2

Textile products and fiber production

Section A

2.1 Textile materials (fabrics, fibers, and filaments)

2.1.1 The nature of fabrics

Textile fabrics usually have the attributes of being soft and pliable with a capability of being molded or draped over non-flat surfaces. The 'hand' of a fabric (which describes its tactile characteristics) is very important in determining its acceptability for many applications. For example, to obtain the desirable characteristics required of apparel, the fabric must be made from fine yarns; also there must be some degree of freedom for them to move within the fabric structure. The sensation obtained when there is contact between human skin and fabric is determined to some extent by the stiffness of the hairs or fiber loops projecting from the surface of the fabric. The finer these outstanding hairs or fibers, the softer the fabric feels to the light touch. For this reason, too, many fabrics are made from fine filaments or fibers.

2.1.2 Fibers and filaments

Let a filament be defined as a continuous fine strand whose length is so very long that it can be considered infinitely long. Staple fibers, examples of which are cotton and wool, exist in relatively short fiber lengths. We will refer to 'continuous filaments' and 'staple fibers' to help differentiate between filaments and fibers. Most natural fibers are staple fibers although silk is an exception. (Silk is sometimes chopped to make staple fibers.) Man-made fibers can be used as staple or continuous filament. The very fine fibers used in textile fabrics make it necessary to use special units to express the idea of fineness or 'diameter'. Unfortunately, the many sectors of industry have each invented their own systems over the years. Appendix 1 gives some of the measuring systems used.

Another desired attribute of most textile fabrics is that they should have a good appearance. This usually implies that the fabric must look even and have no blotchiness, cloudiness, barré (see Fig. 2.1 and note that the bars are components of the condition known as barré), or streakiness. This, in turn, implies that the yarns should have uniform fineness, hairiness, and color along their whole lengths. With such materials, faults such as thick and thin spots in the yarn and neps should be avoided because of their disturbing effect on the appearance of the fabric. (Neps are tiny balls of fiber, which degrade the appearance of fabrics). Also, light reflects differently from various surfaces and a change in the structure of a yarn (or fabric) can cause unwanted change in the appearance of the fabric. For example, variation in yarn twist, hairiness, or fiber fineness can cause such undesirable changes. One must pay careful attention to preserving quality in these respects; for this, and other reasons, quality control is an important topic. Appearance is extremely important in the marketplace. With many of the yarns, great efforts are made to ensure yarn uniformity in all details. However, there is a special class of fabrics, which uses color patterns, random disturbances (such as nubs), and thick and thin spots in the yarns to produce effects which give interesting textures; such yarns are termed 'fancy yarns' or 'effect yarns'. Nubs are random thick spots induced into the yarn to produce visual effects in the fabric.

Each sort of yarn has its set of physical and mechanical properties which influence the performance of the yarn. To best select yarn for a particular purpose, one must understand the properties of the materials. Since there is an interaction between the technology and the properties of the yarn produced, it is very important to study all aspects of these topics.

2.1.3 Classification of fibers

The principal division is between natural and man-made fibers. The 'natural' classification is subdivided into fibers of vegetable, mineral, and animal origins.

The vegetable subclassification is shown partially in Fig. 2.2. Dotted lines indicate that there are other members of this particular subdivision that need not be considered here because of their small market share. Cotton fibers are the most important in this category, and they will be considered. Stem fibers are also known as bast fibers. Details of the fibers in the two bottom rows will be described later. Full classifications can be found in the literature [1–4]. About the only mineral fibers are asbestos and glass. Asbestos, in modern times, has been associated with asbestosis and has been banned in many parts of the world. Glass has a substantial market in industrial insulation, non-wovens and, of late, optical fibers for communication. The glass is

Fig. 2.1 Knitted fabric with barré

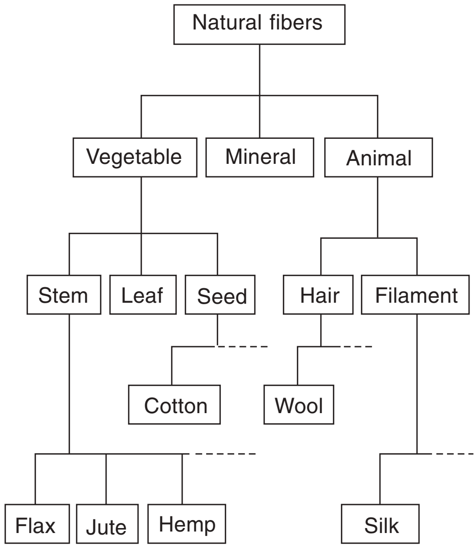

Fig. 2.2 Natural fibers – partial classification

melted and extruded and the techniques of production have much in common with man-made fibers. Wool is the most important animal fiber and large quantities of fiber have been used for carpets and apparel. Like the vegetable ones, they are natural and variable.

2.1.4 Polymeric materials

Fibers are made of polymers; some are natural polymers and some are man-made. A class residing in between these two consists of regenerated fibers, made, for example, from regenerated cellulose from trees, waste cotton fibers or others of the many natural sources of cellulose, and modified natural fibers, made by reacting natural polymers with chemicals to alter their properties. It is a misconception to view only synthetic fibers as polymers. Natural polymers are cultivated in the agricultural sector whereas man-made fibers are produced in the industrial sector. The synthetic polymer is first produced in chip or similar form, or is supplied directly to extruders in a liquid state. If it is produced in chip form it is later melted or otherwise liquefied and extruded.

A textile polymer is made up of long-chain molecules. A long-chain molecule may be regarded as a long string of atoms; these 'molecular strings' are flexible (if they are not cross-linked) and give to the fibers many of their desirable characteristics. The analogy between the behavior of a long flexible fiber and a long flexible molecule is no accident. However, the analogy must not be carried too far because there can be strong bonds between the molecular chains that make up the fibers, which are not simulated by the fibers in a yarn.

The polymer has to withstand the end use conditions. For example, it would be of little use making a fabric that would melt or soften in hot water. It also has to be strong enough to fulfill its purpose. Other properties have similarly to be taken into account.

Many polymers can be set by raising their temperature above the so-called glass transition temperature (T_g), deformed and then cooled. T_g is the temperature at which the polymer softens. Some fibers (such as cotton) cannot be permanently heat set, but easy care properties can be induced into fabrics by a chemical treatment called cross-linking. This treatment joins groups of molecular chains together and reduces their ability to move with respect to one another. The linking reduces the loss of energy of deformation and makes it more likely that the retained energy is available to return the fabric to its original shape. The cross-linking also makes the fiber structure stiffer. Many cross-linked fabrics, especially for apparel, have easy care properties. Some fabrics have creases or shaping set into them; thus, even after laundering or cleaning, they retain the desired shape or crease. One class of yarns is made by setting the filaments themselves into certain shapes and this is called texturing. When heat or mechanical stress causes a variation in the molecular structure, it can alter the way dye is taken up at various places along the length of the yarn. It can cause a fabric to look streaky.

A classification diagram for some man-made fibers is given in Fig. 2.3; again, some members of the various subdivisions are omitted. Polyesters' long-chain synthetic molecules are composed of esters of aromatic dicarboxylic acids and glycols. There is a family of polyesters but one of the most common is polyethylene glycol terepthalate (PET), which is widely used in staple form. It is often blended with cotton for apparel. The blends give some of the benefits of each component. The moisture absorption and feel of cotton are perceived to add comfort to apparel made of the fiber. Polyester has durability and recovery properties that add to the easy care attributes of any fabric made from it.

Polyamides are long-chain synthetic polymers made from diamines and dicarboxylic acids. The most widely used are collectively known as nylons and the various chemical types are indicated by adding numbers which indicate the monomers from which they are formed, e.g. nylon 6, nylon 6.6, and nylon 11. They are widely used in both staple and filament forms for carpets. Growth of this market has been at the expense of wool. Acrylic fibers are another class of synthetic polymer, composed of at least 85% by weight of acrylonitrile units. Where less than 85% and more than 35% of the polymer comprises acrylonitrile units, the fibers are termed 'modacrylics'. Textured

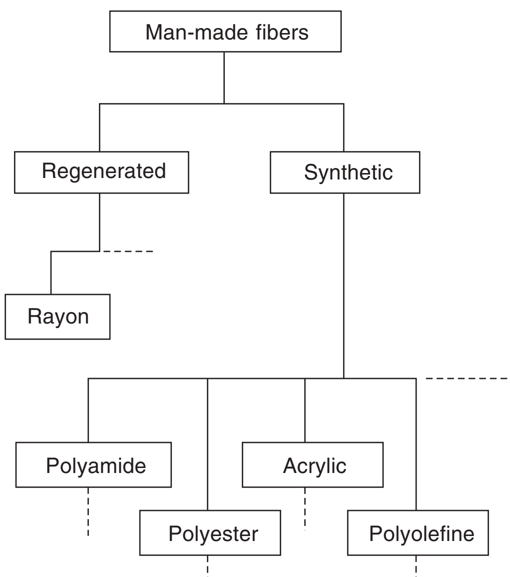

Fig. 2.3 Man-made fibers – partial classification

acrylic fibers have become popular for garments such as sweaters and have displaced wool for some portions of the market

Polyolefines, such as polyethylene and polypropylene, are made by polymerizing olefins such as ethylene (ethene) and propylene (propene). Polyolefines have come into widespread use for wrappings and have displaced jute from a large segment of that market. Wrapping fabrics are not necessarily made from conventional yarns; they may be non-wovens, or made from tapes rather than the more or less cylindrical yarns. These alternatives will not be further discussed. There are a number of special polymers used to make high performance fibers and filaments for industrial applications. For example, various aramid fibers have high tenacity and high temperature resistance. They are a form of polyamide. There are also the polyurethanes, some of which are endowed with enormous elongational capabilities.

2.1.5 Staple versus filament

As previously mentioned, most natural fibers exist in discrete lengths whereas man-made fibers are produced as extremely long filaments, which can be processed as continuous filament yarn or may be converted into staple fiber. Natural fibers are agricultural products subject to changes in properties due to exigencies arising from variations in growing conditions. Man-made fibers are usually controlled more closely but variations still occur; many of the factors that do vary are rather subtle in their effects. There exists an extremely important demand from the non-technical end user in favor of the natural fibers and blends between natural and man-made staple fibers. Aspects of hand and appearance in consumer products are very important in this market and some of the expectations of better quality from man-made fibers arising from closer control have not been realized. Users of technical products such as ropes, belting, and other industrial materials are usually more concerned with strength rather than appearance and technical factors assume a greater importance. The point is that there are market divisions with widely differing requirements.

The production of the two classes of fiber, natural and synthetic, is radically different and has to be discussed separately. Since natural fibers are those with the longest history, they will be discussed first. The sharp contrast between the methods involved in the two cases will be noted. But it will be appreciated that often a spinner has to deal with both man-made and natural fibers and there is a need to know about the sources and idiosyncrasies of both.

Section B

2.2 Natural fibers (types and production)

2.2.1 Cotton

Cotton fibers

Cotton is a vegetable fiber that grows from the surface of the seed. Each fiber is essentially a long thin tube of cellulose with a central feed channel, called a lumen, which runs almost the whole length of the fiber. In modern production, cotton is cultivated as an annual plant rather than letting it grow into a tree. Harvesting is easier working in this way and fiber properties are better controlled; also, cotton plants left in the ground after harvesting are subject to attack by pests. The use of this so-called 'stump cotton' has been banned in the USA.

The length to diameter ratio of the fiber is in the order of several thousand; this makes it mechanically flexible and suitable for textiles. Wild and cultivated species of cotton [5] have been placed in the genus of *Gossypium* and in the order of *Malvales*. Five species have been cultivated, *Gossypium herbaceum, Gossypium arboreum, Gossypium hirsutum, Gossypium barbadense,* and *Gossypium peruvian.* The first two of these are sometimes known as Asiatic species, the third is commonly known as American upland cotton, and the last is known as long-staple cotton (*Sea Island, Egyptian, Peruvian tanguis, Pima* and others). Asiatic species have historically been known for having short fiber lengths, whereas the *G. barbadense* is known for longer fiber length than the average. Much breeding work has been done to change the characteristics of the short fibers, particularly if they were coarse (i.e. of high linear density).

Cotton fibers are elongated single plant cells, varying in length, the average length of which changes according to species and conditions of growth. Fibers develop as elongations of the outer layer of cells of the cotton seed and each fiber consists of layers. The outer and inner layers are called the primary and secondary walls, respectively. The wall has a structure of fibrils as sketched in Fig. 2.4(a). A growing fiber exists as a tube with a wall thickness defined by the primary and secondary walls. The wall thickness and length alter as the fiber grows but there is little change in the outer diameter of the fiber. A cross-section of the undried fiber reveals the existence of daily growth rings, in more or less concentric circles surrounding the lumen. At temperatures less than 72°F or more than 90°F, the plant becomes dormant but within this range, growth occurs and the diurnal changes in temperature produce the growth rings.

An erstwhile fiber tube flattens when it matures and dries. The deformed tubular fiber gives a variable cross section that is sometimes as sketched in Fig. 2.4(c) and sometimes in other configurations of a flattened tube as shown in the micrograph in Fig. 2.4(d). According to Scott Tagart [6], the wall thickness is not constant, and when the lumen dissipates, an irregular collapse is caused by irregularities in the wall. It is not possible to show the length of the fiber in proportion to its cross-section and only a part is shown in Fig. 2.4(b). The convolutions or spirals of the twisted ribbon of the dried fiber make it easily spinnable, which is an important consideration. It has been stated that there can be as many as 250 twists along a single fiber but the direction of twist does not remain constant; there are a number of reversals along the length.

Wall thickness is also important because immature fibers with thin walls tend to collapse into neps during processing. These neps are a great nuisance during processing and can seriously degrade the value of the final product. Also wall thickness and structure can affect dye affinity which, in turn, affects the color of the finished product. Fiber length is also of great importance and a premium is paid for long fibers.

Extremes in length vary from less than 0.5 to over 2 inches. The former is of little use in yarn manufacture and the latter is expensive and somewhat rare. Also various species of cotton have differing average diameters when growing and, of course, the

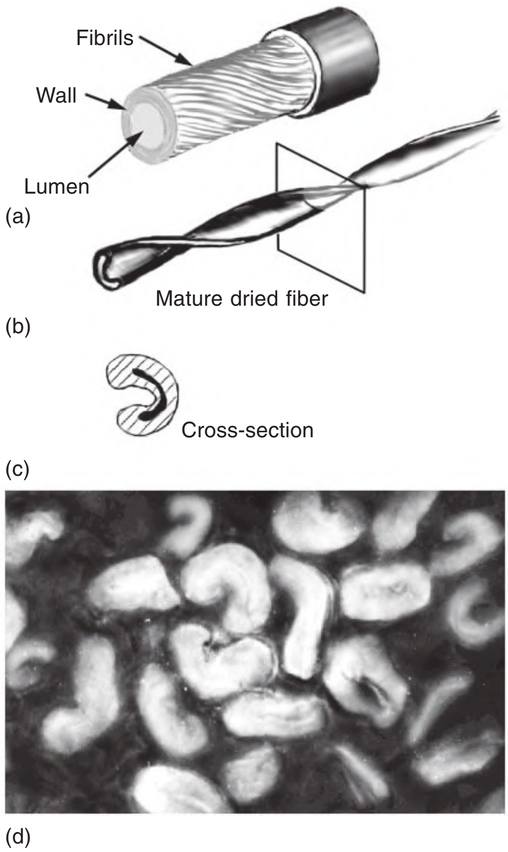

Fig. 2.4 Cotton fiber

diameter varies with the growing conditions. The concept of diameter is of little value because of the changes caused by drying as just mentioned. Rather, it is preferred to talk of fiber fineness or linear density.[1] Color of the fiber is also important; some species are white and others have various depths of yellowness, which affect the final product. There are some cotton fibers which have been bred to have a range of natural colors but these only occupy a small proportion of the market at the time of writing. Variations in fiber characteristics make it very important for a mill to choose the fiber carefully and to blend it well and consistently.

After the cotton flower has gone, a 'boll' is formed, which is a fairly small, fat, pear-shaped capsule. It bursts open as it ripens exposing the mass of fluffy white fibers. Seed fuzz begins to develop from epidermal cells at about one week after the opening of the flowers, whereas the fibers useful in spinning begin to form on the day of flowering. The short fuzz is known as 'linters' and is sometimes used for paper making, wadding or as a source of cellulose. Fibers useful for spinning are known collectively as 'lint'; these useful cotton fibers are obtained from the output of the gin.

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1 Mass/unit length of fiber. Also, the term 'micronaire' is used which is really a standardized test of air permeability of a given mass of fiber in a certain restraining volume.

Fibers are attached to the seed at one end of the fiber, and they develop as the seed ripens. The fiber, at the attachment point, is hooked, and this portion of the fiber is susceptible to nep production. The aggressiveness of the ginning process (separating of fibers from unwanted material) determines how much of the hooked portion passes into the lint used by the spinner and thus the nep potential of the fiber.

There is continuous activity by breeders who strive to improve the fiber length, strength, and other fiber properties. For example, over the period from 1990 to 1994, the average fiber strength of US cottons improved from 26.3 to 28.4 gf/tex. The strongest specimens yielded values as high as nearly 40 gf/tex. Fiber fineness is also judged to be very important. In addition, the breeders strive to introduce varieties which are resistant to disease and give high yields. In recent times, genetic splicing [7] is augmenting the practice of culling the best from a large number of varietal developments using traditional techniques.

Cotton growing

Cotton is a tropical plant requiring moisture and sunshine. Cultivation requires a climate that avoids frost damage to the growing plant. If the climate supplies insufficient rainfall, then it is necessary to use irrigation. The requirement for sunshine means it is normally grown between the latitudes 47°N and 40°S, which includes the Americas, Africa, Australasia, and Asia. Little is grown in Europe.

More than 500 species of insect attack cotton plants and many of them are very destructive. Lush foliage, large flowers with their nectaries, and the extended fruiting period make cotton a host for many insects. Consequently, care has to be taken to control boll weevil, bollworm, aphids, nematodes, and other pests, but the use of modern pesticides has reduced the problem. The boll weevil and such insects destroy the boll by consuming leaves, bulbs, and the bark of the plant. Damage caused by aphids, whitefly, and the like is more subtle. Secretions deposited after the boll is opened convert to sugar [8], which makes the fibers sticky and difficult to handle in processing. Deposits on metal surfaces in ginning and mill equipment can cause substantial losses in production. Control in the field is not simple. Early season pesticide application can disrupt the natural suppression of other pests and accelerate resistance to evolution. Mid-season aphid populations cause yield reductions and late season populations produce sticky cotton. Some aphids are highly reproductive under the optimal environmental conditions. The presence of other aphid hosts such as sweet potato nearby can increase the damage because of the increased populations surrounding the cotton fields. For example, cotton leaf hair is an important factor in infestation of cotton [9] by the *Bemesi tabaci* whiteflies from the sweet potato. The infestation produces sticky cotton. Sugar deposits can come from other sources, such as honeydew (a secretion from aphids). Irrespective of source, they pose a problem that still causes anxiety. Pathogenic fungi, bacteria, and viruses also attack cotton. The point of this discussion is to show some of the difficulties and underline the need for mills to watch for these deposits and infestations because of the difficulties they can create in yarn manufacture. Various methods of measuring cotton stickiness [10, 11] are available.

Yield, disease resistance, fiber length, strength, fineness, and maturity are primary factors used to select cultivars [12].[2] As time goes by, new strains of cotton are

2 A cultivar is a plant of a kind which originates and persists under cultivation.

produced which improve the performance of ginning and textile machinery, as well as enhance the value and quality of the product. The growing of cotton needs skill and attention but space precludes any great discussion of matters other than those which affect the spinner. Suffice it to say that the rows of plants have to be spaced to allow agricultural machinery to move down the rows. Modern practice uses picking, spraying, and other machines that straddle two or more rows. Because of this, the machines are characterized by their tallness. There is a necessity to control weeds, especially those which produce oily seeds, act as hosts for the pests just described, or otherwise inhibit growth of the fiber.

Before harvesting, the plants are defoliated by chemical means; much of the embrittled foliage falls off in the field and some is removed in handling. This reduces the trash in the fiber before it is harvested. In advanced countries, bolls of fiber are machine-picked and transported to a gin in a module (which contains about 6000 lb of cotton) or trailer (which contains, on average, about 4000 lb).

Two types of mechanical harvesting involve the use of a spindle picker and a cotton stripper. The processes are often referred to as 'machine picking' and 'machine stripping' respectively. The spindle picker uses tapered, barbed, rotating spindles to remove seed cotton only from well-opened bolls. 'Seed cotton' refers to material from which the seed has not yet been removed. The cotton stripper is non-selective; it includes cracked and unopened bolls along with burrs and other foreign matter in its output. Fouled spindle pickers produce spindle twists that are twisted masses of fiber difficult to handle in any process. Stick content and grade reduction due to bark is controlled by the aggressiveness of the roll settings on the stripper. Under conditions of improper setting and wear, particles of rubber from the stripper become embedded in the lint and cause 'black spotting' in the yarns ultimately produced. Thus, the product reaching the gin is affected not only by the seed and the growing conditions, but also by the setting and maintenance of the harvesting machinery. Unopened ('green') bolls are not only regarded as non-lint but they also carry considerable moisture. When the green bolls burst, the moisture migrates through the surrounding seed cotton. Changes in retained moisture in the supply can upset the moisture content of the cotton already being processed; defects may be created in the product supplied to the mills. Moisture content is frequently expressed as 'moisture regain', the amount of moisture in a sample compared with that in an oven-dried sample. A fairly typical distribution of unwanted material in lint is given in Table 2.1.

As the growing plants pass their harvest time, they are prone to become gray because of weathering. The decision when to pick can provide a problem if the weather is uncertain. Harvested fibers left out in the open can become discolored and stained by exposure to the weather; the severity of this staining is thought to be

Table 2.1 Non-lint content of some cottons. Values expressed as mass percentage, i.e. $\{(\text{non-lint/useful lint}) \times 100\%\}$

	Machine picked	**Machine stripped**
Burrs	7%	90%
Sticks	2%	23%
Fine trash	5%	22%
Motes	6%	5%
Total non-lint	20%	140%

influenced by the amount of wax produced by the plant. Thus, differences between varieties and growing sites can play a part in this respect. However, moisture content is a most important factor and length of storage is obviously a factor too. Consequently, care is taken to keep the newly harvested cotton under proper storage conditions. Suitable outside storage sites [13] should be well drained and free of gravel, stalks, long grass, and debris. They should have a smooth, firm, and flat accessible storage surface. Obviously staining or weathering can degrade the part of the crop affected.

The variability of the products in the various stages of yarn manufacture will be discussed in later chapters. However, the stage is set by the variabilities within the cotton itself. For example, it has been variously reported that the fiber fineness within a single plant can have coefficients of variation of the order of 15%. This can be compared to coefficients within a single field of cotton that are of the order of 10%. These variations become partly homogenized by the blending that occurs in the various process stages but it is important to realize the magnitude importance of these sources of variance.

Cotton ginning

An important step in the production sequence is ginning. In the ginning operation, sticks and coarse trash are removed from the input material. Also, since the input to a normal gin is from a variety of growing areas and a gin processes very large quantities of fiber, the process acts as a first blending of massive quantities of fiber. The term 'gin' is sometimes used to describe a whole establishment that provides the service of ginning, but sometimes it is used to describe the machines. The part of the machine line that separates fiber from seeds is often referred to as a gin stand.

The Churka gin, which, like all gins, had the purpose of separating the seed from the lint, was developed in some unknown period BC; Eli Whitney is credited with inventing the cotton saw gin in 1794. The basic idea was, and still is, to grip the lint protruding through a set of ribs by a moving surface and wrench the fiber from the seeds, which are unable to pass through the ribs. Rotary saw blades are commonly used as the moving surface just mentioned, but a specially prepared roller surface is sometimes substituted. A perfect operation would result in damage to neither seed nor fiber, and the undesirable small portions of fiber at the attachment points to the seed would be excluded. Unfortunately, this state of perfection is not possible. The aim is therefore to minimize the damage and thereby maintain the salability of both products. Apart from this, ginning has developed into a process stage that involves more than just removal of the seed from the lint. Before going on to discuss the elements in ginning, let us consider the seed.

Seed is an important by-product of cotton manufacture and most of the seed is crushed for oil or used for animal feed. The percentage of the US crop that was crushed for oil declined from over 85% in 1970 to about 50% in 1994. On the other hand, the percentage used for feed changed from about 10% to over 35% over the same time. To the spinner, the seed represents a hazard because, if seed-coat fragments are excessive, mill processing is made more difficult. The economics of ginning are affected by the sale of the by-products, and thus they have some effect on the cost of cotton to the mill. Ginning, warehousing, and merchandising [14] accounted for 90% of the cost of cotton lint in 1977, of which over half was taken up in warehousing and merchandising. The costs generated between the ginning and the mill processes are significant. It becomes all the more important to ensure that, not only is the cost controlled, but also that the quality of the product is maintained within specified limits. The cost of cotton to the mill represents roughly half that of yarn and the spinner must therefore have a strong interest in the basic fiber production.

A modern ginning establishment [15] contains some or all of the following process items:

1. One or more green boll traps, used to remove green bolls, and heavy foreign matter such as rocks. These green boll traps are often little more than a U-shaped diversion to the flow of air and seed cotton. A counter-weighted trap door releases the green bolls when they have collected in sufficient quantity to counterbalance the forces holding the trapdoor shut.
2. Automatic feed controls to provide an evenly dispersed fiber flow without wet clumps.
3. Dryers such as is shown in Fig. 2.5 – two dryers are normally used which expose the flowing fibers for 10 to 15 seconds to hot air and raise the fiber temperature to no more than 350°F.
4. Two or more cylinder cleaners – these consist of spiked cylinders rotating at 400 to 500 r/min over grid bars. Interaction between the moving and fixed elements breaks up large wads of fibers to permit more even distribution of moisture and temperature among the fibers. This, in turn, induces removal of fine foreign materials such as leaves, trash, and dirt.
5. ‘Stick’ machines to remove burrs and sticks.
6. A conveyor-distributor to convey cotton to the gin stands, where the separation of fibers from seeds takes place.
7. A feeder to control the flow rates to the gin stands.
8. The gin stand – this is the central item in the system, about which more is written in the following paragraphs.
9. Lint cleaners to remove immature seed fragments and other trash.
10. Bale presses to compress the lint into bales to facilitate transport and storage.

The need to clean the fiber at ginning is driven by the urge to elevate the grade to get the best possible financial return for the farmer. However, a high grading obtained by excessive cleaning always causes disappointment in the mill due to fiber degradation and the fiber may, therefore, not fetch the high price envisaged.

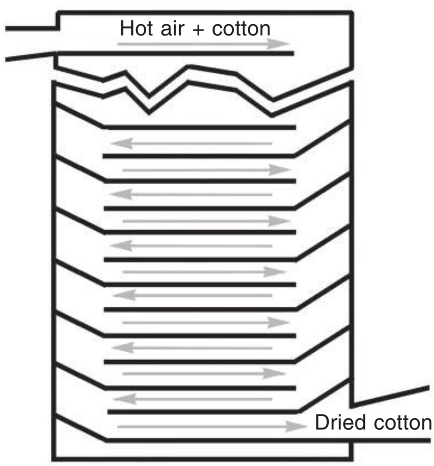

Fig. 2.5 Drying fiber at the gin

To make removal of trash easier, the cotton is heated to get the moisture content down to about 7%. Hot air is used for the drying, and the time to dry the cotton depends on the starting moisture content and the air temperature and flow rate. (The moistures content of a fiber in hot air declines approximately exponentially with time.) There is a temptation to use high air temperatures in order to speed up the process. However, this, or the slowing of the fiber flow, or changes in initial moisture content can lead to overheating. Associated ills are damage to the fibers by scorching, electrostatic charging of the fibers, and driving of the more volatile components of the wax that coats the fibers. Wax on the fibers is a valuable lubricant without which later processing would be very difficult. Electrostatic charges impede the separation of the fibers and lead to fiber damage. For those reasons, too low a moisture content arising from overheating the fiber is counterproductive.

A modern saw gin stand [16] has between 100 and 200 disc-like saws separated by ribs about 0.5 inch wide. Saws up to 18 inches in diameter are used. A simplified sketch of a typical saw gin stand arrangement is given in Fig. 2.6(a), but the sizes of the saw-teeth and brushes have been exaggerated for clarity. The cutting edges of the teeth are angled (line CD, which is parallel to the tangent of the rib AB) as shown in Fig. 2.6(b). The reason for this is to prevent the seeds from sliding to the base of the teeth and accumulating there. The gin stand comprises a feed system and spiked

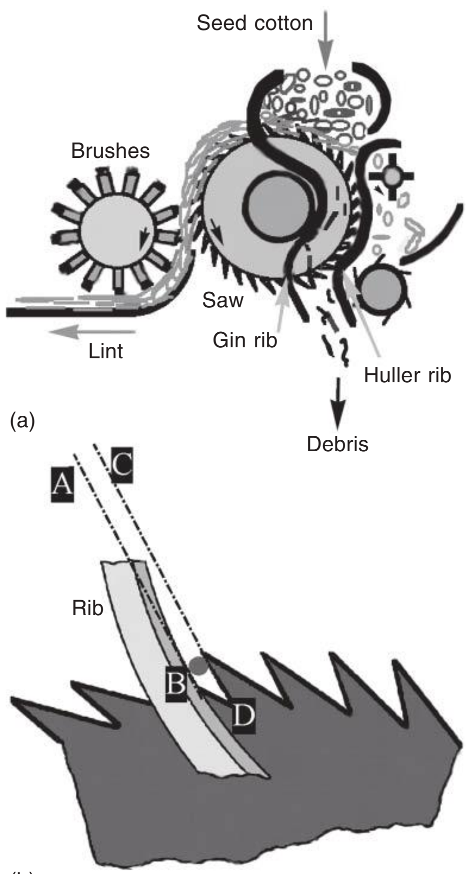

Fig. 2.6 Elements of a saw gin stand

roller cleaners, as well as the gin components shown. Seed cotton is introduced to the saws by a feed roller. The teeth of the saws pull the lint through the rib gaps into a moting chamber (not shown) where seed particles are removed by a mote bar. From there, the lint is carried to the brush doffer, which removes the lint and transfers it to the air transport system which, in turn, carries the fiber to the lint cleaner. Most cleaners consist of saws and mote bars that flail the lint against the bars. Brushes move lint from the saws.

An alternative to the saw gin is the modern roller gin (Fig. 2.7) which was developed in the 1950s and is used mostly in Arizona, California, Texas, and New Mexico. An important feature of this gin is the covering of the roller, which has to be resilient, yet durable, and have a surface that will grip the fiber. The productivity is only about 20% that of a saw gin. Since ginning accounts for about 38% of the cost of cotton, roller ginning is used only when there is a particular need to preserve fiber quality. Pima cotton (*Gossypium barbadense*) and similar long-staple cottons are usually roller ginned.

Woody and other unwanted materials are unavoidably collected in the fiber when mechanical harvesting has been used. All unwanted matter is collectively referred to as trash. Seeds and non-lint materials are removed in cleaning but some good fiber is also lost. Too rigorous a cleaning can damage fibers and degrade the product. In seed removal, it is inevitable that some fiber damage will occur; seed particles are removed by the violent action of separation. Moisture is very important in this respect. For example, the strength of upland cottons is about 1.8 times the force needed to separate the fiber from the seed at 7% moisture content. The short fiber content of the lint is increased by about 1% for each percentage reduction in moisture content [17] This is partly because the increased fiber electrification in the ginning process makes fiber separation more difficult. Some unwanted matter is taken out by the lint cleaners, which operate in series with the gin. It is a matter of debate how much cleaning should be done at the gin and how much in the mill. If dirty cotton is shipped to the mill, the yield of usable cotton per bale drops and the effective cost of the fiber rises, but the quality of the fiber is better. Similarly, the mechanical removal of fiber, which accompanies any cleaning operation, reduces the 'out-turn' of the gin. (Out-turn is defined as the mass output as a percentage of the corresponding input.) This tends to reduce the financial return to the ginner and farmer, unless there is a compensating

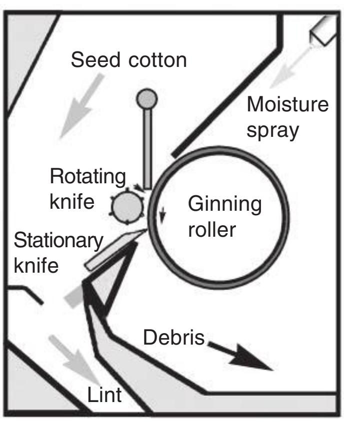

Fig. 2.7 Elements of a roller gin

increase in premium due to improved cleanliness or grade. The use of a larger number of lint cleaners leads to a reduction in trash content but only at the expense of a decrease in fiber quality. The addition of a third lint cleaner in ginning causes a greater loss in fiber quality than that caused by the second cleaner. Since fiber damage is irreversible, there is some question as to the wisdom of using a third lint cleaner in ginning. However, the question is one that is usually settled by the market.

After the completion of ginning, the fibers are compressed into bales to facilitate transport to the mills. A bale usually weighs about 500 lb and is wrapped in a fabric to protect it from damage, and strapped with wires or metal tapes to maintain the compression during transport and storage. These ties are strained up to 2000 lb force and extreme care has to be taken in bale breaking (i.e. removing them). The pressure used to compress a bale is also of importance. If several bales decompress to differing heights when introduced into the bale laydown in the mill, the bale plucking machinery will not sample the bales correctly until the top of the laydown has been leveled. Improper sampling of this sort could lead to barré (see Fig. 2.1) in the final product. Bales come in a variety of sizes and, even within the USA, there are several standards such as flat, modified flat, and universal. A bale is box-shaped (i.e. a rectangular prism) whose dimensions are X, Y, and Z. With US cotton, $X \approx 55$ inches, $Y \approx 20$, 21, 25, or 28 inches, and Z depends on the degree of compacting. For a 500 lb bale, densities vary between 20 and 30 lb/ft^3. In earlier times, bast fibers were used to make the bale wrapping, but now they are commonly made from polypropylene tape. The wrappings assume significance because failure to remove all vestiges of the wrapping leaves 'foreign fibers' in the product stream, which cause blemishes in the final product.

2.2.2 Wool

Wool fibers

Wool is normally defined as the fleece of sheep, the fleeces from other animals can also be used as textile fibers. Camel and goat hair (some goat fiber is known as mohair) are highly prized although they have only a small market. For this reason, they will not be described here.

Wool is a protein called keratin, which has a main polypeptide chain with amino acid side chains. It is an outgrowth of the epidermis (skin) of the sheep and the surface of the fiber has minute overlapping scales extending lengthwise and pointing to the end remote from the root or cuticle. The root is embedded in the epidermis. Wool grows in tufts, in or near the follicles in the skin of the animal; however, the useful, outermost portions of the fibers on the animal are no longer growing. Growth occurs by multiplication of the soft cells of the papilla, which exist at the base of the follicle. The papilla is a vascular arrangement of connective tissue extending into and nourishing the root of a hair. The useful part of the fiber is displaced from the cuticle as new cells are added and the fiber gets longer. A scaly surface is produced, as shown in Fig. 2.8. Thus, the fiber grows in length even though the outer part is no longer living. Lack of nutrition, or disease, affects the development of the fiber; if there are periods when the animal is adversely affected, portions of fiber become weak. Wool with such weak spots is referred to as 'tender'. The central part of the fiber near the skin contains the medulla (the inner pithy part of the structure) and the cortex (a layer of tissue connected to the papillae).

Certain moth and beetle larvae such as *Tinea bisselliella, Tinea pellionella,* and

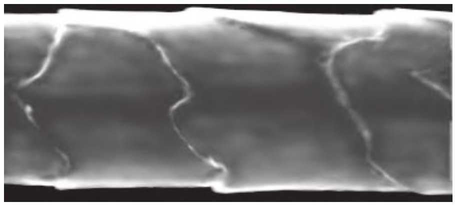

Fig. 2.8 Portion of wool fiber showing scales

Anthrenus verbasci attack wool and it is necessary to protect the fiber. Mothproofing does not always protect against beetle larvae because the eggs may have been laid before the treatment. Some insecticides do not protect against all pests that attack the fiber and insects build up resistance [18]. Thus, it is desirable to have a broad range of protection. Common agents used are organochlorine compounds; microbial pathogens, parasites, and biological control also offer possibilities of control.

Wool is a source of anthrax contamination in humans but heating during the drying cycle is sufficient to be lethal to the micro-organisms concerned. Any danger comes from handling untreated wool from geographic areas having problems with the disease.

Coarse wools are stiffer than finer wools and this property is especially important at the tips of the fiber. Garnsworthy *et al.* [19] deduced that, if the fiber ends protruding from an apparel fabric are capable of supporting loads of over about 1 mN, the wearer will suffer mechanical irritation of the skin. These stiff fiber ends irritate the human skin by mechanical disturbance of the surface of the epidermis. The effect can be lessened through surface treatment of the fabric, but the main point here is that fineness of the fiber is a significant property. In some applications, such as in carpeting, stiffer fibers are preferred, but in most, more flexible fibers are preferred to avoid the problems of 'prickle'.

Follicles are deep pits in the skin of the animal where the fibers are nourished and where wax and sweat glands are situated. (Sweat glands are known as 'suint glands'.) Thus, wool removed from the sheep is coated with wax and suint, as well as vegetable matter picked up by the animal during foraging. Raw wool in this state is referred to as 'greasy wool' or 'grease wool'. The foreign materials, which can represent over half of the weight of the unprocessed fleece, have to be removed before the normal mechanical textile operations can be performed. Such cleaning operations used to be carried out in the mill but, increasingly, they are being performed nearer the shearing operation. Cleaning is divided into wet and dry cleaning; the former operation is referred to as 'scouring'. Further discussion of cleaning is given in Chapter 8.

Wool fibers are naturally crimped. The fiber crimp levels range from 6 per inch (in cross-bred wools) to about 24 per inch (in Merinos). The fiber cross-section is slightly elliptical and the balance of forces in the growing fiber cause it to curl in growth. The fiber crimps are related to this curling.

Sheep bred for fine wool usually produce almost white wool and the presence of any color can downgrade it. The color can vary from white through yellow and fawn to brown; also shades of gray may be present.

Tenacity varies in the approximate range of 100 to 150 mN/tex when dry but only 80% to 90% of that when wet. Elongation varies between about 25% and 35%. The average diameter of the fibers varies from 8 to 60 microns (approx 0.0003 to 0.0024 inches) and the useful length can be anywhere between a fraction of an inch to 40 inches. Obviously, the length depends on the growing time, the breed, and other considerations. Some fibers consist of only cuticle (outer skin) and cortex whereas others are medulated; some fibers contain parts that are medulated and parts that are not. The term 'medulated' refers to a pithy core sometimes found in a fiber. Besides normal wool, the animal grows 'kempts', which consist of coarse straight fibers with tapered tips that are often shiny. They show up as undesirable inclusions in the final product and therefore should be avoided. Discriminating between the various sorts of wool is the job of the 'classer' (classifier) and it will be realized that classing is a highly skilled job; much of the skill is based on experience.

No single, universal classification system exists, but one commonly used grades the fiber according to the finest yarn that can be spun with it. An alternative system is the 'blood' system, which refers to the closeness to the Merino breed of sheep. Highly graded fibers are classified near to 100% blood and, as the percentage blood reduces, so the quality is lowered. Another system grades from 'super' down through AAA, AA, A, and 1st, to 2nd. As we have seen elsewhere, fiber length, fineness, strength, elongation, uniformity, color, and luster are important and are all parts of the value judgment. Fiber lengths greater than about 2.5 inches are regarded as suitable for combing and for processing into worsted yarns. Fibers less than about 1.25 inches are used in the woolen system. The yarn count is usually quoted in the woolen or worsted systems, where the count is measured in hanks/lb. The lengths of yarn in these types of hank are 1600 yd and 560 yd, respectively.

Wool production

Wool is obtained by shearing it from living sheep or by pulling it from the skins of slaughtered sheep. Shorn or sheared wool is the most common. Pulled wool may alternatively be described as 'skin wool', or 'slipes'. Fiber taken from a dead sheep is called 'dead' or 'murrain' wool [20].

Australia and New Zealand produce a large percentage of the world's wool. Much of New Zealand wool [21] comes from the NZ Romney sheep and its crosses; Coopworth and Perendale breeds are also significant. In Australia, the finer Merino wools predominate. In these countries, very large areas are often involved in sheep raising. Sheep can exist in rough mountainous regions under arid conditions, where forage is variable and herbage sparse. With large flocks, careful organization is required to harvest the wool because it is necessary to collect and confine the animals in close quarters to permit marshaling to allow the clip to proceed efficiently. Fine wool Merino sheep are able to survive under such conditions. Naturally sheep can also do well with lusher vegetation, as evidenced in England and New Zealand. However, some of the wools produced are relatively coarse and more suitable for carpets than apparel.

Each sheep is periodically sheared to remove the fleece. The natural mutual cohesion of the fibers enables them to cling together even after shearing. A skilled shearer clips close to the body to keep the fleece essentially in one piece, and produces over 100 fleeces per day. Removal of heavily soiled wool around the crotch (crutch) of the animal is called 'crutching' and it is usually carried out before lambing and before the normal shearing; this reduces the amount of soiled wool to be removed later. After shearing, the fleece is sorted and classed. Sometimes the fleece is skirted locally (i.e. inferior pieces such as the short belly fiber are removed) and these skirtings are packed separately. Dirty or stained wool and rough, coarse ends are removed. Sweaty locks and parts containing a high percentage of burrs are also removed. All sorts of vegetable matter picked up by the animal in its wanderings are usually included in the term ‘burrs’. The remaining fleece is divided and rolled to bring the rib and shoulder portions to view. The fleeces are then classed and shipped to warehouses for storage and eventual distribution. Discolored wool, ‘bellies’, and some other portions are sometimes sold separately from the main fleeces. Also wools containing faults are separated; these include cotted, stained, and muddied wool, as well as double fleeces. The term ‘cotted’ refers to heavily felted and matted material; double fleeces refers to the material removed from sheep missed in the previous shearing. Annual shearing is the normal practice and the yield thus normally depends on the growth rate of the wool. If left longer than a year, the fiber length may be more than that obtained with present practice; however, any increase in value with fiber length has to be set against the reduction in average annual yield.

The jobs described are seasonal and are highly labor intensive; this drives up the cost of production. Some consideration has been given to dosing the animal with a drug to weaken the fiber near the follicle [22] so that the wool could be pulled from the skin surface rather than be sheared; it will be interesting to hear of the outcome. As mentioned previously, some movement has been made to clean the fleeces before sending them to the mills. Scoured wool and ‘tops’ command higher prices of course; the cost of shipping is lowered and environmental problems for the buyer are greatly reduced. ‘Tops’ are thick ropes of fiber, otherwise called sliver. Some 65% of New Zealand wool is now scoured before shipping. In contrast, as of 1988, 80% of the total Australian clip was shipped as greasy wool. However, it should be noted that wools from these countries go to different markets because of the differences in fineness of the wool and the differing preferences of their buyers.

Arriving fleeces are closely examined by the buyer, despite the prior classing. Different qualities, known as matchings, are placed in separate lots to maintain quality control. The necessity to re-class underlines the variability of the wool from any one sheep, let alone the variations between the sheep. Up to the 1970s, most of the judgment regarding quality was made by appearance and touch. However, since then there have been developments in instrumentation that have been accepted and applied. According to Whitely [23], 90% of the variation in clean prices is accounted for in fiber diameter and vegetable-fault level. Style categorization is an indicator of staple length, average fiber diameter, and vegetable fault content. Scanning systems are beginning to be used to record color, crimp, and staple length of the greasy wool as it passes on a conveyor. This gives a glimpse of the advances which are being made, not without opposition. Similarly difficult transitions have been met with other fibers and in other geographic areas. However, the drop in wool prices has reduced the resources available to promote the process of adopting instrumented measurements.

The value of wool depends, amongst other things, on its fineness. Heavier wools are discounted [24] and fiber fineness is an important factor in setting the price (which is not always directly related to value). Wool prices languished through the last decade or so, with the result that research and development was slowed. The lack of significant growth has also been a disincentive for machinery makers to invest in solving the difficult technological task of improving productivity. There have been fewer developments than in the short-staple arena; there seems to be some recovery but, as is so often the case with textiles, it is difficult to predict the outcome.

2.2.3 Bast fibers

Flax

Flax (*Linum usitatissimum*) is an annual, herbaceous plant grown in temperate and subtropical areas. After flowering, the bolls or capsules contain up to ten seeds. The fibers occur in the bark of the stem and it is the long stemmed varieties that are used for linen. Bast stems contain bundles of fibers that act as hawsers in the fibrous layers lying beneath the bark of dicotyledenous plants. (A dicotyledon is a plant having two seed leaves.) They help hold the plant erect. The Soviet Union was the largest producer before the collapse of communism but is no longer. Some satellite countries of the former USSR, such as Slovakia, produced large quantities of flax and linen yarns, some of which were directed to the manufacture of tarpaulins and other industrial uses. Linen yarns have remarkable resistance to sub-zero temperatures, which cause deterioration of properties in many synthetic fibers. Any conception that linen is solely an apparel fiber is misguided. In fact, in common with other bast fibers, it is beginning to find a use as a reinforcement for composite materials in automobile manufacturing because of its strength and biodegradability. Other major producing countries in recent times have been Poland, Germany, France, Ireland, Rumania, Belgium, and Holland.

Strands of commercial flax fiber may consist of many individual fiber cells. The cells vary from about 0.25 to 2.5 inches in length. They exist as thick walled, cylindrical tubes with a diameter of about 0.0008 inch and the central lumen (the central canal in the cell) tapers to a point towards the end of the fiber. The fibers do not have the convolutions typical of cotton and the width of the fiber may vary several times along its length. It is stronger than cotton but it is an inextensible fiber and the elongation at break is only about 2%. It is 20% stronger wet than dry. Flax is still the main vegetable fiber grown in northern Europe [25].

The plants are subject to attack by pathogenic fungi (wilt) and viruses (curly top). Wilt-resistant varieties have been developed. Reasonable control can be exercised by chemical treatment of the seed and the use of fungicides.

Flax is harvested when about half the seeds are ripe (yellow or brown, shiny, and flattened) and the leaves have fallen from the lower two-thirds of the stem. Modern practice is to use pulling machines that remove the plants bodily from the soil and bind them into bundles which are set into ‘stooks’ or ‘shocks’ in the field for drying or curing. The stooks are assemblies of bundles of stems arranged like an elongated cone that promotes natural airflow through the bundles. When they have dried, the stalks are de-seeded by threshing, combing, or beating, and the product at this stage is referred to as ‘straw’.

Before the fiber can be used for textile products, it has to be removed from the stems. The dried straw is ‘retted’ to break down the gums that bind the fibers together in the bark. ‘Retting’ is a controlled rotting process which is brought about by exposure to the weather, or soaking in ponds, sluggish streams, or vats. Bacterial action and the physical effects of weathering or soaking cause the decomposition of the gums. Retting is complete when the bark becomes loose so that it can be easily removed from the woody portions of the stems. The process takes one to three weeks according to the weather or the temperature of the water. The retted straw bundles are set up in open shocks or ‘wigwams’ to dry. The fiber is separated from the woody material by ‘scutching’. This involves the use of fluted rolls and beating blades which break the brittle woody parts into ‘shives’ but leave the fibers largely intact. The scutched fiber is baled and sent to the mill.

Jute

Jute fibers are obtained from two species of *Corchorus,* namely *C capsularis* and C. *olitorius*. There are also a number of jute substitutes such as Bimli (from *Hibiscus cannabinus*) and China jute (from *Abutilon theophrasti*). Jute fabrics formed the 'sackcloth' of Biblical times and are now used for wrappings, bindings, etc.

Commercial jute fiber consists of overlapping cells which average 0.08 inches long by 0.0008 inches equivalent diameter (cells are not round; the equivalent diameter has the same cross-sectional area as the cell). The color varies from yellow to brown with various degrees of grayness and tends towards brown when exposed to sunlight. Like flax, the fibrous material surrounds the woody core and is embedded in the non-fibrous material under the bark. The strands nearest the bark run the full length of the stem and other strands further from the bark become progressively shorter. The cells are about 0.1 inches long and, although retting destroys the tissue that holds the fiber bundles together in the natural state, it usually does not separate the cells in a given fiber.

Cultivation requires well-drained, fertile soil and a hot, moist climate. The crop is ready for harvesting when the flowers begin to fade. If cut too early, the fiber is weak, and if cut too late, it is strong but coarse and lacking in luster. Like flax, the stalks are retted to free the fibers from the natural gums that bind them. If the stems are removed from the retting basins too soon, the fiber is difficult to remove and suffers mechanical damage. If they are allowed to stay immersed too long, the fiber is degraded and is weakened. The separation of the fiber is termed stripping. The material is graded and baled before shipping to storage.

Hemp

The botanical name for hemp is *Cannabis sativa.* Sisal and manila hemps are hemp substitutes. As mentioned earlier, *C. sativa* produces fiber, seed, and narcotics. Cultivation is not unlike that of other bast fibers and, again, the time for harvesting has to be judged carefully. The fibers are soft and fine if they are harvested as the pollen begins to shed, but they are weaker than those obtained from later harvesting. Hemp made its mark because of the strength of the fiber. The cells vary from about 0.5 to 1 inch long, and, like flax, they are thick-walled tubes, although the lumen has blunt ends. The fibers may be up to 6 ft long and are roughly cylindrical with cracks, swellings, and other irregularities.

The process of retting is similar to that already described for other bast materials. The devices for separating the fiber and ligneous material are called 'brakes' and the process is called breaking, but essentially the process is similar to that already described.

Ramie

Ramie comes from plants with the botanical name *Boehmeria niva* or *B. tenacissema.* Fibers are removed by decortication, which is a process whereby the fibers are removed from soaked stalks by scraping or beating. Gums are then removed by soaking in caustic soda followed by neutralization in an acid bath. The fiber is then washed and oiled. The thick-walled cells often reach 18 inches long. Normally the fiber is rather stiff but mercerized ramie has some qualities that allow it to approach the performance of cotton.

2.2.4 Silk

Silk fibers

Silk is different from the natural fibers previously discussed because it occurs as a filament, and the highest quality silk is worked as filament rather than as staple fiber. That is not to say that it cannot be chopped and mixed with other staple fibers. The visual and tactile characteristics of silk make it very attractive in both forms. As with all textile fibers, silk has long-chain molecules as its backbone, but attached to these are various sorts of side chains. Crease resistance and yellowing are two problems that have been addressed by epoxide treatment [26]. Some of the treatments are intended to cause the fiber to behave in a more nearly elastic manner.

Silk is extruded by the silkworm into a cocoon and the silk has to be reeled from that cocoon before it can be used. Silkworms are of the *Lepidoptera* family, and of the *Bombyx* species, which feed only on mulberry leaves. Cultivated species are often *B. mori,* but there are also other species such as *B. textor* and *B. sinensis*. Indian Tasar silkworms are *Antherea proylei* and *A. mylitta,* which feed on leaves other than mulberry. *A. assamensis* (Mugar) silkworms and others are also used for fiber harvesting.

The silk glands of the larvae produce fibroin. The freshly made fibroin is transferred to two holding cavities for the fluid to ripen. When the caterpillar reaches maturity, fibroin is extruded through a spinneret in common with a second secretion called sericin. Fibroin is an amphoteric colloid protein and sericin is a natural gum. This sericin solidifies straight away and two entering filaments of fluid are converted to a single emerging strand that is used to cover the insect in an oviform envelope. The filament varies from white to yellow in color. It has a high tenacity and it is capable of 20% elastic (i.e. fully reversible) elongation, which is remarkable.

After the seracin gum has been removed, raw mulberry silk strand consists of two smooth rod-like fibroin filaments and has a white lustrous appearance. The cross-section of each filament is roughly triangular.

Obviously, a supply of larvae is needed, but this will not be addressed here. Also, adequate supplies of appropriate leaves are required to feed the larvae; thus the first step is to cultivate the mulberry trees or other plants. A uniformly hot climate is needed to hatch silk ‘seeds’ or eggs, which are usually set out in trays. Incubation is timed to coincide with the leafing of the feed plants. After being taken from the incubator, the trays containing the newly hatched eggs are spread with gauze on to which chopped leaves are spread. The feeding period continues for about 40 days. The caterpillars, to spin their cocoons, inhabit a structure of cells. This structure is rotated whilst the cocoon is being spun. The cocoon takes about 60 hours to complete. It is essential to keep the cocoons separate during spinning because, if they stick together, it is almost impossible to reel the silk from the cocoon. The chrysalises are then killed, often by steam, otherwise the pupae would damage the cocoon in emerging therefrom. In some areas, reeling is carried out in a portion of a silk processing establishment called a filature. The reelable cocoons are boiled in water for about 10 minutes to soften the sericin. The ends are then sought for each of several cocoons and the group is reeled to make a skein or small bundle (called a ‘book’). Sericin has poor solubility in the presence of tannins and this makes it difficult to degum non-mulberry silks containing tannins. Modern developments include automatic reeling machines; also enzymatic and other forms of decomposition have been used with some success.

The books are baled for further processing elsewhere. The count of raw silk is expressed as denier. The inverse of 4 464 531 yd/lb is equivalent to 1 denier. The discarded non-reelable cocoons are mechanically converted to staple and are used to make a spun silk described as 'schappe'. The materials from breaks in reeling are also used for spun silk yarns. Staple silk spinning is, in some countries, a cottage industry with spinning wheels and mules still in use. These cottage industries are often promoted for social reasons. Throstle spinning and ring spinning are used in other areas. Matsumoto *et al*. [27] describe an improved throstle in which a rolled sheet of silk fiber is inserted into an intermittently rotating stuffer tube.

Section C

2.3 Man-made fibers (polymer extrusion and yarn production)

2.3.1 Outline of processes to produce man-made fibers

It is possible to emulate the silkworm by liquefying the polymer before forcing it through a 'spinneret' to produce a number of fine streams. The streams of liquid are then solidified to make filaments. These filaments usually have to be 'drawn' at a later stage to further orient the molecular structure to give the desired physical properties. The method of liquefying the polymer depends upon the type of polymer. In some cases a solvent is used, and in others the polymer is melted. Polymer solutions are solidified by removing the solvent by evaporation (dry spinning), or by coagulating them in a liquid bath (wet spinning). Polymer 'melts' are solidified by cooling them below their melting points (melt spinning). Some fiber cannot be melt spun because the material starts to decompose before it melts, or because the melting temperature is not within an acceptable range. For example, with some acrylic polymers the high temperatures required for melt spinning can cause the fibers to discolor. Therefore, either a wet spinning method is used, or a melt spinning operation is operated using a blanket of inert gas to prevent oxidation (oxidation causes the yellowing, as well as some other undesirable changes to the polymer).

Melt spinning is the most important of the two processes. In all cases, the liquefied polymer has to pass through some form of pump to produce the necessary pressure to force the material through the very fine holes in the spinneret. In commercial production, the pressures are high. The flowing polymer has also to be filtered to prevent lumps, such as gels and foreign bodies, from clogging the holes in the spinneret.

Dry spinning

Dry spinning is used to produce cellulose acetate fibers from an acetone solution; also several vinyl fibers and polyacrylonitrile fibers can be produced from solution in other organic solvents. The first step is to produce polymer solution, which is then filtered and pumped through the spinneret as indicated in Fig. 2.9. Choice of solvent is governed by considerations of solvent power, boiling point, heat of evaporation, stability, toxicity, hygroscopicity, ease of recovery, and cost. Low boiling point solvents with high heats of evaporation may cause polymer condensation on the surface of the filament and produce an undesirable surface.

It takes a finite time and considerable energy to remove the solvent from the filaments in dry spinning. The process of solvent removal reduces productivity and increases costs. This is because the mass transfer and heat transfer are far from instantaneous. The spinning apparatus has to incorporate a long ‘chimney’ to remove solvents (see Fig. 2.9). The volatile solvents needed for the process are nearly all toxic and/or flammable. The vapors cannot be released into the air and they have to be recovered. Also, solvents are expensive and it is an economic and ecological necessity to recover them. Increases in delivery speed sometimes require disproportional capital costs; there is also an upper limit to the production speed. Normal spinning speeds lie in the range 800–1000 m/min. There is a limit to the length of undrawn and unsupported filament that can be handled.

Flow through the spinneret is controlled by several factors. These include the pressure and viscosity of the liquid. A typical solution runs at viscosities in the range 500–1000 poise; this viscosity is mainly determined by the concentration of solvent and the temperature of the mixture. The yarn take-up speed depends on numerous factors that include shrinkage associated with solidification.

The types of polymer and solvent affect the cross-sectional shapes of the filaments. Rarely are the fibers round in cross-section, and changes in cross-sectional shapes can be important in determining luster as well as other physical properties of the fiber. When the material is chopped into staple fiber, the cross-sectional shape can

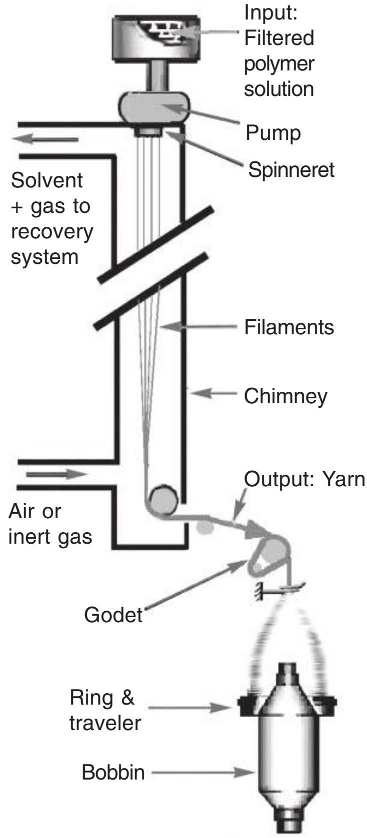

Fig. 2.9 Dry spinning

affect cohesion between the fibers which will, in turn, affect the processability as well as the properties of the final staple yarn.

Wet spinning

Wet spinning is a chemical precipitation process. Coagulation of the filaments involves two-way mass transfer with the coagulating agent (e.g. acid) diffusing inwards into the filaments and the chemical products of coagulation (e.g. salts, H_2S) diffusing outwards. It is sometimes necessary to use an intermediate process to produce a solution. For example, in viscose rayon production, a soluble derivative (cellulose xanthate in this case) is produced and this is dissolved in dilute dolium hydroxide to produce the liquid suitable for extrusion. Solvent is leached out by the liquid in the bath; the latter must be miscible with the solvent but must be a non-solvent for the polymer. Thus, in a generalized diagram of such a process, it would be necessary to specify the extrudate as filtered 'polymer derivative' or 'polymer solution' according to whether an intermediate step is necessary or not, but in the case cited above, the extrudate is a polymer derivative (Fig. 2.10).

During coagulation, several simultaneous processes occur, in different ways for different polymer/solvent systems. Their coagulation is slow; up to 3× drawing is possible. The more rapid the coagulation, the more inhomogeneous is the cross-section. The heat- and mass-transfers between the extrudate and the liquid of the coagulation bath affect the temperature and solvent distributions within the fiber. Any maldistributions make it difficult to obtain uniform properties throughout the cross-section of the strand. The outside surface of the filaments hardens and this tends to inhibit the mass transfer required. Furthermore, the migration of the solvent through this hardened 'skin' reduces the volume of the material enclosed with the result that the skin wrinkles. Thus, wet spun filaments usually have a convoluted cross-section. Wet spinning is commonly used to produce viscose rayon, and polyacrylonitrile (PAN) fibers. (It will be noted the acrylic fibers can also be manufactured by dry spinning; see above.)

The polymer derivative usually has to be ripened because as it ages, it changes

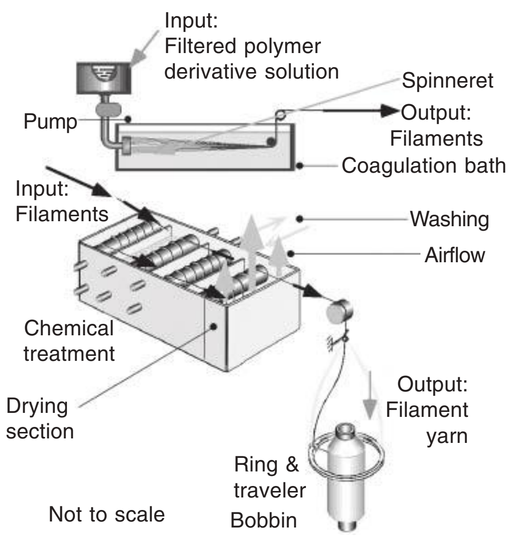

Fig. 2.10 Wet spinning

viscosity and character. Often it is necessary for there to be a storage system between the preparation of the polymer derivative and the final extrusion in order to accommodate the ageing process.

The viscosity of the polymer solution is an important variable. Generally, the higher the concentration of polymer (desirable for economic reasons), the higher the viscosity. High viscosity solutions spin well because the desirable cohesive effects of high viscosity outweigh the undesirable effects of unavoidable surface tension which tend to cause the liquid to degenerate into droplets. However, a high viscosity liquid is difficult to filter and pump, and there must be a compromise. Frequently, the solution is heated to reduce the viscosity during filtering. Cellulose fibers may be spun at about 50°C (122°F), whereas polyacrylonitrile fibers are frequently spun at 170°C to 180°C (338–356 °F). A typical spinning speed is several hundred meters per minute.

Following the actual spinning operation, it is usually necessary to have a chemical treatment such as neutralization of the acid from the coagulating bath, etc., followed by washing and drying. The application of spin finish and the winding of the filament yarn follows this operation. Wet spinning plants have environmental problems and the counter-measures push up the costs of production.

Melt spinning

In melt spinning, the material supplied to the extruder is sometimes in a solid granular or 'chip' form, especially for small operations. In this case, the chip is conveyed from the storage silo to the hoppers of the extruders by a pneumatic transport system. From each hopper, the polymer passes through the extruder, conveyed by an 'auger' or 'screw' (Fig. 2.11). The polymer is then melted by the heated barrel and by friction

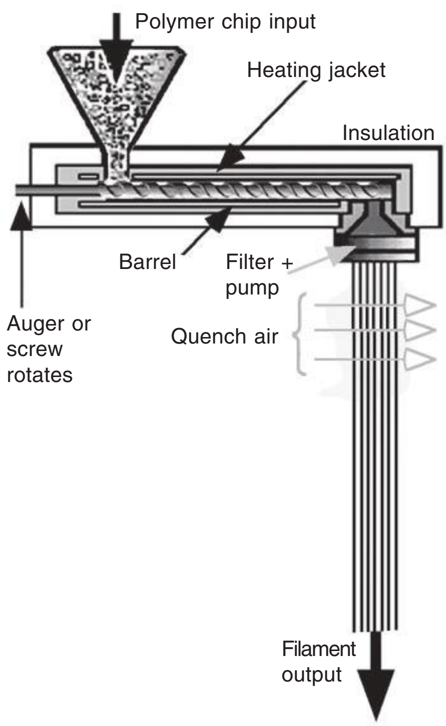

Fig. 2.11 Simple fiber extrusion

from the screw. Heat flow is the major factor in determining the viscosity of the liquid polymer in the working extruder. The viscosity affects the pressure generated by the screw forcing the liquid polymer through the spinneret. Additional back-pressure is generated by a filter pack. The design of the screw is a very important feature of a modern extruder.

In other cases, the polymer can be supplied in a continuous molten form (rather than in the intermediate chip form) direct from the polymerization reactor or an intermediate heated storage tank. By supplying the polymer through heated pipes, it can be maintained in the liquid form and air can be easily excluded to prevent oxidation with its deleterious effects. The liquid polymer may be pumped through the filter pack and spinneret by several sorts of pumps including the extruder screw. Back-leakage, polymer overheating, and degradation by excessive working are factors that have to be taken into account in choosing an appropriate pumping system. It should be noted that these entire polymerization/spinning systems are very large and the total polymer synthesis and extrusion equipment requires considerable floor space and headroom. Usually a multistory building is required. The capital cost is very high.

As mentioned, the rate of heat transfer from the extruder barrel into the polymer is very important in determining the viscosity of the molten material approaching the spinneret. This, in turn, helps to determine the flow rates and the ultimate yarn properties. The rate of heat flow *away* from the extruded filaments leaving the spinneret helps to determine the morphological structure of the yarn. Morphology relates to the degree of crystallinity and orientation. At high speeds, the shear rate in the extrusion zone (which is a function of the filament velocity) also affects the morphological structure. The amount of subsequent drawing of these filaments yet further affects the properties of the yarn. Such drawing might be carried out near the extrusion operation, or during texturing, or both. The properties of the extruded filaments and fibers are important but it is beyond the scope of this book; the reader is referred to reviews by Mukhopadhyay [28] and Brunnschweiler and Hearle [29].

The mechanical process appears to be inherently simple. However, as indicated above, there are a number of less obvious complexities involved which become very important at the high speeds now in use (of the order of 5000 m/min). Since the drawing speed is limited by the mechanical nature of the process, the extruder delivery speed would become virtually fixed at a relatively low level if the filaments were fully drawn. If part of the drawing procedure is deferred until the material is in the texturing machine, the yarn leaving the extrusion frame is only partially oriented. The orientation is completed by drawing in the texturing process and the use of this strategy results in economic advantage. Draw ratio changes affect the strength of the partially oriented yarn (POY). The strength of the POY produced at low draw ratios is insufficient for high speed texturing and it becomes desirable to draw at the texturing stage to increase the filament strength. Some drawing is necessary at the extrusion stage to give sufficient strength and stability to the POY. Thus, when the POY is being produced for draw-texturing, the texturing speeds in effect become linked to the extrusion speeds. Draw-texturing relates to the process where drawing is carried out at texturing. Since it is economically advantageous to do as much drawing as possible at the texturing stage, the choice of draw ratio at spinning becomes fairly critical.

Commercial filament extrusion is more complex than indicated in Fig. 2.11. The filters are larger and the molten polymer is distributed to groups of spinpacks fed from a main spin distributor and pump system. The whole system is carefully crafted to avoid stagnant flow zones, to conserve heat, and to preserve the temperature of the melt with heat transfer fluids that are sometimes of two-phase type, which hold the temperature at the boiling point of the fluid. An example of a two-phase system is given in Appendix 3, but the example is not intended to imply that steam is always used. It will be realized that it is very important to control the temperature and viscosity of the melt because the uniformity of the yarn depends on it. For example, with some polyesters it is necessary to hold the temperature between the limits 300 ± 1°C. Mechanical working of the melt also affects the viscosity; therefore the design of the extrusion and distribution systems is critical. The extrusion systems also have to be made to permit the changing of filters and spinning heads with minimal interruption to production. It has to be realized that cessation of flow causes problems and if the polymer is allowed to solidify, this is a disaster!

The extruder

The screw and barrel of an extruder fulfill a number of functions. First, the screw acts as a propulsion unit that transports the feed material to the spinneret. Second, it acts as a pump in which the feed is compacted or compressed and later (after the polymer has melted) forced through the various obstacles ahead. Third, it acts to work the melt and to make it more homogeneous. The barrel acts as part of a heat-exchanger to maintain the temperature of, or to melt, the moving polymer.

The molten material has to be filtered (perhaps with the generation of extra pressure) before it passes to the spinneret. The first part of the process is part of the extruder head and comprises the phases of propulsion, compression, heating, working, filtration, metering, and extrusion of the polymer through the spinneret. Filtration and metering will be discussed later. The second part follows and comprises quenching, drawing, and winding the filaments.

Clearance between the screw and the barrel (Fig. 2.12) is of some importance. If the clearance is too large, there is appreciable pressure loss and the molten polymer leaks backwards down the screw. If the clearance is too small the screw may seize up. As the barrel is heated, the bore diameter increases due to metal expansion, and as it cools the bore becomes smaller due to contraction. Because of thermal inertia, the barrel can cool down faster than the screw. Care has to be taken to ensure that the contracting barrel will not grip the screw and cause a seizure. The procedures for starting and stopping have to be carefully executed to avoid such mechanical seizures.

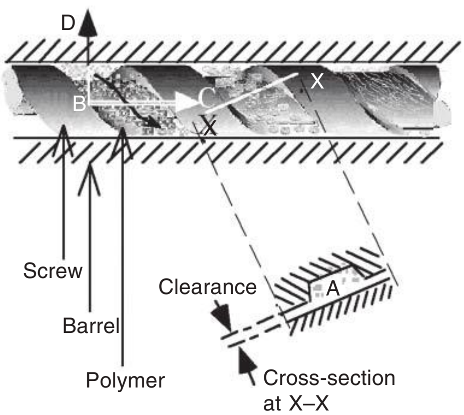

Fig. 2.12 Polymer flow in the extruder barrel

Of course, the extruder should be empty or the polymer in the barrel should be heated to liquefy it before any attempt is made to start. If the polymer were to become cross-linked due to oxidation and it were no longer possible to melt it, the material would have to be chipped out mechanically. It is therefore normal to operate extruders continuously for 24 hrs/day, 7 days/week, to avoid these problems.

The screw rotates and the movement of the surface of the helical portion in direction D causes the polymer to move in the direction C (Fig. 2.12). Polymer flows along the groove in the screw, and the mass flow, Q, at any cross section such as (X-X) is given by:

$$Q = \rho AV \qquad [2.1]$$

where Q is the mass flow
ρ is the density of the polymer (defined as 1/specific volume)
A is the cross-sectional area
V is the mean velocity component in direction of flow.

As the chip is compacted, liquefied, and then pressurized, ρ changes and it is necessary for AV to change accordingly. Consequently, the core of the metal screw is tapered with the thick end towards the outlet. The forced flow pressurizes the fluid polymer ready for delivery to the pump/filter system that precedes the spinneret. The spinneret should produce one filament per hole; thus for a normal yarn, it must contain many fine holes. The shape of the holes determines the cross-sectional shape of the filament; however, the cross-sectional areas of the filaments vary from those of the spinneret holes for the reasons discussed later.

Hot fluids usually circulate through channels in the barrel to provide the heat rather than using direct heating. Heat flow into the polymer is equal to a proportion of the heat flow from the heating medium plus local frictional heating. The absorbed energy is carried away from the system by the polymer as a change in state from solid to liquid and/or as a change in temperature. Heat transfer properties are also affected by the changes in state and temperature. The frictional heating component and the heat transferred from the heater are directly affected by the changes in the polymer and there is a very complex interactive situation. Local pressures, specific volumes, coefficients of friction, and viscosities of the melt vary according to the temperature of the polymer. Since the actual extrusion through the spinnerets is highly dependent on the viscosity of the melt, careful control is required of the variables.

The complexity of the operating conditions, plus the ambiguity in flow caused by the multitude of parallel flow streams, leads to the possibility of uneven distribution of the polymer flow. This phenomenon, known as 'channeling', can cause more polymer to flow through some spinneret holes than others. The result is that filaments have differences in linear density. Furthermore, the flow pattern can change continually during operation, particularly if the polymer viscosity is incorrect. Operating under such faulty conditions leads to quality control problems concerning 'denier' variations.

It is important to protect the polymer at high temperature from oxidation. Any such oxidation causes changes in viscosity, cross-linking, and deterioration in the final product. Consequently, antioxidants are usually included in the original polymer chip or molten polymer supply Also, hydrolytic degradation is limited by drying the polymer just before extrusion.

Filtering and metering

The material leaving the screw may not be perfectly homogeneous. It is particularly important to remove any hard elements or highly viscous concentrations (i.e. gels) from the fluid polymer stream lest they block the very fine holes in the spinneret. The metal block in which the holes are drilled is called a die. Such blockages not only interrupt the individual fluid streams from the affected holes but, even if the impediment removes itself, it is unlikely that a filament will be re-established. Instead, one is likely to get a drip (which is unoriented). Such unwanted polymer drips can coalesce with adjacent filaments and the result is a fault that can seriously affect subsequent operations in staple or textured yarn manufacture. For these reasons, it is normal to filter the molten material before it reaches the spinneret. Metal webs, fabric, or carefully graded sand is often used for this purpose, but in the latter case the body of the filter has to be carefully constructed to preclude particles of sand from clogging the spinneret holes. The filter introduces a high shear stress in the polymer, which affects its viscosity and further complicates matters. In some cases, the filter assembly is made in two parts, one of which is waiting to be used while the other one is in use. At an appropriate time, when the pressure drop has risen or a given time of use has expired, the second filter is substituted. This enables the first one to be cleaned at leisure.

If the linear density of the filaments is to be maintained, it is necessary to accurately control both the liquid flow rate and the yarn or tow take-up rate. To accurately control the flow rate of the liquid polymer, it is necessary to use a metering device (which is usually in the form of a pump), so that changes in viscosity and viscosity distribution shall have little effect on the mass flow rate. The pressure upstream of the metering pump has to be controlled so that it is not adversely affected by the metering device. Leakages in the metering pump can also adversely affect the denier of the filaments. Such variations are not easy to see at the extrusion stage and therefore very careful observation and testing are required to give a high quality product. Any variations permitted to go unchecked are likely to show up in the final product as faults in dyeability and bulk which will create customer complaints. Diameter D_1 (Fig. 2.13), and polymer density (ρ) determine the linear density of the filament. This, in turn, is determined by the mass flow (Q) and the velocity of take-up (V). The mass flow is the same at all cross-sections. Hence, Equation [2.1] may be applied.

It will be seen that the size of the hole in the spinneret, D_1, plays no direct part in determining the linear density of the filament. However, the shape and size of the hole determines the flow lines in the polymer as it begins to solidify, and the shape of the hole does affect the cross-sectional shape of the filament. Also the shape of the hole, viscoelastic variables of the polymer, and the speed of take-up affect the ratio D_1/D_3. If the polymer solidifies quickly after leaving the spinneret, these factors can materially affect the morphological character of the filaments produced. This is

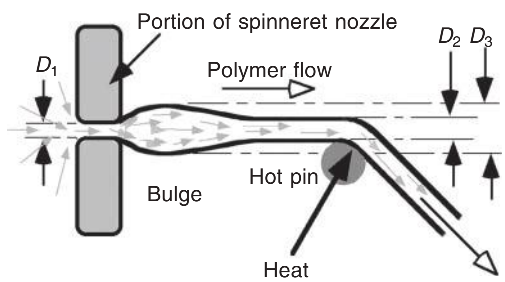

Fig. 2.13 Polymer bulge

because the crystal nucleation is affected by variations in shear stress, temperature, and viscosity in the regions near to the spinneret holes. Also, under certain conditions, there can be periodic changes in D_2, due to vibrations within the polymer stream, and these vibrations can lead to variations in the denier of the fibers.

Filtering does not reduce the debris generated at the exit of the extruder die and it is possible that such debris might cause trouble in ensuing processes. Good housekeeping at the extrusion stage is an essential ingredient of quality control.

Quenching

Liquid emerging from the spinneret has to be converted to a solid filament at a reasonable distance from the spinneret face (i.e. the corresponding temperature has to fall below T_m). Unless this occurs, it is very difficult to control and draw the filaments at that stage. With slow crystallization, it may be extremely difficult to handle the filaments once they are produced because of the lack of orientation. Hence, it is normal to quench the newly emerging material with a low speed flow of dry air or inert gas, usually blown perpendicular to the polymer stream. It is important to restrict the velocity of the gas flow to prevent one molten (or semi-molten) filament blowing into the path of an adjacent one. When such filaments touch, they will usually cohere and produce ‘married fibers’, which can be a great nuisance. Materials with significant numbers of married fibers or polymer drips cannot be used and are scrapped. Equal distribution of the quench medium is also important because of the necessity for equal cooling rates throughout the whole filament bundle. Unequal cooling rates not only vary the morphology of filaments across the bundle but also make some filaments more likely to break than others. This, in turn, affects the rate of creation of undesired drips. In any case, the ill effects would show up in the final product as changes in dye affinity.

At very high production rates, the speed of the filaments affects the quenching rates significantly. Where it is intended to orientate the polymer during extension, the filaments must be cooled quickly before the effects of stream orientation are dissipated. Elongational forces acting on the viscous fluid passing into the draw-down zone, where the semi-molten polymer changes to a solid, tend to align the molecules. If cooled quickly, such orientation can be frozen to give a material which can be handled and which might be, if research results can be transferred to commercial application, suitable for use in draw-texturing.

The relative velocity of the quench air affects the Reynolds Number of the air ‘skin’ surrounding the polymer stream and this in turn affects the heat transfer or cooling rate in the quenching phase. (The Reynolds Number is the ratio of viscous and inertia forces; it is a dimensionless parameter useful in normalizing the mathematical units.) The cooling rate helps determine the morphology of the POY.

Perhaps the most difficult problem concerning quenching occurs in tow production because of the number and size of the spinnerets as well as the density in which the filaments are packed in the extrusion zones. Also, with the large number of ends, the chances of a break are much greater.

Filament take-off and drawing

Solidified filaments are gathered and carried from the spinning zone by devices that grip them without squashing them. The filaments are often wrapped around rotating cylinders or ‘godets’ and the capstan friction generated applies enough driving force to withdraw them, draw them and transport them to the take-up system. The speed of take-up is very high but it is very rare for the filaments to be drawn significantly at this stage. After the draw stage, the filaments are at least partially oriented and the delivery speed is even higher than that of the take-up. However, it is necessary to draw the freshly extruded filaments at some stage, to orient the molecular structure and give the desired mechanical properties. It might also be mentioned that it is extremely important that the drawing be uniform from filament to filament and along the length of each filament. Thus, any mechanical inaccuracies in the draw rolls produce periodic variations in the draw. A common cause of this sort of error is due to the uneven build-up of finish on the rolls (see next section). Unfortunately, this not only causes variations in linear density, but also variations in dye affinity; such variations lead to streaking and barré. The drawing of a yarn can produce filament to filament variations in draw ratio and this can produce similar undesirable effects. During normal drawing, a neck (Fig. 2.13) is formed, and the position of this neck usually has to be stabilized by a hot pin or plate.

Undrawn polymers change their characteristics fairly rapidly; this is referred to as ageing. The more the polymers have been drawn, the slower the ageing takes place, and fully drawn filaments have very long shelf-lives. In drawing filaments, ageing of the spun, undrawn yarn has to be controlled because it affects the natural draw ratio, the drawing tension, and the physical characteristics of the material. The phases of extrusion and final drawing occur at different locations when working with POY, and the material is stored during the interim. Consequently good inventory control is needed to keep the product within acceptable time limits between extrusion and final drawing.

To start up a high speed drawing operation, it is necessary to use an aspirator. Such a device sucks the yarn from the spinneret (or other source) as fast as it is produced (it being realized that the source cannot be shut off in many cases). The ends are then 'painted' round the threadline and are wrapped around the take-up godet or rolls before cutting free the material inside the aspirator – a simple operation that needs skill to execute.

Fiber finish and treatments

Fiber finishes are necessary to lubricate the fibers or filaments and to reduce static electrification during subsequent operations; these finishes are mostly applied by the fiber maker. Without such 'spin finishes', the increase of drag due to the high coefficients of friction might cause end-breaks or other processing difficulties. Static electricity causes fibers to attract or repel one another, and causes some fibers to adhere to other surfaces (such as machine parts). In either case, a high degree of static charging causes considerable difficulty in processing. The fiber finishes can, in some cases, be used to provide a degree of cohesion between the filaments by acting as a sort of size, similar to that used in weaving. They also protect machine surfaces from wear and can prevent local fusion of fibers (especially at points where the fibers or filaments rub guides and other machine parts during high speed winding). Fiber finishes usually comprise a base lubricant, an antistatic agent, an emulsifier or solubilizing agent, and various special additives. The special additives include bactericides, antioxidants, and friction modifiers. The base lubricants are usually alkyl esters of fatty acids, hydrocarbon oils, waxes, vegetable oils, or mixtures thereof. These finishes have to be formulated with a regard to their sorption, moisture uptake, and surface tension characteristics, as well as to their effect on the dielectric and flow properties of the finish. Care also has to be taken to control the volatility, smoke potential, and flash point of the finish so that problems in subsequent processing are minimized. These factors are particularly important in texturing, where surface temperatures of the fiber can reach high levels. During processing, particles of finish and fiber become detached and deposited on various machine surfaces. Two examples of the problems caused by this may be cited. In texturing, they can form deposits on the heaters and other working parts. In rotor spinning, deposits in the rotor can be troublesome as discussed in Chapter 7. It is very important that the amount of finish applied to the fiber be strictly controlled and that the nature of the debris should be such as to minimize difficulties in the ensuing processes. Also, the finish should have no detrimental effect on the package including its shelf-life. Sometimes the polymers include substances such as titanium dioxide (TiO_2) as brighteners or other modifiers. Brighteners hide any tendency to yellowness in fabrics made from the fibers and makes colors more brilliant, but sometimes the additives are abrasive. For example, fibers containing TiO_2 tend to wear guides and it becomes necessary to use ceramics at the wear points and to avoid frictional contact as much as possible in the design of the yarn-handling portions of the equipment.

2.3.2 Man-made staple fiber production

Tow

Fiber produced for the manufacture of man-made staple yarn is first produced as tow. The word ‘tow’ has many meanings but in the present context it means a thick bundle of continuous filaments. Tow has to be cut, broken, or abraded to convert it into staple fiber. The abrasion technique is restricted to light tows and for a very few specialty purposes; it will not be further discussed here.

Fiber makers cut tow and blend it before baling to ensure uniformity of the product. A very large volume of fiber is cut in this way for short-staple spinners. Some long-staple is also dealt with in a similar way but some is supplied to the mill in tow form. This tow is cut or stretch-broken in the mill. Tow intended for stretch-breaking (see below) in the mill usually has a linear density of about half a million denier. (The linear density of tows for use by the fiber makers for cutting into staple is many times greater.) It is difficult to find common ground in the early processes because the needs vary so widely, as can be seen by examining Table 2.2.

Stretch-breaking tow

Stretch-breaking is a form of drawing in which the draw ratio exceeds the breaking elongation of the filaments, with the consequence that they break as they pass through

Table 2.2 Fiber to sliver conversion

Process fiber	**Clean mech**	**Clean chem**	**Cut or break in a mill**	**Open**	**Card**
Filament tow			X		
Bast fiber	X	X	*	X	X
Wool	X	X	*	X	X
Cotton	X	**		X	X
Man-made SS				X	X
Baled MM LS			**	X	X

Notes: X = always, * = in some cases only, ** = rarely, SS = short staple, MM = man-made, LS = long staple.

the draw zone and create staple fibers. The most popular use of stretch-breaking is to produce long-staple sliver from which high bulk staple yarns are made.

There are several phases in the process which will be described separately but, in fact, all the phases are often incorporated into a single machine. The phases are: (1) heat the unbroken filaments and cool under tension, (2) break the fibers by applying elongation stress, perhaps accompanied by a beating action, (3) relax the fibers by heating to create bulk in the product. There may be one or more repeat stages of phase (2) (called re-breaking) before stage (3).

In its simplest form, the machine produces a variable fiber length and the mean length is determined by the ratch setting (the distance between consecutive roll pairs in a roller drawing system). To break a large bundle of strong filaments requires a very robust set of drawing elements with strong gripping power. For this reason, the total fiber denier must be limited simply because the load cannot exceed the gripping power of the rolls. Also damage to the rolls has to be avoided. If load-sharing between filaments in a disorganized bundle is poor, uneven breaking will occur. Thus, it is desirable to have a sheet of parallel fibers entering the break zone but this is not practicable. In the early stretch-breaking machines it was not possible to process tows heavier than about 100 000 filaments of 1.5 dpf (denier per filament). More modern machines can process tows of up to 500 000 filaments and the acceptable fiber fineness has increased also. The exact specification of machine capability depends on the fiber because the fiber properties obviously play a large part in determining acceptable loads. The loads on the rolls are measured in tons and the machines have to be very robust. The machines are mainly used as tow-to-top machines that produce sliver. A 'top' is the name for a sliver as used in the wool processing mills.

It is usual to heat the filaments above T_g (glass transition temperature) whilst they are under tension and allow them to cool before the tension is released (phase 1). The heat-stretch phase of the process (Fig. 2.14(a)) reduces the breaking elongation in the stretch-break zones and makes this part of the operation easier. After the heat-stretch

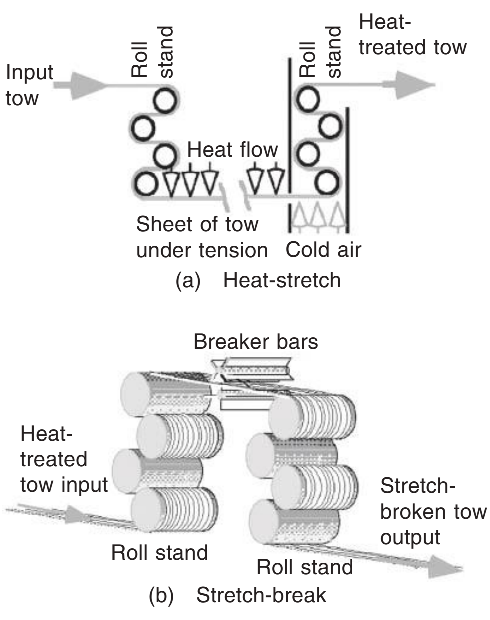

Fig. 2.14 Stretch-breaking tow

zone come the stretch-break zones where the cooled, heat-stretched tow is broken into staple fibers (phase 2). The locked-in extension is released when the fibers are reheated above T_g and this process causes shrinkage (phase 3).

This is a valuable way of inducing bulk in the material. Older machines used intersecting breaker bars to control the staple length (Fig. 2.14(b)). This practice is declining and stretch-break/re-break systems are taking their place. The re-break stage is merely the stretch-breaking of sliver that has already been stretch-broken once; the second stage selectively breaks the longer fibers and reduces the variation in length. The intersecting breaker bars have an onerous duty and wear rates are something of a problem. Modern machines are very robust and are designed for very high speeds. The capital cost is high but they can be cost-effective where 100% man-made fibers are to be processed and the system can be integrated into the operation without undue disruption.

Stretch-breaking not only changes the linear density of the bundle by drawing but it also changes the linear density of each of the filaments. The filaments are stretched to their breaking point and this involves an elongation of the fibers. Elongation is accompanied by a reduction in linear density of the fiber; the change in dpf (denier/filament) can be significant. The fact that the fibers are stretched whilst heated causes flats to form on their surfaces [30] and this gives the resulting yarns a greater crispness in hand than otherwise would be the case.

Fiber cohesion is low in freshly broken tow and, to be able to manipulate the material, it is necessary to improve it by fiber crimping. The usual crimper is a stuffer box in which the sliver is fed to a heated stuffer chamber at a speed faster than the offtake in a manner similar to that described in Chapter 4. Fibers buckle under the compressive load and become crimped (16 to 20 crimps/inch is normal). Crimped fibers cohere well and a sliver made of such fibers can be handled and carded properly. Where breaker bars are used, significant amounts of fly (airborne fiber and debris) can be generated and this fly must be taken away from the breaker zone otherwise the product becomes contaminated, to the detriment of following knitting operations.

One great advantage of the stretch-breaking process is that it produces high bulk yarns [31]. Bulk is generated by the differential shrinkage of the fibers, the stage being set for this in the heat-stretch zone. Not all fibers suffer the same tensions or reach the same temperature with the consequence that not all of them shrink equally. The fibers that shrink the most cause the others to become compressed along their length; the compressed fibers buckle and the buckled fibers take up more space. Thus, a stretch-broken sliver is naturally bulky, but the effect can be heightened by mixing non-heat-stretched sliver with heat-stretched sliver at the drawframe and then autoclaving (heating with steam under pressure) to produce the shrinkage required. These bulky stretch-broken yarns are a close approximation to wool yarns and they produce soft 'woolly' fabrics. The yarns are often referred to as high bulk staple yarns. Whilst the traditional way of developing the bulk was to use an autoclave, some modern machines have a continuous heating system attached to them, which fulfills the same purpose. The operating temperature is about 240°F (115°C) and steam is often used as the heating medium (see Appendix 3). Within limits, an increase in heater temperature or draw ratio generally increases the tenacity of the fiber, but too high a temperature leads to degradation of the polymer, which, in turn, leads to a loss in strength. Too high a draw ratio or too low a heater temperature leads to end-breakages (i.e. stoppages) during processing and causes increased amounts of fly. Stretch-breaking is technically possible for tow-to-yarn systems (direct spinning) as well as tow-to-top systems (tow-to-sliver) but the high cost of tows of suitable quality renders the system uneconomical for direct spinning. Also there is no chance of blending between the outputs of different machines to reduce the risk of barré. The object lesson here is that production efficiency cannot always be reconciled with quality of product.

Cutting tow for long staple

In cutting tow to produce long-staple fibers, a spiral cutter is commonly used, which meshes with a smooth, hardened anvil roller as shown in Fig. 2.15(a). The tow is spread out into a sheet of uniform thickness before passing through the cutter. The staple length is controlled by the pitch of the cutting edges and, to a lesser extent, by the angle at which the fibers pass through the system. Also, involuntary variations in fiber attitude cause a spread in staple length, Fig. 2.15(c). It is possible, by altering the angle at which the tow passes through the cutter, to slightly change the staple length as shown in Fig. 2.15(d). Only minor changes can be made by altering this angle and any major change requires that a different cutter be used. Any damage to a cutting edge is likely to allow double-length fibers to be discharged and these can cause difficulties in the following drawing and drafting processes. For this reason, the cutting edges are not razor-like but are rectangular, and function by locally crushing the filaments at the point of contact between the cutter and anvil roller. There is difficulty in handling fine denier fibers if the cutter is not precisely set and in perfect condition. Maintenance of the cutter is a vital part of the operation.

Fibers tend to be bonded along the cuts by the pressure exerted by the cutter and this is undesirable. Therefore, the ribbon is caused to flex to create shear, which debonds the fibers as shown in Fig. 2.15(b). Also, tow leaving the cutter has well-defined lines of weakness along each cut since there can be little fiber entanglement. If the emerging ribbon of freshly cut tow was simply condensed, the resultant sliver would be extremely weak. To overcome this, the sheet is sheared by a process called 'shuffling' as shown in Fig. 2.15(e). In the case shown, an apron is used as the bottom element to provide a reaction to the two top rolls. The position of the cut end in the top of the sheet is now displaced from those below as shown in Fig. 2.15(g). The distribution of cut ends disperses the zones of weakness. Finally the sheet of cut fibers is rolled to make a sliver as shown in Fig. 2.15(f). The elements shown in these diagrams are often parts of a single machine so that the input is filament tow and the output is staple fiber in sliver form.

Fiber finish and subsequently added dressings are often added in the mill to aid the tow cutting process [32] but such additives can adversely affect the performance of the sliver in the yarn making operation. A dressing that makes the cutting operation easier may cause fibers to cohere in a non-uniform manner. This, in turn, may cause unevenness in the yarns produced. The Pacific Converter type of cutting equipment, which is the type just described, is often used to produce a sliver or top, whereas the cutters used to produce short-staple fibers are quite different.

Cutting tow for short staple

Long-staple processing is more tolerant of multi-length fibers than is short-staple processing. Short-staple or mid-range systems are less tolerant of fibers greater than the ratch setting of the drafting system because they bridge the drafting zones and either break or slip at the drafting rolls. A ratch setting is the distance between

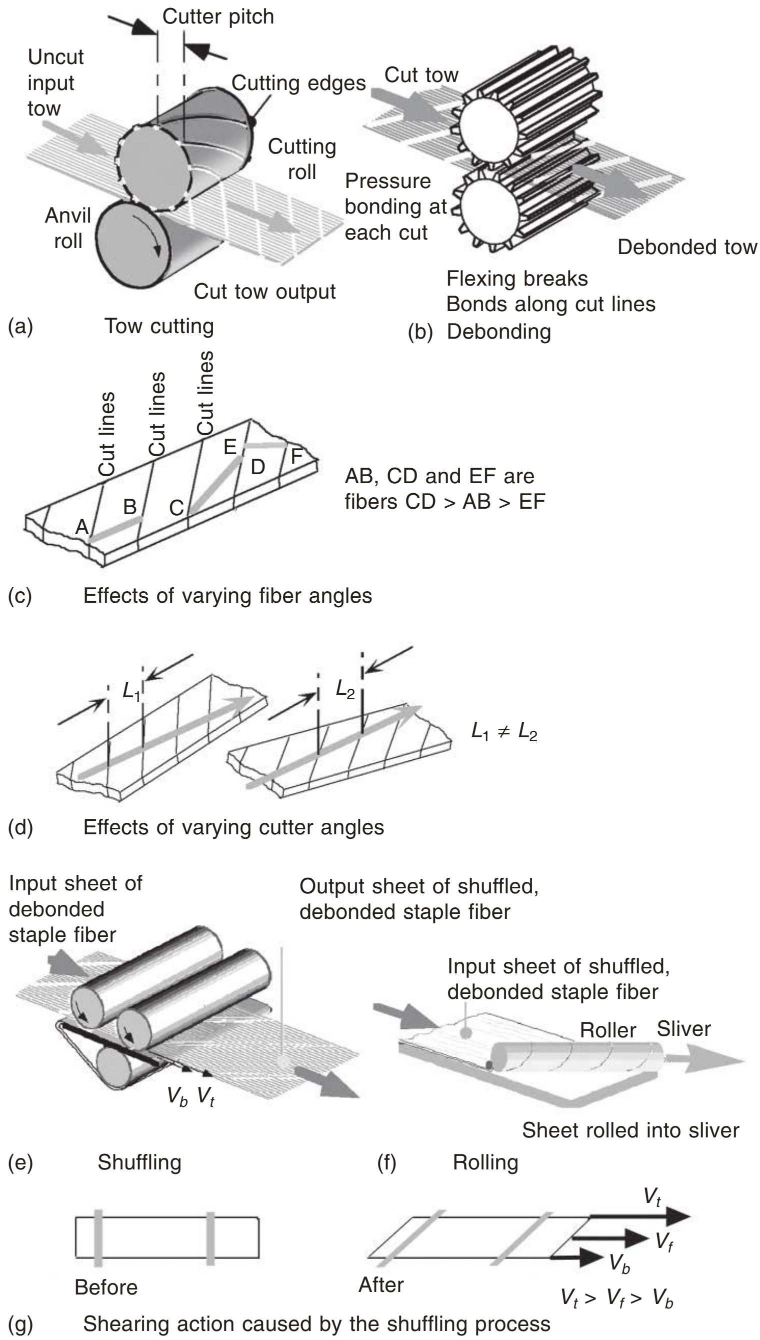

Fig. 2.15 Tow-to-top conversion by cutting

adjacent sets of rolls in a drafting system (see Chapter 3). These events disturb the flow of normal fibers. This is detrimental to the efficiency of the process and the quality of the product. One solution is to wrap the tow around a cutter of the type shown in Fig. 2.16, first to create pressure between the filaments and the cutting edges and second to apply internal suction. Few over-length fibers pass into the

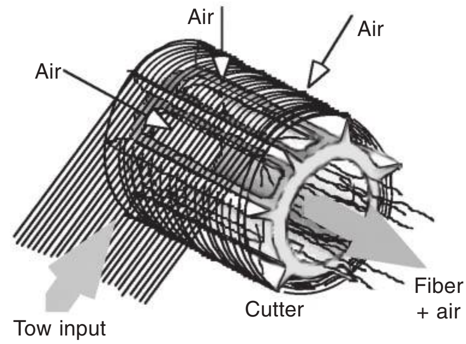

Fig. 2.16 Tow cutter for short staple

output and the system is suitable for producing short or mid-range staple fiber. The fibers are baled for transmission to the mill. To permit carding, it is necessary for the fibers to be crimped so that there is a degree of mutual cohesion, as was discussed earlier.

Tow size and quality is important; the larger the tow, the more difficult it becomes to maintain uniform tension in processing. Lack of uniformity in thickness across the tow sheet can cause problems and, in particular, the tendency for the sheet to fold at the edges can lead to problems. Tow knotting is also an operational problem because the knots have to be removed before cutting. The knot removal operation can leave gaps in the ensuing webs which result in excessive waste.

Fiber crimping and finish

As discussed, it is normal to crimp the fibers. A ribbon of fibers can be deformed under heat by overfeeding it into a stuffer box or by passing it through the mesh of fine toothed gears (gear crimp) as shown in Fig. 2.17. Alternatively, tow can be stretched hot and then cooled to lock in the extension in the manner previously

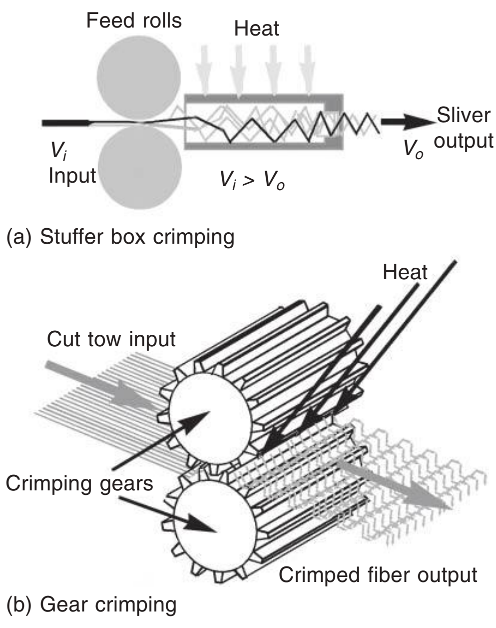

Fig. 2.17 Fiber crimping

described. The fibers must be properly lubricated to prevent damage in the opening and carding processes. Also, it is essential that the finish applied to the fiber should minimize any tendency for the fibers to charge electrically due to friction suffered in processing. Electrostatic charges interfere badly with normal processing and application of a suitable finish in appropriate quantities is very important. As pointed out earlier, any finishes applied to aid the conversion to sliver must not cause it to perform badly in the yarn manufacturing operation.

General comments
Conversion of tow to sliver is a short mechanical process that can be described in relatively few words. Nevertheless, adequate quality control involves not only the mechanical processes but also the chemical and morphological characteristics of the polymer and fiber finish. Brevity of explanation should not be taken to mean that any one of the processes is unimportant.

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