a year. A 12-month growth is required for the worsted sector, but, for lambswool products, wool is shorn from a lamb not older than 7 months, and wools (referred to as *slipe* or *pulled* wool) are also removed (pulled) from the skins of slaughtered sheep. The shorn fleece is appraised for quality and *skirted* by removing badly contaminated pieces of wool (e.g., paint markings, etc.) from the neck, legs, belly, and rump areas. These heavy contaminated parts (see Table 1.7) are rejected or may be grouped and sold for some woolen yarn production.

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**TABLE 1.7**  
**Wool Contaminants and Treatments**

<b>Impurity</b>	<b>Description</b>	<b>Cleaning process</b>
Accretions	Pigmented fibers (black)	General sorting, dispensing, and scouring
Secretions	Dung, etc.	
Excretions	Grease, sweat	
Organic and mineral impurities	Parasitic insects, vegetable matter, sand and dirt particles	Carding, carbonizing for heavy contamination
Markings	Paints, etc.	Sorting and dispensing
Chemical treatments	Dips, pesticides	Scouring

---

Wool fibers vary in length, diameter, and other properties from one part of the sheep to another. The fleeces are sorted by dividing the wool into various matchings based on length, waviness, and a general appearance of characteristics. Traditionally, the wool sorter's matchings were given quality numbers, such as 70s, 64s, 60s, etc.; the higher the number, the better the quality of the wool. Thus, wool classifications with their average quality numbers typically would be

1. Merino wool, 60s and above
2. Fine crossbreds, 56s to 58s
3. Medium crossbreds, 46s to 50s
4. Low crossbreds, 44s
5. Carpet-wool types

At one time, these numbers were related to the fineness of worsted yarn count into which the fiber could be spun, but this is no longer the case. Although wool quality numbers may still be referenced, wools are sold by their measured properties, i.e., objective specifications or "sale by description." Objective specifications may include measurement of

1. Fineness (mean fiber diameter and distribution)
2. Length and distribution
3. Tensile properties
4. Vegetable matter content
5. Bulk
6. Medullation
7. Color
8. Grease content and yield
9. Moisture content

These properties are important to processing performance and to the basic characteristics of the end products. Properties 1, 2, and 4 are also measured during preparation stages in yarn production so that appropriate spinning conditions can be used to obtain optimal yarn quality. The International Wool Textile Organization (IWTO)\* has recommended test procedures for determining these properties.

### *Fineness*

The average fineness of a wool clip is an important dimensional characteristic greatly affecting its processing value. Unlike cotton and man-made fibers, the wool fineness is traditionally expressed by the average of the measured diameters, in microns, rather than a measure of its linear density, which nevertheless can be calculated.

The mean fiber diameter can be used to estimate the finest spinnable yarn count according to minimum number of fibers required in the cross section; 40 for worsted spinning, and 100 for woolen spinning.<sup>41</sup> The mean fiber diameter therefore influences spinning efficiency and yarn quality. It also affects fabric handle, and, in the apparel market, the demand for lighter garments with the highest possible comfort has meant a low micron value being equated with quality. Worsted yarns are generally used for apparel, and fiber fineness therefore is a critical factor. Woolen yarns for carpets are seldom spun near the minimum number, so there is flexibility in selecting the mean fiber diameter. However, lambswool and Shetland woolen yarns for apparel are often spun to as fine a yarn count as possible.

Fine fibers give a soft handle and therefore greater comfort. For garments worn next to the skin, the mean fiber diameter in the spun yarn should be less than 28  $\mu\text{m}$ . This is not an exact limit, but it is referred to as the *itch point* or comfort limit, because people generally experience discomfort if greater than 3 to 4% of the fibers in the yarn are coarser than this value.<sup>42,43</sup>

The fibers of merino wools have diameters of 10 to 30 microns. As a result, the mean of a given mass can be from 15 to 25  $\mu\text{m}$ . Merino wools are suitable for garments worn next to the skin. Blends of wool incorporating coarser fibers can be made to give an average diameter of 25  $\mu\text{m}$ , but the fineness range can be 15

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\* The International Wool Textile Organisation (or IWTO) represents the wool and wool textile industries worldwide. It links participants of the entire wool pipeline, from producers of the raw material through traders and early stage processors, and on to the late-stage spinners and weavers. Founded in 1927, IWTO membership currently includes 23 countries. IWTO provides a forum for discussion of problems that affect the wool industry internationally.

to 45  $\mu\text{m}$ . Thus, for comfort garments, both the mean micron value and the distribution should be as small as possible.

Although wool fineness is always given as a diameter, strictly speaking, the cross-sectional shape of wools can vary greatly; some are nearly circular, and most have varying degrees of ovality or ellipticity. A suitable way of expressing the ellipticity is by the ratio of the major to minor axis to give what may be called a *contour figure* (CF). Generally, fibers of CFs less than 1.22 will process acceptably well.<sup>39</sup>

### *Fiber Length Measurements*

The measured parameters may be separated according to the state of wool and the processing route. For greasy wools, the staple length is measured along with the staple strength (see “Tensile Properties” below), whereas parameters associated with the fiber length distribution are determined following initial processing of the greasy wool through to combing in the worsted sequence (the wool state being referred to as *combed top*) or carding for semi-worsted (the *card sliver* state). In woolen spinning, reference may be made to the *length after carding*, which effectively deals simultaneously with the staple length and staple strength.<sup>41</sup>

Once wool is in combed top or card sliver state, little further change in length or strength occurs, provided appropriate process conditions are used. In these material forms, the IWTO-recommended wool length measurements are the Hauteur, H, the Barbe, B, and the 30- and 40-mm short-fiber content. The Hauteur is the mean of all fiber lengths related to number of fibers in the wool sample. Yarn spinnability improves with increasing hauteur, although beyond 80 mm, the improvement is only slight.

Hauteur and the CV(H) (the coefficient of variation of the fiber lengths) can be obtained from the hauteur diagram, which is similar to the staple diagram. The hauteur diagram indicates the percentage number of fibers that exceed a stated fiber length. Thus, subtracting this percentage value from 100 gives the percentage of fibers shorter than the stated length. The optimal CV(H) for spinning purposes is between 42 and 52%.<sup>44</sup>

Barbe is the fiber weight biased mean length, and along with CV(B), it can be obtained from a fiber weight diagram. Like the hauteur diagram, every point on the fiber weight diagram indicates by what percentage of the sample weight a particular fiber length is exceeded, and the amount by which this percentage differs from 100% indicates the weight percentage of the shorter fibers in the sample. The coefficient of variation of fiber lengths, CV(B), indicates how much the individual fiber weights vary from the weight biased mean length, B. The optimum for spinning is around 30 to 33%.<sup>44</sup>

The time between successive shearings of sheep will influence fiber length values, and the longest lengths are associated with coarse fiber types for carpet yarns. Good hauteur values for worsted spinning are from 60 to 80 mm with short fiber content < 30 mm of 7 to 15%. Lambswool can have mean fiber lengths ranging from 30 to 55 mm, with CVs around 35%. The better qualities are at the higher end of the length range and can include shortened worsted grades, i.e., broken top; poor quality lambswool has mean lengths around 20 mm and CVs as high as 70% and may include carbonized wool. This is where part of the fleece that is heavily



contaminated with vegetable matter is chemically and mechanically treated for cleaning. (See [Chapter 2](#).)

### *Tensile Properties*

In general terms, the breaking load is the force required to rupture a single fiber or group of fibers, whereas tensile strength is the breaking load normalized by the measured linear density of tested sample. There are three measures of wool tensile strength: the fiber strength, staple strength, and bundle strength. As may be expected, coarser fibers have greater breaking loads, but the material strength may be the same as finer fibers. There are natural variations along the fiber length that introduce variations in strength, and seasonal changes or poor husbandry can cause nutritional influences resulting in thin sections along fiber lengths and thereby weaker or tender fibers.<sup>45</sup>

The three measures of strength will not necessarily give identical values. The single strength is a true measure of fiber strength but, to be meaningful, many fibers have to be tested. Testing is therefore tedious, costly, and generally not suitable for commercial practice. The staple and bundle strengths, being based on a fiber group, will be influenced by how parallel the fibers are in the group. Nevertheless, these may be used in forecasting yarn quality and processing performance, i.e., predicting yarn strength and spinning performance.

A staple is a well identified bundle of fibers that is removed from a mass of greasy wool as a unit, and the strength of this bundle is usually accepted as a measure of the wool strength. Usually, the staple length is first measured, then the staple is stretched to its breaking load and the broken staple weighed. The linear density is calculated from the weighed mass and measured length, and the normalized load gives the staple strength in newtons per kilotex (N/ktex). The test is usually carried out on the automatic tester of length and strength (ATLAS) instrument, which measures the staple length by photoelectric scanning.

The results of work carried out by the Australian wool research organization CISRO<sup>46</sup> show that H and CV(H) values of tops can be reasonably well predicted from measurements of raw wool using the following formulas.

$$\text{Hauteur} = 0.52 \text{ SL} + 0.47 \text{ SS} + 0.95 \text{ D} - 0.19 \text{ M}^* - 0.45 \text{ VM} - 3.5$$

$$\text{CV(H)} = 0.12 \text{ SL} - 0.41 \text{ SS} - 0.35 \text{ D} + 0.20 \text{ M}^* + 49.9$$

where SL = staple length  
SS = staple strength  
D = fiber diameter  
M\* = adjusted% middle breaks  
VM = vegetable matter base (see below)

Wool has useful elasticity. When slowly elongated without rupture and then subsequently released, it will recover, initially showing a temporary set extension that is slowly lost with time; wool fibers can be elongated up to 30% and fully recover

with time. This inherent elasticity is a contributory factor to the ability of wool to recover from wrinkling, particularly noticeable in lightweight fabrics.

### Color

Wool from most domesticated breeds of sheep is nearly always white, although the degree of whiteness may vary considerably, and some pigmented fibers can be present as contaminants. However, years of breeding have resulted in the majority of wools containing a negligible amount of such fibers. Greasy wool may be discolored, usually varying in shades of grey or yellow. Most of this color is removed by scouring, as it is largely caused by grease and dirt. Some stains are not scourable, in which case the fibers may be dyed a dark color.

Measuring the color of the substrate is an important part of modern dyehouse practice. Discoloration restricts the colors to which wools can be dyed, so white wools are preferred. Wool color measurements should be carried out on scoured samples. This is termed the *base color* or *clean color*. If color measurements are to be made of uncleaned wool samples the values are called *as-is color*. Tristimulus\* values X, Y, and Z are determined to identify the precise color. Y is associated with brightness, and Y–Z is a measure of yellowness. A bright white wool has a high Y value and a low Y–Z value. Typical values for wools of good, average and poor color are as follows:

Tristimulus Values				
Color assessment	X	Y	Z	Y–Z
Good	60.0	61.5	58.5	3.0
Average	56.1	57.1	52.0	5.0
Poor	51.5	52.8	45.3	7.5

N.Z. Standard 8707:1977.

### Vegetable Content, Grease, and Yield

Greasy fleece contains moisture absorbed by the fiber, wool grease (lanolin), suint (perspiration), pesticides, dirt, and vegetable matter. It is of commercial importance, therefore, to establish the actual percentage of pure dry wool in a consignment of greasy wool, i.e., the yield. The main producing countries follow a market procedure where wool bales are sampled and tested before auction so that buyers see a representative sample and full test information prior to sale.

The percentage of the impurities varies considerably in the different classes. Merino quality will contain around 45 to 55% of impurities. New Zealand wool usually contains less than 1% vegetable matter. These impurities may be categorized as indicated in [Table 1.7](#). The table also indicates the production stages in which the impurities are removed during yarn manufacture. Importantly, the advent of pollution control measures [e.g., European Pollution Prevention and Control (IPPC) Directive 96/61/EC] means that the scouring process (see [Chapter 2](#)) has to conform to environmental best practice for scouring effluent so as to meet the stringent

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\* Color is determined by tristimulus values defined by Commission Internationale de l'Eclairage (CIE) publication for illuminant D65.

**TABLE 1.8**  
**Comparison of Fiber Properties for Staple-Spun Yarns**

Fiber type	Fineness (dtex)	Staple length (mm)	Tenacity (cN/tex)	Breaking extension (%)	Density (g/cm <sup>3</sup> )	Percent moisture 20°C/65% RH
Cotton	~1.7	<40	34	7	1.52	7
Wool	2.2–38	35–350	10 <sup>b</sup> 15 <sup>c</sup>	40	1.31	17
Cellulosic:	1.3–3.3	Cut to any length required in manufacture				
Rayon			12–20 (8)	25 (35)	1.52	12–13
Lyocell			35 (29)	14		
Polyamide	<1 <sup>a</sup> –18		49–38	22–45	1.14	4
Polyester	<1 <sup>a</sup> –6		35–31	25–40	1.38	0.4
Polypropylene	2.2–120		80–75	17–20	~0.9	0
Acrylic	<1 <sup>a</sup> –22		25–20	28–35	1.14–1.17	1–2

a. microfibers 0.5–0.9 dtex

b. single fiber

c. staple bundle wet strength

regulations imposed. This, in turn, means a stronger shift to wools of low residue, particularly with respect to pesticides applied externally to sheep (ectoparasitocides).

### *Crimp, Bulk, Lustre, Resilience*

Crimp, which is usually measured microscopically, occurs in the form of waves or curls along the fiber length and gives wool its natural resilience. The number of waves is closely associated with fiber fineness; finer fibers generally have more crimps per inch. Fiber crimp is a major factor affecting yarn bulk in that crimped wool produces more bulky yarns. Loose wool bulk — an indirect measure of fiber crimp — is closely linked with yarn bulk, which is related to cover in a carpet, and in woven or knitted fabrics.

Resilience is the springiness of a fiber mass, or the ability of a fiber to come back to its original volume after compression. There is a strong correlation between compressibility, yarn bulk, and covering power. Resilience is important in wool, as it enables wool fabrics to retain shape, have good drape, and resist wrinkling. It is also a property that is highly desired in carpet wools.

Wools vary in lustre, and lustrous wools can be difficult to process, as they are less cohesive. In carpets, such wools are associated with shading effects. Lustre is inversely correlated with bulk, so measurement of bulk can advantageously be used to assess lustre where lustre is required.

### *Medullation*

The hollow medulla cells reflect light and make medullated fibers, especially kempy fibers, appear opaque. When these fibers are dyed together with nonmedullated

fibers, they look much lighter because of the reflected light. In fine wools, the percentage of medullated fibers is very low, ~0.1%. Their presence may be detrimental to the wool quality. They are more difficult to spin, introduce a harsh handle (feel) to fabrics, and, by their tendency to give a lighter shade, can be a cause of uneven dyeing faults in fabrics, producing a “tippy” effect.

These hollow fibers are sometimes considered to be desirable in carpets, because they impart improved resistance to compression of the pile. Their stiffness gives increased bulk to yarns and a firmer handle and resilience to carpets. Yarns become much hairier, which is desirable for Berber carpet yarns. However, with light, plain shades, medullated wool is undesirable. New Zealand Drysdale wool is a medullated fiber that is used in blends for carpet yarns.

### 1.7.2.3 Speciality Hair Fibers

Animal fibers, other than sheep’s wool, that are used in the production of textile fabrics are generally classified as speciality hair fibers (see [Figure 1.10](#)). They may be spun in their pure form (i.e., 100%) or as a blend component for enhanced fabric aesthetics, especially for increased fabric softness and lustre. Because of their properties giving exceptional fabric aesthetics, they are also commonly referred to as *luxury fibers*.

Luxury fibers, which include silk, are not produced in large quantities, but their much-desired sensual characteristics make them important raw materials in the luxury apparel and fine furnishings sectors. The more important of the speciality hair fibers are from the goat family; the Angora goat that produces mohair fibers and the Kashmir goat from which we obtain cashmere fibers.

Mohair accounts for only 0.1% of the global production of natural fibers, i.e., 15,000 tonnes ([www.fao.org](http://www.fao.org)) compared with approximately 19 million tonnes for cotton and 1.3 million tonnes for wool. An accurate figure for cashmere fiber production is difficult to acquire. However, current estimates of global production of the fiber are within 4500 to 5000 tonnes.

#### *Mohair*

Mohair is the hair fiber that forms the long lustrous coat of the Angora goat, *genus Capra*, a species indigenous to Turkey but said to have originated in Tibet (although this is subject to speculation). The Angora breed is thought, however, to be around 3000 years old and to have evolved within the Anatolian Plains of Turkey, close to the modern city of Ankara (formerly Angora), from which the breed derives its name. The name for the fiber (mohair) comes from the Arabic word *mukhayyar* [mukhyar] meaning “best of the selected fleece.” Today, the major producers of mohair are southern Africa (South Africa and Lesotho), followed by the U.S. (Texas). Other significant but much smaller producing countries are Turkey, Argentina, Australia, and New Zealand.

Mohair is a very hard wearing and versatile fiber, which is used in its pure form and in blends for both clothing and furnishing fabrics. Mohair fibers give good comfort fabrics; besides being a desired raw material for warm winter luxury garments, the fibers are also processed into suiting fabrics that are comfortable to wear in humid conditions and are popular in the Far East, particularly in Japan. About

12% of total mohair production goes into furnishings, such as upholstery velours and moquettes; mohair fiber gives these fabrics good soil and pill resistance and also has useful flame resistance and high sound absorbency.

### *Types of Fleeces*

Based on the formation of the lock, there are three primary types of fleece.

1. Tight lock (which is in ringlets along its length)
2. Flat lock (which is wavy and gives a bulky fleece)
3. Fluffy fleece

The preferred fleece is the tight lock, but the fiber of the flat lock has acceptable properties. The fluffy fleece is open in character, and the fiber is weak and of the lowest quality.

Fleece quality is determined by the diameter, lustre, and softness of the fibers; by the yield after scouring; and by the level of kemp fiber contamination. Grading is based primarily on fiber diameter, and the age of the goat is probably the most important factor in terms of both the quality and the quantity of mohair produced.

Fleece production increases from birth and peaks at approximately three or four years of age, averaging around 4 to 5 kg p.a. for females and 5 to 6kg p.a. for males. Kid mohair is generally from offspring less than a year old; it is the finest and softest mohair fiber and is used for high-fashion garments. The fiber from a one- to two-year-old goats is termed *young goat mohair*; this is longer than kid mohair and has acceptable softness and lustre. *Adult mohair* is the material from animals over two years old, which give the longer and coarser fibers.

The unwanted part of the fleece is the kemp fibers. These are short, very medullated, coarse fibers that have reduced dyeability and, in the dyed fabric, appear lighter in color than the finer mohair fiber. Kemp is undesirable in a fleece, and various genetic selection breeding programs are underway in producer countries, aimed at eliminating or reducing kemp fibers to negligible levels.

### *Physical Properties*

The unscoured raw fiber has a yellowish or greyish-white color and contains 15 to 25% impurities such as sand, dust, and grease, the latter being less than 4%. After scouring, the fiber becomes lustrous, and the best qualities are clear white. On average, Angora goats grow fiber at a rate of 20 to 25 mm per month, so the staple length depends on the time of shearing. Half-year growths range from 100 to 150 mm, and a full-year's growth is around twice the half-year length. Because of the differing ages of the kids at shearing, the length distribution is wider than for young and adult goats.

Fineness is the main factor of importance. The fiber diameter increases with the age of the goat. Kid's fleece has an average fiber fineness of 23 to 30  $\mu\text{m}$ , with a dispersion of 11 to 35  $\mu\text{m}$  at the finer end and 14 to 40  $\mu\text{m}$  at the coarse end. The fineness of young and adult goat fleeces may range from 30 to 60  $\mu\text{m}$ , with corresponding dispersions of 15 to 50  $\mu\text{m}$  and 35 to 90  $\mu\text{m}$ .

Mohair, like wool, consists of the protein keratin. Microscopically, the fiber structure is also similar to wool, but there are important differences that give it its desirable characteristics. The epidermal scales are less distinctive than wool and are only slightly overlapping, lying close to the stem. The scale length ranges from 18 to 22  $\mu\text{m}$ , and there are about 5 scales per 100  $\mu\text{m}$ , compared with 10 to 11 for a fine wool fiber. These differences give the mohair fiber its smooth texture and high lustre, since light rays are directly reflected, rather than scattered, from the smooth surface.

The cortical layer appears as clear striations throughout the fiber length and, with some fibers, cigar-shaped air pockets, called *vacuoles*, are present between the spindle-like cells of the cortical layer. These air pockets appear as black dots in the fiber cross section. The cross section has a high degree of circularity; the major–minor diameter ratio is around 1.12.

The number of medullated fibers is usually less than 1%, and the continuous medullas are the most common type, but interrupted or fragmented types can be present.

### *Cashmere*

Called the “fiber of kings,” cashmere fiber has long been valued for its luxurious softness, and its use in Western civilization can be dated back to Roman times. The fiber comes from the Kashmir goats (*Capra hucus laniger*), from which the name of the fiber is derived and which originated in Tibet. These goats are farmed in the mountainous regions around the Himalayas and Central Asia, particularly the regions around the Gobi Desert (i.e., Tibet and Mongolia) and in Turkestan and the Kashmir region of Northern India. The natural color of cashmere may be white, grey, or tan, and the goats of the Gobi desert region give the much-preferred white fibers. Variants of the breed are found in Iran, Afghanistan, and, to a lesser extent, Turkey. The fiber from these goats is less desired because of its darker color and the coarseness of the fiber, which results in an end product that is not as desirable as that obtained from the white fiber.

The knitting industry is the largest user of cashmere, especially that of the United Kingdom; Scotland is one of the biggest markets outside of China. White, unpigmented cashmere fiber is preferred, because it is the easiest to dye, giving an unblemished color, particularly pastel shades. As a consequence, 60% of the total world production of cashmere fiber comes from China, which amounts to around 3000 metric tonnes. The finest cashmere is produced north of the 40th parallel in Inner Mongolia, north of the Yangtze River, and Inner Mongolia accounts for about 70% of the Chinese production. The less desirable darker fibers are processed mainly for woven cloth.

The Kashmir goat has an outer coat of predominantly straight, coarse, and long “beard” or “guard” hairs and a smaller amount of fine downy undercoat fibers grown during the winter months under the more weather-resistant guard hair. The undercoat fiber is the material that is wanted, and it was traditionally made into shawls, called *pashmina*, by the villagers in the Kashmir region. During the warmer spring period, the down moults and can be removed from the coat by combing or shearing. Traditionally, the two fiber types were separated by hand, but the commercial practice is to use mechanized systems of fiber separation.

### *Physical Properties*

Cashmere undercoat fiber is composed of a cortical layer and epidermis. There are approximately 6 to 7 scales per 100  $\mu\text{m}$ , which slightly project beyond the cortical layer to give the fiber a serrated appearance. The fiber length varies from around 32 to 90 mm. The fiber is effectively circular; the average fiber diameter of a sample of the undercoat is likely to be within 12.5 to 21  $\mu\text{m}$  with a coefficient of variation on the order of 18 to 20%, which means the fiber is of a fairly uniform fineness. Chinese cashmere is at the finer end of the range, with an average diameter of between 12.5 and 16.0  $\mu\text{m}$ , with 15  $\mu\text{m}$  being a standard fiber. The length is usually greater than 32 mm, with a measured length of around 46 mm being considered a long fiber. The variants from Iran, Afghanistan, and elsewhere are usually coarser, with Mongolian cashmere being between 16 and 17  $\mu\text{m}$  and the others 17 to 21  $\mu\text{m}$ . Whereas Chinese cashmere is used for knitwear, the others are spun into yarns for weaving.

The guard hair is made up of the epidermis, the cortical layer, and the medulla, which forms the greater part of the fiber. Guard hairs are 38 to 130 mm long and are not only coarse but very irregular in diameter; the average diameter is around 62  $\mu\text{m}$  with a spread of 30 to 150  $\mu\text{m}$ .

#### **1.7.2.4 Silk Fibers**

Silk fibers are produced as continuous protein filaments by several insects. However, the commercial material, cultured silk, is produced by the farmed larvae of a caterpillar, called the silkworm, which uses the silk to form its cocoon. This species of silkworm is *Bombyx mori*, more commonly called mulberry silkworm because the caterpillar feeds on mulberry leaves. The culture of silk originated in China and, based on Chinese myths, can be dated back to 2640 B.C. The industry gradually spread to such countries as Japan, Turkey, Spain, Italy, France, and U.S. There are also wild varieties of silkworms such as the Eri, Muga, and Tussah (Tussa or Tussur) that are mainly found in India and China and feed on castor oil plants or, in the case of Tussah, on oak trees that are kept as shrubs at a height of 1.5 to 2 m by pruning.

In producing silk, the caterpillar builds its cocoon by winding and gumming the silk thread, layer upon layer, around its body. After its transformation to a moth, the cocoon thread is degummed and unwound to obtain the raw silk of 1.9 to 4.4 dtex fineness, a process called *reeling*, and the resulting filament threads are then twisted together (folded or doubled) to obtain the desired count of continuous filament yarn, the process being termed *silk throwing* and the manufacturer a *throwster*. Hence, thrown silk is a plied yarn made of continuous filament silk. With respect to spun yarns, it is the discrete length silk fiber that is of interest, and waste silk forms the basic raw material.

#### *Waste Silk*

There are two primary sources of waste silk: *gum waste* (occurring, as the name implies, at the reeling stage) and *throwster's waste* (resulting from the production of thrown silk and the subsequent processes of cloth production).

The waste silk can be classified into the following four qualities, according to length:

- First quality: average length 165 mm; spread 73 to 250 mm
- Second quality: average length 114; spread 60 to 152
- Third quality: average length 89; spread 50–152
- Fourth quality: the waste from the production processes used to convert the above qualities in spun yarns

The fiber of the first three qualities is first converted into sliver by gilling and then processed into a yarn (see [Chapter 2](#)). The lowest-quality waste, termed *silk noils*, has many very short fibers but may be used as a blend component in the production of woolen yarns.

#### 1.7.2.5 Manufactured Fibers [Man-Made Fibers (MMFs)]

[Table 1.8](#) lists, alongside values for cotton and wool, the properties of man-made fibers commonly spun either in their pure form (termed 100%), in blends (e.g., 50/50%, 65/35%) with each other (e.g., polyester/cellulosic blends), or in blends with cotton or wool to develop a wide range of yarns that give many fabrics their real utility value.

There is an important distinction between cellulosic and synthetic fibers. Cellulosic fibers (e.g., viscose, lyocell), are made from wood pulp, whereas synthetic fibers (e.g., nylon, acrylic, polyester, polypropylene) are made from chemicals fractionated from crude oil. The actual fiber formation process is called *fiber spinning*, but it is effectively extrusion of polymers through sets of very small holes termed *spinnerets*. In general, fibers may be produced by either a dry-spinning, wet-spinning, or melt-spinning process. In the dry-spinning process, the polymer, dissolved in a solvent solution, is extruded through the spinneret into a vertical chamber through which warm air is circulated to evaporate the solvent and congeal the polymer into filaments. For wet spinning, the solution is extruded into a bath (a coagulation bath) containing an appropriate chemical for coagulation of the polymer to occur by the action of diffusion. With melt spinning, as the term implies, the molten polymer is extruded through spinnerets in a vertical chamber where the molten filaments are cooled with circulating air. Following the spinning stage, the extruded tow of filaments are subjected to a high degree of stretching to align the constituent polymers and achieve the required fiber fineness and usable tensile properties. The tow may be then cut to produce fibers of a length suitable for processing by the various staple-yarn spinning routes.

The manufacturing processes can be adapted to impart specific properties to fibers so as to achieve certain functional requirements, e.g., flame retardancy, and end uses. Choice of spinneret enables different shapes of fiber cross section (round, trilobal, etc.) and fiber finenesses to be made — finer than the finest cotton (<1 dtex, microfiber). Fibers can be straight or crimped, giving a greater bulk than wool to insulate against the cold, and they can be made to transport moisture much better than natural fibers. Additives to the polymer solution prior to extrusion (e.g., delus-



tring pigment) enable dull or semidull as well as bright fibers to be produced. References are given at the end of the chapter for the reader who is interested in the detailed polymer synthesis and extrusion processes for producing fibers.<sup>8,10</sup>

### *Viscose Rayon and Lyocell*

There are several man-made cellulosic fibers, but viscose rayon and lyocell are the more important ones with respect to staple-spun yarns. Both are produced by the wet extrusion process, but, whereas rayon is produced using solutions of sodium hydroxide and dilute sulfuric acid,<sup>10</sup> lyocell is called a *solvent spun cellulosic*, as the production involves organic solvents that are retrieved at the end of the manufacturing process, making it environmentally friendly (certified OEKO TEX Standard 100).<sup>47</sup>

Like cotton, both fibers have good moisture absorbency and are generally comfortable to wear. Lyocell is more absorbent than cotton but less so than rayon. Cellulosic fibers are not resilient to wrinkle, but lyocell has moderate resiliency. It does not wrinkle as easily as rayon and cotton. Lyocell is the strongest of the three cellulosic fibers in both dry and wet states. Market areas for cellulosic fibers include women's fashion garments as well as men's shirts and casual wear.

### *Polyamide (Nylon)*

Polyamide fibers are melt-spun. Characteristically, they are very durable and resistant to abrasion, have good strength and elasticity, are easy to wash, are quick-drying, and give fabrics with good shape retention. Primary consumer end uses are clothing (wool blends for outerwear, stockings and tights, lingerie, corsetry) as well as sports and swimwear.

### *Polyester*

These fibers are also produced by the melt spinning process. The process is highly developed to produce fibers suitable for a wide range of applications. Fibers can have round, oval, or angular profiles to assist in developing soft fabric handle. Polyester fibers have good tensile properties that provide fabrics with above-average wear qualities. They are particularly resistant to light and weather, have good moisture transport, are quick drying, and can withstand climatic effects. Fabrics of 100% polyester or polyester rich blends have good crease resistance and shape retention.

Polyester fibers are the popular choice for apparel, in particular trousers, skirts, dresses, suits, jackets, blouses, and outdoor clothing. Blends with man-made cellulosic fibers, cotton, and virgin wool are widely used; the "classical blends" are around 65% polyester/35% man-made cellulosic fibers or cotton, and 55% polyester/45% wool.

### *Acrylic*

Dry and wet spinning are employed in producing acrylic fibers. The largest proportion of the production is made and used as crimped staple fibers. They can be given high bulk, and they have low thermal conductivity, good shape retention, durability, and easy-care properties. Its softness of touch and bulk makes it attractive for use in the knitwear sector. These positive features of acrylic fibers are also apparent in blends with wool or other natural fibers. Hence, 75% of acrylic fibers are used in

apparel, 20% in home furnishings, and 5% in industrial end uses. For apparel, these fibers are used in jumpers, waistcoats, cardigans, jackets, socks, knee-high stockings, and training and jogging suits, either pure or in blends with wool. Modacrylic fiber is a modified form of acrylic used in flame-retardant garments, in children's and baby wear, and in doll clothes and soft toys.

### *Polypropylene*

These are melt-spun fibers and, although produced in significant tonnage from a yarn perspective, they are largely used in filament form. Little of the fiber is used in staple-spun yarns because of the difficulty in conventionally dyeing the fiber (generally, dye pigments are added to the molten polymer). The vast majority of the staple fiber finds applications in the nonwovens sector. Polypropylene fibers have a density less than 1.0 and, therefore, at a given decitex, are thicker than other man-made fibers and give more cover. They do not absorb moisture, which is an advantage in many technical textiles end uses. They also have a high resistance to chemical attack, and additives may be used to give the fibers resistance to UV degradation.

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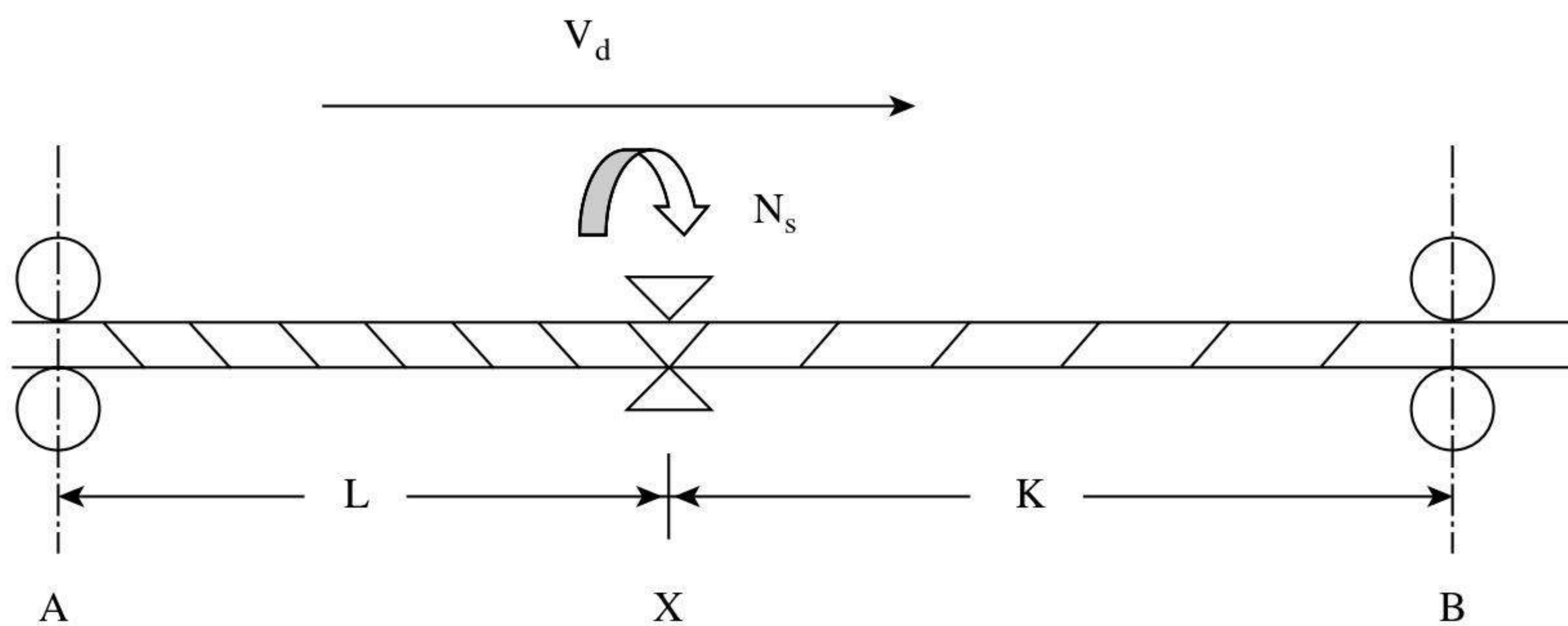
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## APPENDIX 1A

# Derivation of Equation for False-Twist Insertion



where  $N_s$  = the twist insertion rate in turns per minute  
 $V_d$  = filament strand speed in m/min  
Zone AX =  $L$  meters  
Zone XB =  $K$  meters  
 $L$  does not =  $K$

Assumptions:

- At time  $t = 0$ , no twist is present in the strand.
- When twist is inserted in each zone, it is uniformly distributed.
- Twist contraction is negligible.
- At time  $t = t_1$ , there are  $x$  turns/m in zone AX, and  $y$  turns/m in zone XB.

### 1A.1 TWIST EQUATION FOR ZONE AX

At time  $t = t_1 + dt$ , the number of turns in zone AX will be the sum of the following:

- The turns already present =  $xL$ .
- The turns inserted by the twisting device =  $N_s dt$ .
- The turns lost because of the filament length moving into zone XB =  $x V_d dt$ .

Thus, the twist level in AX at  $t = t_1 + dt = x + (N_s - x V_d) dt/L$

The change in twist,  $dx$ , is

$$dx = (N_s - x V_d) dt/L$$

Rearranging,

$$\int \frac{dx}{N_s - x V_d} = \frac{1}{L} \int dt$$

when  $t = 0, x = 0$ , thus the result of the integral gives

$$x = \frac{N_s}{V_d} \left( 1 - e^{-V_d \frac{t}{L}} \right)$$

## 1A.2 TWIST EQUATION FOR ZONE XB

Following a similar reasoning to that above, the change in twist in Zone XB is

$$dy = \frac{[xV_d - (N_s + V_c y)]dt}{K} = -\frac{1}{K} \left[ N_s e^{-V_d \frac{t}{L}} + V_d y \right] dt$$

Rearranging,

$$\frac{dy}{dt} + \frac{V_d y}{K} = -\frac{N_s}{K} e^{-V_d \frac{t}{L}}$$

multiplying throughout by  $e^{-V_d \frac{t}{L}}$  and integrating gives

$$y = -\frac{N_s L}{V_d [L - K]} \left( e^{-V_d \frac{t}{L}} - e^{-V_d \frac{t}{K}} \right) \quad (\text{A.1})$$

If  $L = K$ ,

$$y = -\frac{N_s}{K} t e^{-V_d \frac{t}{K}} \quad (\text{A.2})$$

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## APPENDIX 1B

# Fiber Length Parameters

### 1B.1 STAPLE LENGTH

Staple length came into use well before suitable methods for measuring fiber lengths were devised. It was used by graders, merchants, and spinners for raw fiber business transactions. It is a measured estimate of the principal length of a tuft of fibers. Cotton staples are prepared by hand-and-visual assessment (i.e., hand straightened and parallelized) and therefore influenced by personal judgement, which makes the measured estimate subjective. Accordingly, it is still possible to find individuals differing in their judgement by as much as 1 to 1.5 mm (0.04 to 0.06 in.) in extreme cases. A wool staple is usually considered to be a well identified bundle of fibers that is removed from a mass of greasy wool. However, the “well identified bundle” is a subjective one.

### 1B.2 FIBER LENGTH DISTRIBUTIONS

*Cumulative frequency distribution (CFD)*. This is more commonly called the staple diagram (in short staple spinning) or diagram of Hauteur (worsted spinning). It shows, for a random sample taken from a fibrous mass, the proportion of fibers that are greater than specified lengths. It is produced by sorting, either by number or by weight, the straightened lengths of the individual fibers making the sample. The following CFD was obtained manually by the Suter-Webb method, where a sample of fibers was separated into to small class groups of known lengths, with a class interval of 3 mm (0.12 in.). The groups were weighed and the data used to determine the relative percentages (abscissa) of the fiber mass weighing greater than the specified lengths shown along the ordinate.

### 1B.3 CFD BY SUTER-WEBB

*Percentage of fibers (%)*. From [Figure B.1](#), the “effective length” proposed by Clegg (the length that gives optimum drafting roller settings for this distribution of lengths) and the short fiber content defined by Lord can be determined as illustrated in [Figure B.2](#).

### CFD BY SUTER-WEBB

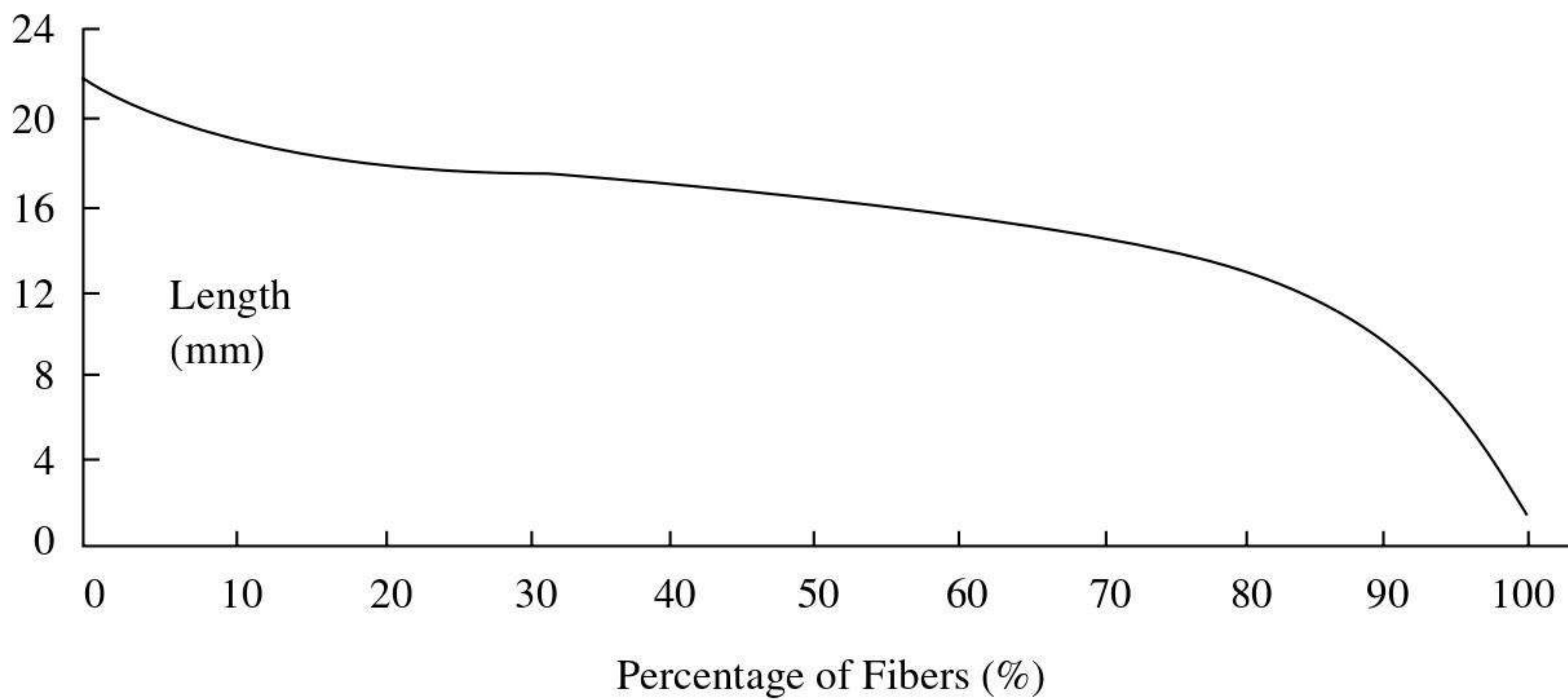


FIGURE B.1

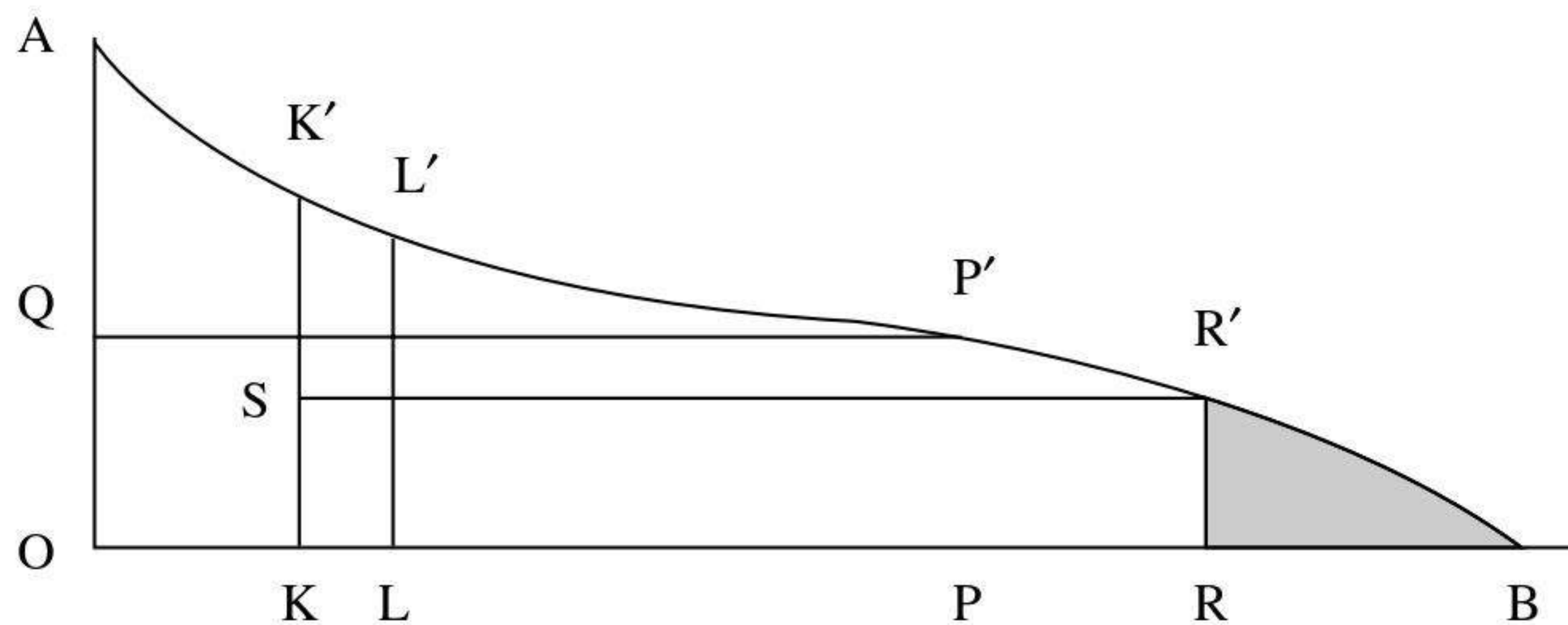


FIGURE B.2

- The ordinate OA is divided in half, to OQ and QA.
- The horizontal through Q intersects the curve at P'.
- The perpendicular through P' intersects the abscissa at P.
- OK is the first quarter of OP.
- The perpendicular through K intersects the curve at K'.
- The bisection of KK' is S.
- The horizontal through S intersects the curve at R'.
- The perpendicular through R' intersects the abscissa at R.
- The “effective length” = LL' corresponding to the first quarter of OR (i.e. L%).
- The short fiber content (SFC) is RB%, i.e. fibers < RR'.

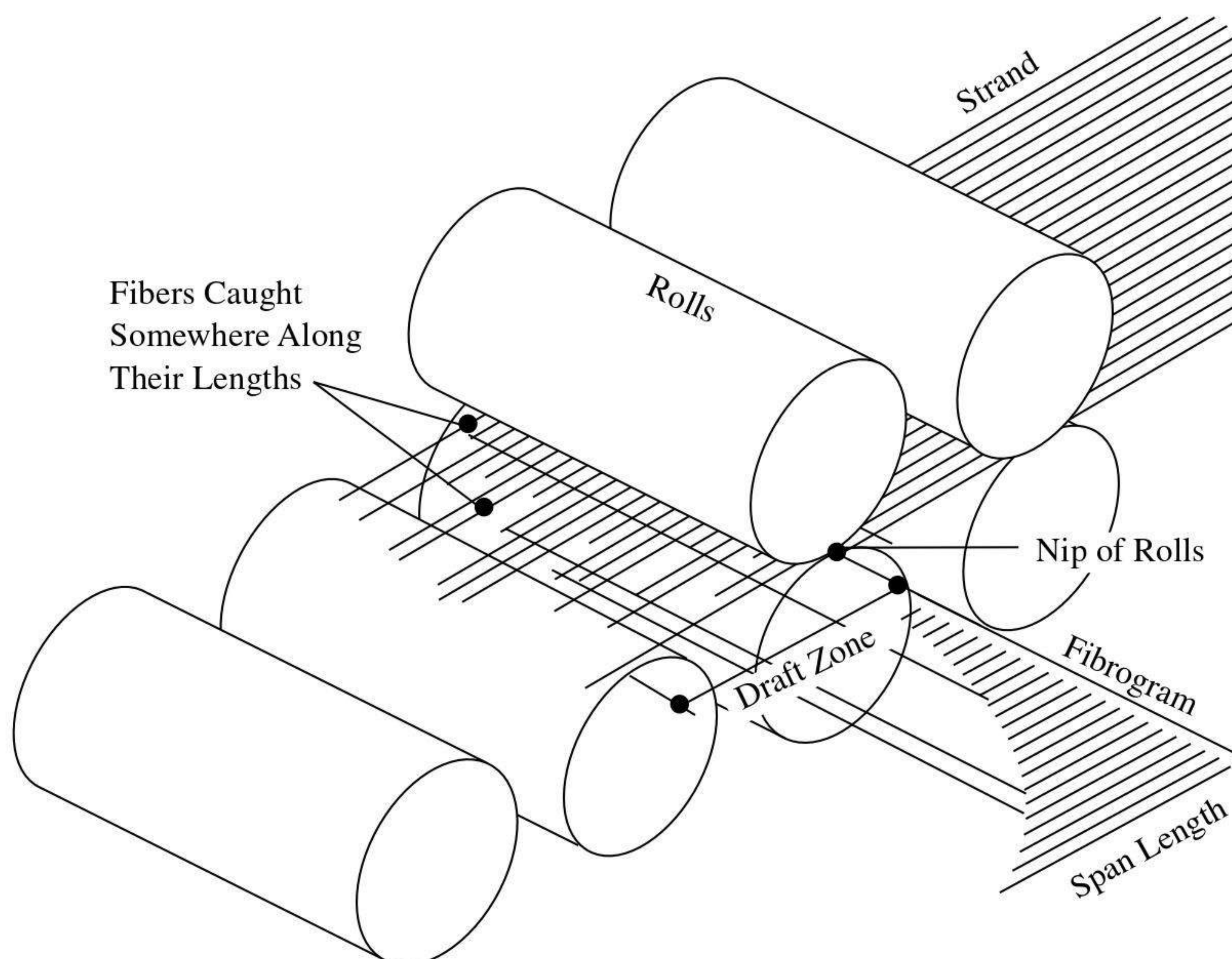
The Almeter is a widely used instrument for determining a the CFD more speedily. This gives the frequency histograms as well as the CFDs of the fiber lengths determine by number and by weight. The mean fiber length (MFL) (sometimes shortened to mean length (ML) or Hauteur (H), the coefficient of variation about the mean, and percentage short fibers according to specified minimum lengths.



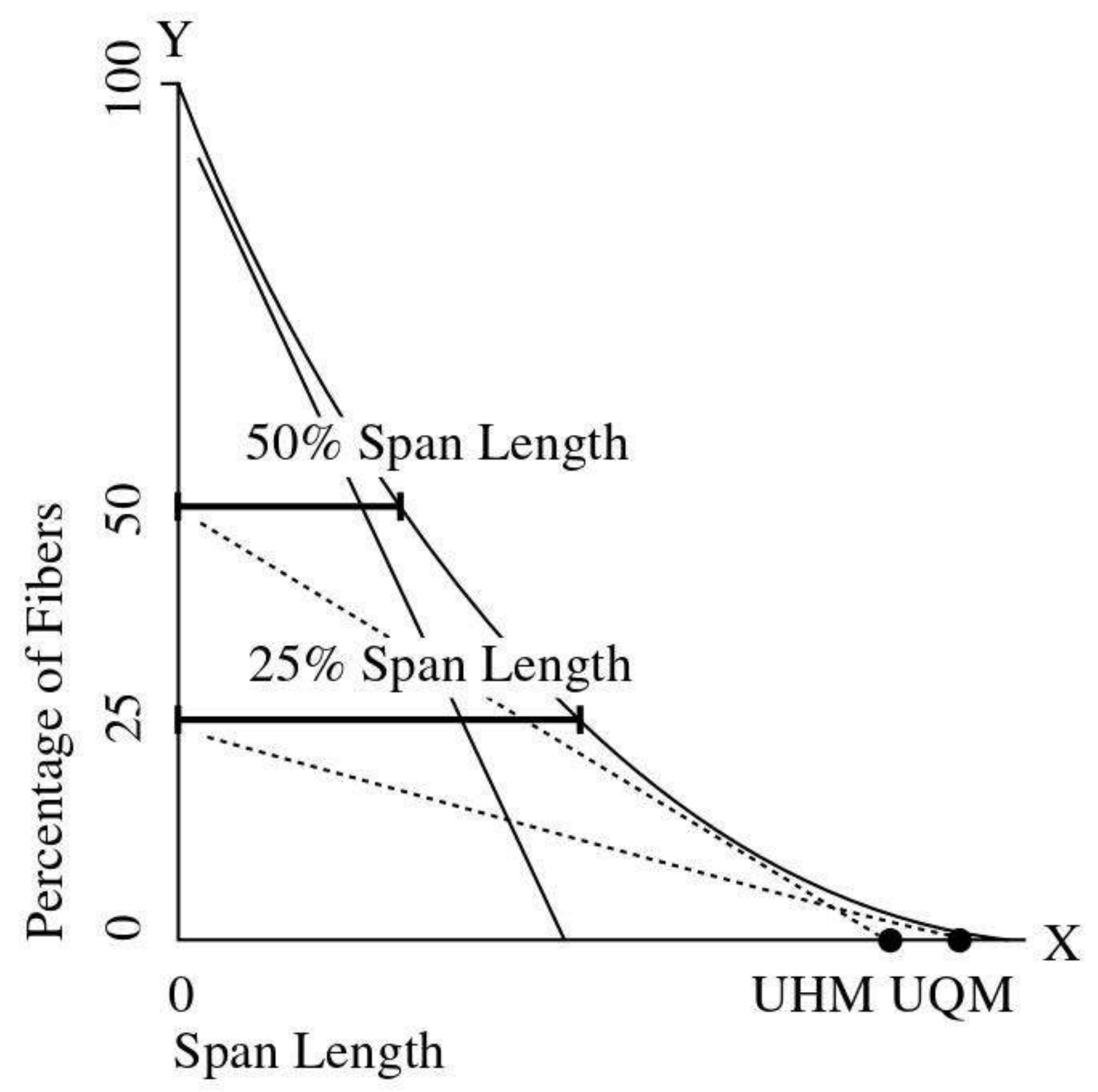
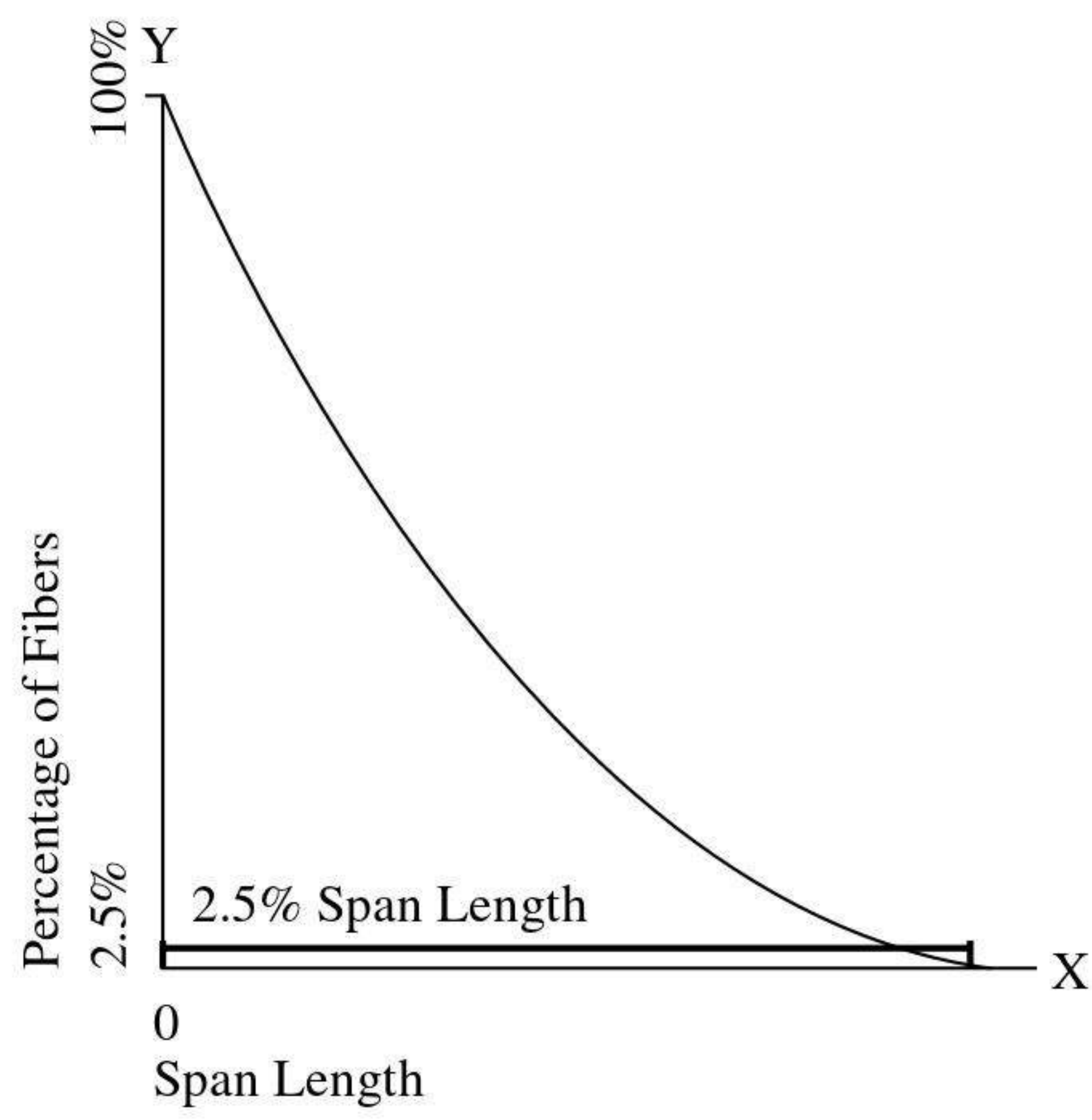
*Cumulative frequency distribution of span length (CFDSL)*. This only applicable to short-staple spinning and is commonly called the *fibrograph* or *fibrogram*. It is based on the way fiber lengths occur in textile processes when caught by roller nips as illustrated in Figure B.3.

At any instant in time, fibers caught by the roller nips will depend on the randomness of their overlapping lengths; therefore, not all the length of a given fiber projects into draft zone. The lengths that project into the draft zone are called the *span lengths*, and the cumulative frequency distribution of the span length gives the fibrogram. In comparison with the staple diagram, its importance is that it gives a graphical representation of the fiber segment lengths found to influence drafting processes. (See Chapter 2.) In this respect, various parameters relating to the actual lengths of the fibers projecting into the draft zone can be determined. They are as follows (see Figure B.4):

1. *Upper-half-mean length (UHM)*. This is defined as the mean length of the longer half (50%) of the fiber distribution by weight (ASTM-D 4604 and D 4605).
2. *Upper quartile length (UQM)*. This is defined as the fiber length that is exceeded by 25% of the fibers by weight in the test sample based on the staple diagram method (ASTM-D 1440-90).
3. *Length uniformity index (LUI)*. The LUI is the ratio of the mean length (ML) and the UHM expressed as a percentage (ASTM-D 4604 and D4605).
4. *Length uniformity ratio (LUR)*. This is the ratio of 2.5% and 50% span lengths.



**FIGURE B.3** (Courtesy of Spinlab, Inc.)



**FIGURE B.4**