1 Introduction

The term *fiber* conjures up an image of flexible threads, beautiful garments and dresses, and perhaps even some lowly items such as ropes and cords for tying things, and burlap sacks used for transporting commodities, etc. Nature provides us with an immense catalog of examples where materials in a fibrous form are used to make highly complex and multifunctional parts. Protein, which is chemically a variety of complexes of amino acids, is frequently found in nature in a fibrous form. Collagen, for example, is a fibrous protein that forms part of both hard and soft connective tissues. A more well-known natural fiber, which is essentially pure protein, is silk fiber. Silk is a very important natural, biological fiber produced by spider and silkworm. It is spun from a solution; the solution, in this case, being produced by the silkworm or the spider. Silkworm silk has been commercialized for many years. However, scientists and engineers are beginning to realize the potential of silk, in general, and spidersilk, in particular.

Indeed, materials in a fibrous form have been used by mankind for a long time. Yarns made of fibers have been used for making fabrics, ropes, and cords, and for many other uses since prehistoric times, long before scientists had any idea of the internal structure of these materials. Weaving of cloth has been an important occupation in most ancient societies. The term fabric is frequently employed as a metaphor for societal characteristics. One talks of the social fabric or moral fiber of a society, etc. It is interesting to note that an archeological excavation of a 9000-year-old site in Turkey led to the discovery of a piece of fabric, a piece of linen, woven from the fibers of a flax plant (New York Times, 1993). Normally, archeologists date an era by the pottery of that era. It would appear from this discovery that textile fabrics came even before pottery. There is also recorded use of sutures as stitches in wound repairs in prehistoric times (Lyman, 1991). An ancient medical treatise, about 800 BC, called *The Sushruta Samhita*, written by the Indian surgeon Sushruta, describes the use of braided fibers such as horse hair, cotton fibers, animal sinews, and fibrous bark as sutures. Incidentally, the word suture comes from the Sanskrit word, *sutra* meaning filament or thread.

The importance of fibrous materials in an industrialized economy can hardly be overstated. The world fiber market runs to millions of tons. The market is dominated by oil-based synthetic fibers (think of fibers such nylon, polyester, etc.) with a share of about 62% by volume. Cellulosic fibers (mainly cotton) make up about 30% by volume. The fiber related industry is a very large sector of the US economy. According to US fiber industry sources, Americans consume over eight billion (8×10^9) kg of fibers per year. In the US, it is an over US$ 200 billion industry, employs about 12% of the manufacturing work force, and consumes about 6% of the energy. The fiber industry has about the same importance in Europe, Asia, South America, and other parts of the world. Thus, by any measure, fiber related industrial activity worldwide represents a very important sector of the world's economy!

Fibrous materials are, in one form or another, part of our daily life. One has only to look at one's surroundings and reflect a little bit to realize the all-pervading influence of fibrous materials in our lives. Fibrous forms of matter span daily use stuff such as apparel, carpets, artificial turfs, barrier liners under highways and railroad tracks, fiber reinforced composites in aerospace industry, defense industry applications involving aircraft, rocket nozzles and the nose cones of missiles and space shuttle, sporting goods (rackets, golf shafts, etc.), boats, civil construction, etc. In short, a quick perusal of our surroundings will show that fibers, albeit in a variety of forms, are used in all kinds of products.

Let's look at some commonplace examples. A good example that many of us tea drinkers go through every day involves the use of a tea bag. The proper tea bag needs to be porous, should not impart a taste to the brew, and of course, should have enough wet strength so that it does not fall apart in the hot water. The introduction of the tea bag has an interesting history. Faye Osborne of Dexter Corporation, Windsor Locks, CT, USA is credited with the invention of the tea bag (Sharp, 1995). After trying a number of vegetable fibers, he arrived at wild abaca fiber (or Manila hemp) and wood pulp to make the paper for the tea bag.

We should digress here a bit and let the reader know that abaca fiber is obtained from the leaf stalks of the plant; it is not related to true hemp. The word Manila refers to the capital of the Philippines, a major producer of Manila hemp. World War II disrupted the availability of Manila hemp fiber. In 1942, Osborne came up with rayon fiber made from old rope from which oil had been extracted. A coating of melamine resin helped increase the wet strength of the paper. Some more sophisticated tea bags are made from polyamide (or nylon) or poly lactic acid (PLA). PLA is a thermoplastic made from a renewable source such as corn; thus, in principle, it is biodegradable. Figure 1.1 shows pictures of a tea bag at three different magnifications. A macro picture shows the tea bag made of nylon fabric; the next two higher magnification pictures show the open, woven form of nylon fabric which allows hot water to flow into the bag for brewing but keeps the tea leaves in the bag. Of course, there are more sophisticated but less appreciated uses of materials in fibrous form for medical uses involving drug delivery, optical fiber that allows examination of inaccessible body parts, etc. Modern usage of fibers in medicine is, of course, quite extensive: surgical dressings and masks, caps, gowns; implantable fibers for sutures, fabrics for vascular grafts and heart repairs; and extra corporeal uses such as fabrics for dialysis and oxygenator membranes, etc. In short, we live in a world in which the matter in a fibrous form is ever present around us.

It is worth pointing out that although around ten billion kg of manmade fibers are produced globally, less than 1% of those would fall in the *High Performance Fibers* (HPF) category. Thus, HPFs represent a relatively small segment, but a vital and essential one. They are driven by special functions that require specific properties unique

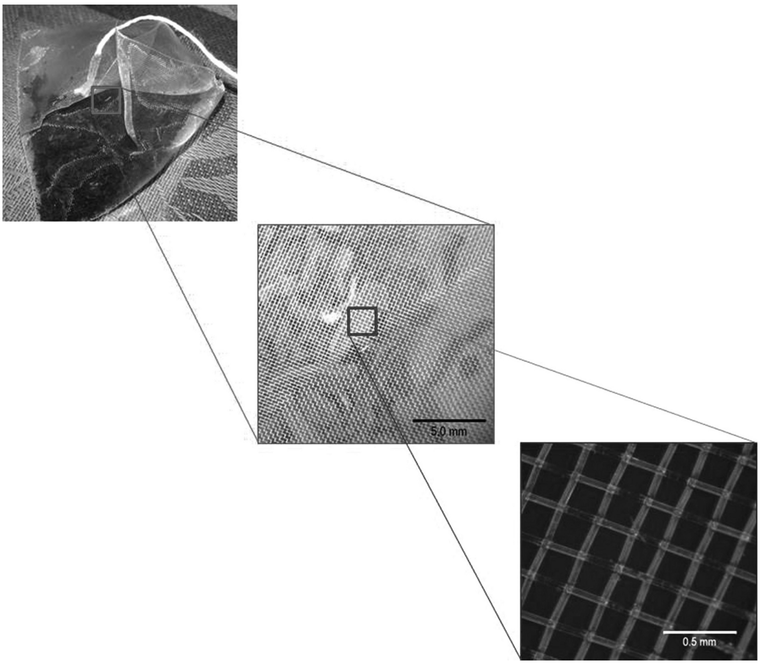

Fig. 1.1 A tea bag made of woven nylon fabric. The first picture shows a low magnification macro of a tea bag and the two blown up images show the open, woven fabric structure of nylon which allows the hot water to flow into the bag for brewing but keeps the tea leaves in the bag. A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.

to these fibers. HPFs usually have very high levels of at least one of the following properties:

- stiffness, strength, ability to resist high temperatures, limiting oxygen index, and high resistance to chemicals;
- they possess a unique combination of properties; i.e., they fill a niche in the upper end of the applications spectrum;
- technology driven, specialty oriented, and are frequently made in smaller batch-type processes.

In this chapter we examine the recent history of synthetic fiber production, provide a convenient classification of fibers, and then introduce the subject of strong and stiff fibers. Strong and stiff fibers came about in the second half of the twentieth century because of many improvements in synthesis and processing, but most of all, owing to a growing realization of the importance of the processing–structure–property triad. This triad of processing–structure–property correlations as applied to the fibrous materials is indeed the basic theme of this book. What we mean by this is that the processing of a material into a fibrous form determines its internal structure at the micro- and nanometer level, and the internal structure, in turn, determines the ultimate properties of the fiber. Time and again, we shall come back to this basic theme in this book.

1.1 Some history

Natural fibers have been around in one form or another from prehistoric times. Cotton fiber is one of the most important natural fibers. It has a lot of history associated with it (Yaffa, 2005). The cultivation of cotton has been traced to some 5000 years back, originating perhaps in the northwest of India. Another important natural fiber is silk fiber, which has been a valuable commodity for a very long time. However, it was not until about 1880 that a Frenchman, Count Hilaire de Chardonnet, became successful in imitating silkworms and produced the first synthetic fiber from mulberry pulp. This was *rayon*, not quite silk, but it had the same silky feel to it. Thus began the era of regenerated cellulosic, natural fibers such as rayon and acetate. Later, in the mid-1920s, synthetic fibers started appearing. The big breakthrough came when Carothers discovered the process of condensation polymerization to produce a variety of polymers such as polyamides, polyesters, and polyurethanes. I think a reasonable case can be made that the modern age of manmade fibers started with the discovery of nylon in 1930s. The names of two chemists, an American, Wallace Carothers and a German, Paul Schlack, are linked inextricably to the pioneering work that led to the discovery of nylon or polyamide fiber. DuPont Co. started producing nylon fiber in 1939. That can be regarded as the beginning of the age of manmade fibers; World War II, however, interrupted the development of synthetic fibers. A series of other synthetic fibers was discovered soon after the war, e.g., acrylic, polyester, etc., and the progress toward the development of synthetic fibers was resumed. It was also during the second quarter of the twentieth century that scientists started to unravel the internal microstructure of some of the natural fibers and soon thereafter produced synthetic fibers that rivaled or were improvements on the natural fibers. Most of this work had to do with applications of fibers for apparel and similar uses; understandably, therefore, most of the information during the 1940s and 1950s about fibrous materials came from people involved, in one way or another, with textiles. Parallel to the developments in the field of organic fibers (natural and synthetic), in the late 1930s and early 1940s, it was discovered that silica-based glass could be drawn into a very high strength fiber. The stiffness of glass fiber does not differ from that of the bulk glass. This is because glass is an amorphous material, and therefore, no preferential orientation takes place during the fiber drawing operation. The stiffness of glass is, however, quite high compared to that of most polymers and therefore glass fiber is quite suitable for reinforcement of polymeric materials. The advent of glass fibers can be regarded as the harbinger of processing and use of fibers in the nontextile domain. Of course, metal wires have been in use for various specific purposes, e.g., copper wire for electrical conduction, tungsten wire for lamp filaments, thermocouple wires made of a variety of metallic alloys for measurement of temperature, steel and other metallic alloy-based wires for cables of all kinds and a variety of musical instruments such as piano, violin, etc. The last quarter of the twentieth century saw extensive work in the area of producing high modulus fibers, organic as well as inorganic. In the 1950s, it was realized that the carbon–carbon bond in the backbone chain of polymers is a very strong one and that if we could only orient and extend the molecular chains, we should get a high modulus fiber from the organic fibers. This was attempted, at first, by applying ever increasing stretch or draw ratios to the as-spun organic fibers. This resulted in some improvement in the stiffness of the fiber, but no better than what was available with glass fiber, i.e., a tensile or Young's modulus of about 70 GPa in the fiber direction. Soon, however, researchers realized that what one needed was orientation *and* extension of the molecular chains in order to realize the full potential of the carbon–carbon bond. Aramid and ultrahigh molecular weight polyethylene (UHMWPE) fibers, with Young's modulus over 100 GPa, epitomize this oriented and extended chain structure. The last quarter of the twentieth century also saw an increasing amount of work in the area of ceramic fibers having low density, high stiffness, high strength, but, more importantly, possessing these characteristics at high temperatures (as high as 1000 °C and above). Examples of such high temperature fibers include boron, carbon, alumina, silicon carbide, etc. Some very novel and innovative techniques based on sol-gel and the use of polymeric precursors to obtain inorganic compound or ceramic fibers such as silicon carbide, alumina, etc. came into being. These very significant advances opened up an entirely new chapter in the field of fibrous materials, viz., fibers that have very high elastic stiffness, high strength, low density, and are capable of withstanding extremely high temperatures. The driving force for this development was the use of these fibers as reinforcements for metals and ceramics, i.e., at medium to very high temperatures.

1.2 Classification of fibers

One can classify fibers in a variety of ways. For example, one may divide the whole field of fibers into apparel and nonapparel fibers, i.e., based upon the final use of fibrous material. The apparel fibers include synthetic fibers such as nylon, polyester, Spandex, and natural fibers such as cotton, jute, sisal, ramie, silk, etc. Nonapparel fibers include aramid, polyethylene, steel, copper, carbon, glass, silicon carbide, and alumina. These nonapparel fibers are used for making cords and ropes, geotextiles, and structural applications such as fiber reinforcements in a variety of composites. These fibers possess higher stiffness and strength and a lower strain-to-failure than the apparel fibers. They are also characterized by rather difficult processing and drastic strength degradation by the presence of small flaws, i.e., they generally have a low toughness.

Another classification of fibers can be made in terms of fiber length, continuous or staple fiber. Continuous fibers have practically an infinite length while staple fibers have short, discrete lengths (10–400 mm long). Like continuous fibers, these staple fibers can also be spun into a yarn, called staple fiber yarn (see Chapter 2). This ability to be spun into a yarn can be improved if the fiber is imparted a waviness or crimp. Staple fibers are excellent for providing bulkiness for filling, filtration, etc. Frequently, staple natural fibers (cotton, wool) and staple synthetic fibers (nylon, polyester) are blended to obtain characteristics that unblended fibers do not possess. Figure 1.2 shows this classification based on fiber size and the different product forms that are commonly available, e.g., woven or nonwoven.

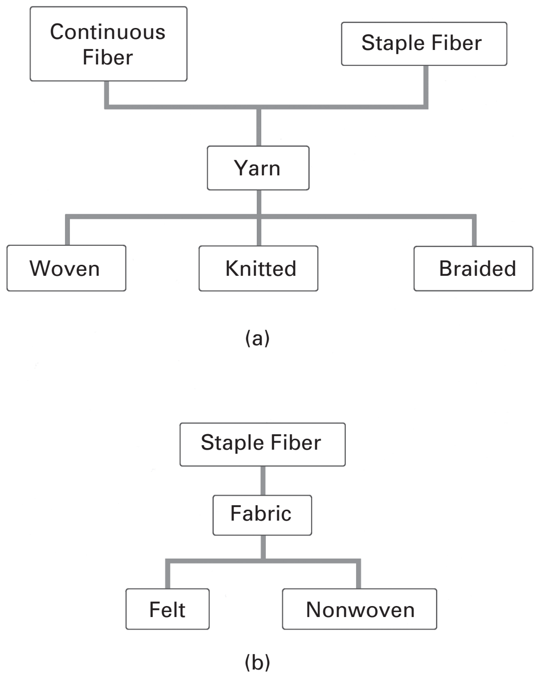

Fig. 1.2 (a) Yarn can be produced from a continuous fiber or a staple fiber. Yarn can be converted into a useful form by weaving, knitting, or braiding. (b) Staple fiber can be made into a fabric, which can be in the form of a felt or a nonwoven.

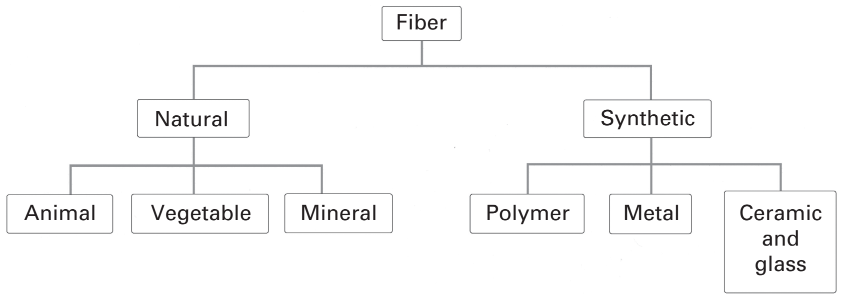

Fig. 1.3 Classification of fibers based on natural and synthetic fibers.

Yet another convenient classification of fibers is based on natural and synthetic fibers, as shown in Fig. 1.3. Natural fibers occurring in the vegetable or animal kingdom are polymeric in terms of their chemical constitution, while natural fibers in the form of minerals are akin to crystalline ceramics. A distinctive feature of natural fibers is that they are generally a mixture (chemical or physical) of different compounds. One can further classify synthetic fibers as polymers, metals, and ceramics or glass. Here, one should also mention a very special and unique subclass of fibers, viz., *whiskers*. Whiskers are monocrystalline, short fibers with extremely high strength. This high strength, approaching the theoretical strength, comes about because of the absence of crystalline imperfections such as dislocations. Being monocrystalline, there are no grain boundaries either. Whiskers are normally obtained by vapor phase growth. Typically, they have a diameter of a few μm and a length of a few mm. Thus, their aspect ratio (length/diameter) can vary from 50 to 10 000. Perhaps the greatest drawback of whiskers is that they do not have uniform dimensions or properties. This results in an extremely large spread in their properties. Handling and alignment of whiskers in a matrix to produce a composite are other problems.

1.3 Stiff and strong fibers

As we pointed out above, materials in a fibrous form are found extensively in nature. Up until the mid-twentieth century, most of the usage of fibers had been in clothing and other household uses. About the middle of the twentieth century, high performance fibers became available for use in a fabric form or as reinforcements for making composites. Our main focus in this text will be on processing, microstructure, properties, and applications of *materials* in a fibrous form, with a distinct emphasis on synthetic fibers for non-textile applications. Such fibers are generally very stiff and strong. This is where some of the important developments have occurred since the middle of the twentieth century. The use of fibers as high performance materials, in structural engineering applications, is based on three important characteristics:

(i) A small diameter of fiber with respect to its grain size or other microstructural unit. This allows a higher fraction of the theoretical strength to be attained than that possible in a bulk form. This is a direct result of the so-called size effect, viz., the smaller the size, the lower the probability of having an imperfection of a critical size that would lead to the failure of the material. Thus, even for a material in its fibrous form, its strength decreases as its diameter increases.
(ii) A very high degree of flexibility which is really a characteristic of a material having a low modulus and a small diameter. This flexibility permits a variety of techniques to be employed for making fabrics, ropes, cords, and fiber reinforced composites with these fibers. We deal with this important topic of fiber flexibility in Chapter 2.
(iii) A high aspect ratio (length/diameter, ℓ/d) which allows a very large fraction of applied load to be transferred via the matrix to the stiff and strong fiber in a fiber reinforced composite (see e.g., Chawla, 2012)

The most distinctive feature of a fibrous material is that it has properties highly biased along its length. Fibers, in general, and continuous fibers, in particular, are very attractive for the reasons given above. A given material in a fibrous form has a high aspect ratio (length/diameter) and can be highly flexible. Such a flexible fiber can be made into yarn, which in turn can be braided, knitted, or woven into rather complex shapes and forms. Think of some materials that are inherently brittle in their bulk form, such as glass, alumina, or silicon carbide, etc. In the form of an ultrafine diameter fiber they can be as flexible as any organic textile fiber, such as nylon, which is commonly used to make women's stockings. Quite frequently, as mentioned above, a material in a fibrous form has a higher strength and, sometimes, as in a highly oriented fiber, even a higher elastic modulus than in the bulk form. These characteristics have led to the development of fiber reinforced composites with a variety of matrix materials such as polymers, metals, glasses, and ceramics (see, for example, Chawla, 2005, 2012; Chawla and Chawla, 2013; Clyne and Withers, 1993; Hull and Clyne, 1996; Suresh et al., 1993; Taya and Arsenault, 1989). In the chapters to follow, I describe the processing–microstructure–properties of some of these fibrous materials. But first I provide some useful information that reconciles the terminology and units used by workers and researchers in the textile field and those in the field of materials science and engineering or engineering in general.

1.4 Terminology and units

There are certain units as well as some terms that are commonly used in the textile industry which are not commonly used in other engineering fields. It would be instructive to get familiarized with these. We provide a summary of these items.

1.4.1 Units

Since fibers are essentially linear entities, it is common to characterize them by their *linear density*. In the textile industry, there are two commonly used units for this purpose: denier (commonly used in the US) and tex (commonly used in Europe). They are defined as

$$\text{denier} = \text{mass in grams of 9000 m length of a fiber}$$
$$\text{tex} = \text{mass in grams of 1000 m length of a fiber}$$

1.4.2 Tenacity and modulus

There are a few other important terms that are commonly used in the textile industry. Two of these terms are commonly used as figures of merit: specific stress and specific modulus.

Many fibers do not have a uniform cross-sectional area, so the conventional engineering definition of stress (force/unit area) is replaced in the textile literature by a term called tenacity which is nothing but force/linear density. Tenacity is also referred to as specific strength. The term works equally for an individual fiber or a yarn. It has the units of N/tex or cN/tex. In the US, tenacity has the units of gram force (gf)/denier:

$$1\ \text{gf/denier} = 0.088\ \text{N/tex}.$$

One can similarly define a specific modulus which will have the same units as specific strength. The relationship between conventional engineering stress and tenacity is given below.

$$1\ \text{Pa} = 1\text{Nm}^{-2} = 1\ \text{N tex}^{-1}.\text{tex m}^{-2} = 1\ \text{N tex}^{-1} 10^6 \rho,$$

where the volumetric density, ρ, is in kg/m^3.

The unit tex (T) is defined as

$$\begin{aligned} T &= \text{volumetric density } (\rho) \times \text{cross sectional area } (A) \\ &= \text{mass per unit length.} \end{aligned}$$

T has the units of g/km. We can write

$$T = \rho(\text{kg/m}^3)A(\text{m}^2),$$

$$T = \rho A(\text{kg/m}),$$

$$T = 10^3 \rho A(\text{kg/km}),$$

$$T = 10^6 \rho A(\text{g/km}).$$

The reader should note that in the above expression, the volumetric density, ρ, must be in kg/m^3!

Since there is a lot of confusion about these units; we summarize the salient points below in bulleted form as well as in a table:

- 1 tex = 9 den → 0.1 tex = 1 dtex = 0.9 den or 1 dtex ~ 1 den.
- The larger the linear density, the heavier is the yarn.
- For fibers of a similar density, tex gives a quick comparison of the cross-sectional area.
- Figure of merit: specific stress or specific modulus, also known as tenacity (units N tex^{-1})
  - LT – low tenacity,
  - MT – medium tenacity,
  - HT – high tenacity.
- 1 Pa = 1 N tex^{-1}.tex m^{-2} = 1 N tex^{-1} $10^6\rho$.

Conversion table

	tex (tex)	decitex (dtex)	denier (den)
tex (tex)	1	10 dtex	9 tex
decitex (dtex)	tex/10	1	0.9 dtex
denier (den)	tex/9	dtex/0.9	1

Some other conversion factors

Breaking force

1 pound-force (lb) = 4.4484 newton (N)
1 newton (N) = 0.2248 pound-force (lb)

Yarn size

1 denier (den) = 1.111 decitex (dtex)
1 decitex (dtex) = 0.900 denier (D)

Tenacity

1 gram-force/denier (1 g/den) = 8.830 centinewton/tex (cN/tex)
1 centinewton/tex (cN/tex) = 0.1132 gram-force/den (g/den)

Mass

1 kilogram (kg) = 2.2046 pound (lb)
1 pound (lb) = 0.4536 kilogram (kg)

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