Chapter 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 that is essentially pure protein, is silk fiber. Silk is a very important natural, biological fiber produced by spider and silkworm. It is a solution spun fiber, with the solution, in this case, being produced by the silkworm or the spider. The silkworm silk has been commercialized for many years while scientists and engineers are beginning to realize the potential of spidersilk.

Indeed, materials in a fibrous form have been used by mankind for a long time. Fiber yarns 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 part of most ancient societies. The term fabric is frequently employed as a metaphor for society. 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 even before the pottery, there were textile fabrics. 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.

The importance of fibrous materials in an industrialized economy can hardly be overstated. For example, 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 fibers per year. In the US, it is an over US$ 200 billion industry, employs about 12% of the manufacturing workforce, 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 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 society. From daily uses such as apparel, carpets to artificial turfs, barrier liners under highways and railroad tracks, fiber reinforced composites in sporting goods (rackets, golf shafts, etc.), boats, civil construction, aerospace industry, and defense applications involving aircraft, rocket nozzles and nose cones of missiles and the space shuttle. 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. A commonplace example that many of us tea drinkers go through everyday 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. 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. Of course, there are more sophisticated but less appreciated uses such as fibers 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. Thus, we live in a world in which matter in a fibrous form is ever present around us.

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 a 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 microstructure, and the microstructure, 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. Natural silk fiber 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 man-made fibers started with the discovery of the nylon in the 1930s. The names of two chemists, an American, Wallace Carothers and a German, Paul Schlack, are linked to the pioneering work that led to the discovery of nylon fiber. Du Pont Co. started producing nylon fiber in 1939. That can be regarded as the beginning of the age of man-made fibers; the Second World War, however, interrupted the progress in 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 the other, 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, there does not occur any preferential orientation after 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 making and using 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 alloys for measurement of temperature, steel and other metallic alloy-based wires for a variety of musical instruments such as piano, violin, etc. The last quarter of the twentieth century has seen 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 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 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. In time, 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 ultra-high molecular weight polyethylene 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 over). 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 compounds 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, namely 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

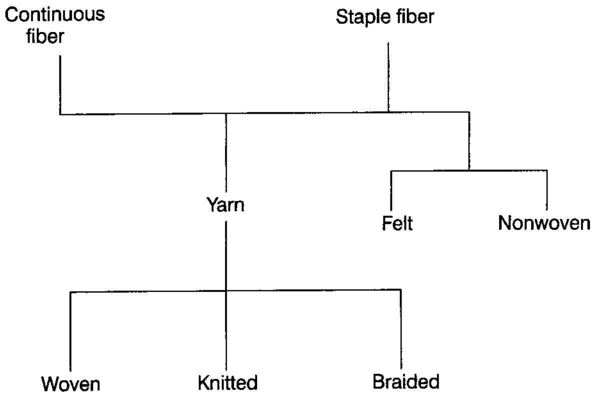

Figure 1.1 Classification of fibers based on fiber length. Also shown are the different product forms.

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 a 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). 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, polester) are blended to obtain the desirable characteristics of both. Figure 1.1 shows this classification based on fiber size, and the different product forms that are commonly available, e.g. woven or nonwoven. Yet another convenient classification of fibers is based on natural and synthetic fibers, as shown in Fig. 1.2. 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, *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 micrometers and a length of a few millimeters. 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

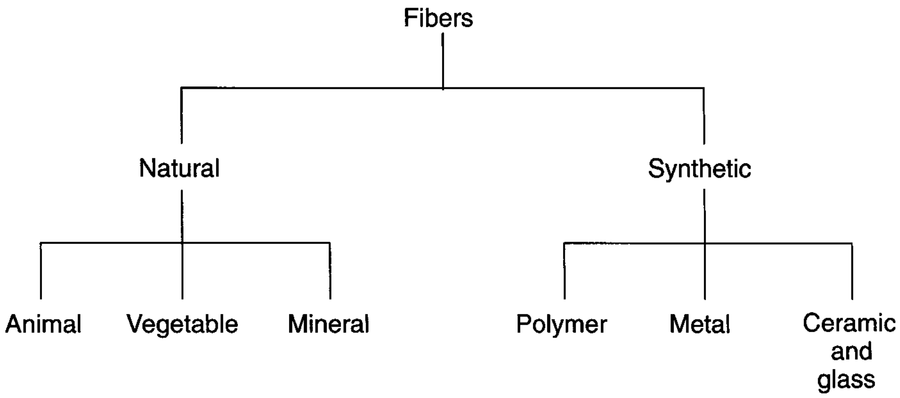

Figure 1.2 Classification of fibers based on natural and synthetic fibers.

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 earlier, fibrous material is 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 nontextile applications. Such fibers are generally very stiff and strong. This is where some of the important developments have occurred in the second half 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 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, namely the smaller the size, the lower the probability of having an imperfection of a critical size that would lead to 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 high 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.

(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 (Chawla, 1987)

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 that is commonly used to make women's stockings. Quite frequently, as we mentioned earlier, 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, 1987, 1993; Chou and Ko, 1989; Hull and Clyne, 1996; Piggott, 1980; Taya and Arsenault, 1989; Suresh *et al.*, 1993; Clyne and Withers, 1993). In the chapters to follow we describe the processing–microstructure–properties of some of these fibrous materials.

Chapter 2

Fibers and fiber products

In this chapter, we define some important terms and parameters that are commonly used with fibers and fiber products such as yarns, fabrics, etc., and then describe some general features of fibers and their products. These definitions, parameters, and features serve to characterize a variety of fibers and products made from them, *excluding* items such as fiber reinforced composites. These definitions and features are generally independent of fiber type, i.e. polymeric, metallic, glass or ceramic fibers. They depend on the geometry rather than any material characteristics.

Fiber is the fundamental unit in making textile yarns and fabrics. Fibers can be naturally occurring or synthetic, i.e. man-made. There are many *natural fibers*, organic and inorganic. Examples include organic fibers such as silk, wool, cotton, jute, sisal and inorganic fibers such as asbestos and basalt. There is a large variety of *synthetic fibers* available commercially. Polymer fibers such as polypropylene, polyethylene, polyamides, polyethyleneterephthalate (PET), polyacrylonitrile (PAN), polytetrafluoroethylene (PTFE), aramid, etc. are well-established fibers. Metallic wires or filaments have been available for a long time. Examples include steel, aluminum, copper, tungsten, molybdenum, gold, silver, etc. Among ceramic and glass fibers, glass fiber for polymer reinforcement has been available since the 1940s; optical glass fiber for telecommunication purposes made its debut in the 1950s, while ceramic fibers such as carbon, silicon carbide, alumina, etc. became available from the 1960s onward.

One can transform practically any material, polymer, metal, or ceramic, into a fibrous form. As we pointed out in Chapter 1, historically and traditionally, fibers formed part of the textile industry domain for uses such as clothing, upholstery and draperies, sacks, ropes, cords, sails, and containers, etc. Gradually, their use entered the realm of more engineered items such as conveyor belts, drive belts, geotextiles, etc. With the advent of high modulus fibers, the use of fibers has extended to highly engineered materials such as composites. Understandably, therefore, some of the terms commonly used with fibers have their origin in textile technology terminology. We examine some of this terminology next. This will prepare some common ground among people interested in fibers, in one way or another, but who come from different disciplines.

2.1 Definitions

We first define some terms commonly used in the field of fibrous materials. We should add that some of these definitions are expanded upon later in this chapter. However, before one can define the term fiber, one needs to define the most important attribute of the fiber that serves to define a fiber, namely the fiber aspect ratio. The aspect ratio of a fiber is the ratio of its length to diameter (or thickness). A *fiber* can be defined as an elongated material having a more or less uniform diameter or thickness less than 250 μm and an aspect ratio greater than 100. This is an operational definition of fiber. It is also a purely geometrical one in that it applies to any material. Having defined the basic unit, the fiber, we are now in a position to define some other commonly used terms related to fibers. These are given below in alphabetical order:

- *Aspect ratio:* The ratio of length to diameter of a fiber.
- *Bicomponent fibers:* A fiber made by spinning two compositions concurrently in each capillary of the spinneret.
- *Blend:* A mix of natural staple fibers such as cotton or wool and synthetic staple fibers such as nylon, polyester. Blends are made to take advantages of the natural and synthetic fibers.
- *Braiding:* Two or more yarns are intertwined to form an elongated structure. The long direction is called the bias direction or machine direction.
- *Carding:* Process of making fibers parallel by using rollers covered with needles.
- *Chopped strand:* Fibers are chopped to various lengths, 3 to 50 mm, for mixing with resins.
- *Continuous fibers:* Continuous strands of fibers, generally, available as wound fiber spools.
- *Cord:* A relatively thick fibrous product made by twisting together two or more plies of yarn.

- *Covering power:* The ability of fibers to occupy space. Noncircular fibers have a greater covering power than circular fibers.
- *Crimp:* Waviness along the fiber length. Some natural fibers, e.g. wool, have a natural crimp. In synthetic polymeric fibers crimp can be introduced by passing the filament between rollers having teeth. Crimp can also be introduced by chemical means. This is done by controlling the coagulation of the filament to produce an asymmetrical cross-section.
- *Denier:* A unit of linear density. It is the weight in grams of 9000 m long yarn. This unit is commonly used in the US textile industry.
- *Fabric:* A kind of planar fibrous assembly. It allows the high degree of anisotropy characteristic of yarn to be minimized, although not completely eliminated.
- *Felt:* Homogeneous fibrous structure made by interlocking fibers via application of heat, moisture, and pressure.
- *Filament:* Continuous fiber, i.e. fiber with aspect ratio approaching infinity.
- *Fill:* see *Weft.*
- *Handle:* Also known as softness of handle. It is a function of denier (or tex), compliance, cross-section, crimp, moisture absorption, and surface roughness of the fiber.
- *Knitted fabric:* One set of yarn is looped and interlocked to form a planar structure.
- *Knitting:* This involves drawing loops of yarns over previous loops, also called interlooping.
- *Mat:* Randomly dispersed chopped fibers or continuous fiber strands, held together with a binder. The binder can be resin compatible, if the mat is to be used to make a polymeric composite.
- *Microfibers:* Also known as microdenier fibers. These are fibers having less than 1 denier per filament (or less than 0.11 tex per filament). Fabrics made of such microfibers have superior silk-like handle and dense construction. They find applications in stretch fabrics, lingerie, rain wear, etc.
- *Monofilament:* A large diameter continuous fiber, generally, with a diameter greater than 100 μm.
- *Nonwovens:* Randomly arranged fibers without making fiber yarns. Nonwovens can be formed by spunbonding, resin bonding, or needle punching. A planar sheet-like fabric is produced from fibers without going through the yarn spinning step. Chemical bonding and/or mechanical interlocking is achieved. Fibers (continuous or staple) are dispersed in a fluid (i.e. a liquid or air) and laid in a sheet-like planar form on a