FUNDAMENTALS *of* FIBER SCIENCE

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Preface

Fiber science is the study of the formation, structure, and properties of fibers on various scales, ranging from the atomic to microscopic to macroscopic (large enough to be visible). It provides the fundamental knowledge for the industrial application of fibers in a wide range of areas, including apparel, home furnishing, nonowovens, composites, biomedical materials, energy storage and conversion, etc. Fiber science is, therefore, an essential part of the education of fiber scientists, engineers, and technologists in both academic and industry settings.

This book deals with the fundamental aspects of the formation, structure, and properties of fibers. It starts with the chemical and physical structures of polymer fibers, non-polymer fibers, and nanofibers, followed by their formation mechanisms. Properties of fibers are then discussed and correlated with their structure and formation mechanisms to establish the formation-structure-property relationships, enabling readers to advance to more complex engineering and design for numerous applications and to grasp the underlying concepts of fiber manufacturing techniques. Although the book is arranged to give a sense of direction to the readers to start from the beginning and proceed to the end, each chapter is self-contained and can be read independently.

This book covers both polymer and non-polymer fibers, as well as novel nanofibers. The book is not intended to provide a comprehensive review on all aspects of fibers. Instead, it is to provide the background of knowledge and understanding of fiber science, and to establish the foundation necessary to understand and contribute to the development of the subject in the 21st century. Hence, the book will be useful to all scientists and engineers involved in academic and industrial research related to different aspects of fiber science and to undergraduate and graduate students in the fields of fiber science, textiles, composites, polymer science and engineering, materials science and engineering, and chemical engineering.

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CHAPTER 1

Introduction

Fibers are used for making materials for a wide range of applications, including apparel, home furnishing, nonwovens, composites, biomedical materials, energy storage and conversion, etc. The study of these materials begins with an understanding of the fibers from which they are made. Fiber science is the study of the formation, structure and properties of fibers on various scales, ranging from the atomic to microscopic to macroscopic (large enough to be visible). These three aspects are not independent from each other. Figure 1.1 shows the relationships among the formation, structure, and properties of fibers. Establishing quantitative and predictive relationships among the way fibers are formed, their structures and properties is fundamental to the study of fibers.

There are many different types of fibers. Most fibers have diameters greater than 1 micrometer, and they can be divided into polymer fibers and non-polymer fibers. Polymer fibers include synthetic polymer fibers and natural polymer fibers. Synthetic polymer fibers are made from polymers synthesized from raw

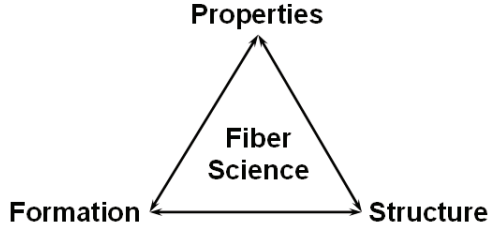

Figure 1.1. The triangle shows the interdependence of formation, structure, and properties of fibers.

materials, such as petroleum-based chemicals or petrochemicals. In general, synthetic polymer fibers are created by forcing, usually through extrusion, polymers through small holes (called spinnerets) into air or other mediums to form filaments. Natural polymer fibers include those produced by plants and animals. They are typically biodegradable and can be classified as natural cellulose fibers and natural protein fibers. Celluloses and proteins also can be modified and extruded into fibers using methods similar to those used in making synthetic polymer fibers. The resultant fibers are typically called manufactured cellulose and protein fibers. Non-polymer fibers are those that are not made from polymers, and include carbon, glass, ceramic, metal, and composite fibers, etc. In addition to traditional classifications, microscale polymer and non-polymer fibers, nanoscale fibers (i.e., nanofibers) have been developed using methods, such as electrospinning, centrifugal spinning, melt blowing, bicomponent fiber separation, phase separation, template synthesis, and self-assembly. Nanofibers also can be made of different materials and are typically intended for special applications. Figure 1.2 shows the fiber classification that is used in this book.

Part 1 of this book focuses on the chemical and physical structures of fibers, and it starts with synthetic polymer fibers. The fundamental knowledge on the chemical structure of synthetic polymer fibers is essential for understanding their physical structure and properties. The chemical structure, such as chain structure and configuration, of synthetic polymer fibers is determined when the polymer is synthesized. In general, the process for making the polymer into fibers does not change the chemical structure. The chemical structure of synthetic polymer fibers

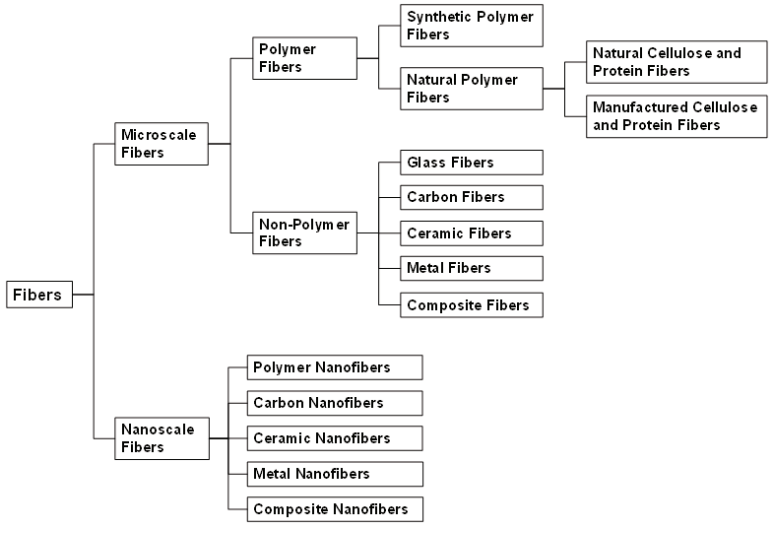

Figure 1.2. Classification of fibers. This is different from the commonly used classification of textile fibers. In the textile fiber classification, fibers are divided into natural fibers and man-made fibers.

does not depend on their shape or morphology, either. In addition to chemical structure, the physical structure of synthetic polymer fibers also is important in determining the fiber properties. Unlike chemical structure, the physical structure does depend on the processing and the final shape of the fibers. Chapters 2 and 3 deal with the chemical and physical structures of synthetic polymer fibers, respectively.

The chemical and physical structures of natural polymer fibers are more complex than those of synthetic polymer fibers. Two most important building units for natural polymer fibers are cellulose and protein. Natural cellulose fibers come from the "stringy" portions of plants ranging from the fine seed fibers of the cotton plant to the coarse pineapple leaf fibers. Natural protein fibers are hairs of animals, like the sheep and the delicate filaments spun by silkworms and insects. In addition to these natural fibers, manufactured cellulose and protein fibers also are based on natural biopolymers. Although these fibers are processed like synthetic polymer fibers, they are discussed in this book together with natural cellulose and protein fibers since they have similar chemical structures. The chemical and physical structures of natural polymer fibers are discussed in Chapters 4 and 5, respectively.

Chapter 6 addresses the structure of non-polymer fibers. A wide range of non-polymer fibers, such as carbon, glass, silicon carbide, boron, asbestos, and metal fibers, now is available commercially. Compared with polymer fibers, non-polymer fibers often are stronger, stiffer, more heat resistant, and nonflammable. However, except for metal fibers, non-polymer fibers also are characterized by their brittleness. These property characteristics are directly related to the atomic arrangement and the defect structure of non-polymer fibers. Chapter 6 discusses the structure of two most used non-polymer fibers: carbon and glass fibers.

Nanofibers are an important class of material that is useful in a variety of applications, including filtration, tissue engineering, protective clothing, composites, battery separators, energy storage, etc. Nanoscience is the study of atoms, molecules, and objects with sizes ranging from 1 to 100 nm. However, the term "nanofibers" has been traditionally used for fibers with diameters less than 1000 nm. Chapter 7 addresses the main structural characteristics of nanofibers.

In Part II, the formation of different fibers is discussed. Synthetic polymer fibers and manufactured natural polymer fibers can be produced by melt spinning, solution spinning, gel spinning, liquid crystal spinning, dispersion spinning, etc. To convert the polymer components into the desired fiber structures, it is important to understand the flow behavior of polymers. Chapter 8 describes the basic knowledge related to the flow behavior of polymers. The use of such knowledge in the formation of synthetic polymer fibers and manufactured cellulose and protein fibers is covered in Chapters 9 and 10, respectively. Chapter 10 also addresses the formation processes of natural cellulose and protein fibers, such as cotton, wool and silk, which are controlled by the genetic codes and are complex.

Non-polymer fibers can be produced by many different methods, depending on the type of materials used. For example, carbon fibers often are made by high temperature treatment of carbon precursors in an inert atmosphere. Glass fibers and some ceramic fibers can be directly spun from their melts. Ceramic fibers also can be obtained by the calcination of ceramic precursor fibers or by the chemical vapor deposition of precursor gas on a carbon fiber substrate. Chapter 11 focuses on the formation of carbon and glass fibers.

Electrospinning is the most reported method for producing nanofibers. Electrospinning uses an electrical charge to draw fine jets from a solution or melt. It has been combined with other methods to produce nanofibers of polymers, carbons, ceramics, metals, and composites. In addition to electrospinning, there are other methods that can be used to produce nanofibers. For example, centrifugal spinning utilizes the centrifugal force generated by a rotating spinneret to produce nanofibers. Melt blowing is typically used to produce fibers with diameters greater than 1 μm by using high-velocity air; however, it can produce nanofibers by using carefully selected materials and processing parameters. Bicomponent fiber separation, phase separation, template synthesis and self-assembly also are useful methods for fabricating nanofibers from different materials. Chapter 12 discusses the fiber formation process and processing-structure relationships of electrospinning. Other nanofiber formation methods are covered in Chapter 13.

Part III of the book discusses different properties of fibers. Fiber properties can be classified into primary and secondary properties. Primary properties are those that fibers must possess so they can be converted into useful products. Examples of primary properties are aspect ratio, strength, flexibility, cohesiveness, and uniformity. Secondary properties are those that are desirable and can improve consumer satisfaction with the end-products made from the fibers. Secondary properties include, but are not limited to physical shape, density, modulus, elongation, elastic recovery, resilience, thermal properties, electrical properties, color and optical properties, moisture regain, resistance to chemical and environmental conditions, resistance to biological organisms, and resistance to insects. Chapter 14 provides an introduction to these primary and secondary properties.

Among various properties, mechanical properties probably are the most important properties of fibers. There are many different types of mechanical properties, including tensile, torsional, bending, and compressional properties. Among them, tensile properties are the most intensively studied for fibers, probably because of their unique shape. However, other types of mechanical properties also are important. Chapter 15 first describes the basic definitions of Hooke's law, stress, strain, and tensile, bulk and shear moduli, and then gives more detailed discussion on the tensile, torsional, bending, and compressional properties of fibers.

Fibers often exhibit both viscous and elastic characteristics when undergoing deformation. As a matter of fact, all materials can exhibit elastic and viscous characteristics simultaneously if the time scale of observation is comparable to the relaxation times needed for large-scale atomic rearrangements in these materials.

However, the relaxation times of most non-polymer fibers are significantly greater than the time scale of normal observations, and hence it is hard to observe their viscoelastic behavior at room temperature. On the other hand, polymer fibers have relaxation times that are comparable to the time scale of observation, and they easily display viscoelastic behavior. Chapter 16, therefore, focuses on the viscoelastic properties of polymer fibers.

Thermal properties of fiber-based products are important in many applications. For example, the main function of textile fabrics is to protect the wearer from cold or heat, and to ensure appropriate heat transfer between the human body and the environment in order to maintain the physiological thermal balance of the wearer. Composites also need appropriate thermal properties so they can be useful in aerospace and space industries. The thermal properties of fibers are the starting point for understanding the final properties of these products, although many other factors also play important roles. Chapter 17 deals with the most basic thermal properties of fibers, including heat capacity, specific heat, thermal conductivity, thermal expansion and contraction, glass transition, melting, and degradation and decomposition.

The electrical behavior of non-polymer fibers is varied from excellent electrical conductors (e.g., carbon fibers) to good insulators (e.g., glass fibers). However, with only a few exceptions, pure polymer fibers are insulators with electrical conductivities in the order of 10^{-16} S cm^{-1}. Static charges can be easily generated and accumulated on the surface of polymer fibers. This could lead to serious consequences, such as handling problems during fiber processing, breaking down of sensitive electronic devices, ignition of flammable vapors and dusts in certain environments, and clinging tendency and annoying electrical shocks during consumer use. Chapter 18 focuses on the electrical conductivity and static charging of polymer fibers.

Frictional properties of fibers affect the processing, structure and properties of all fiber-based products. For example, friction is the force that holds the fibers together in yarns and fabrics. Without sufficient friction, the strength and structural integrity of yarns and fabrics will be lost. However, if the friction is too high, it could cause equipment failure, fiber surface damage, and even fiber breakage. Chapter 19 addresses the basic principles associated with the frictional properties of polymer fibers.

The transmission, reflection and absorption of light determine the visual appearance of an individual fiber. The appearance of fiber assemblies is then the result of the combined effects of individual fibers, although it also is affected by the arrangements of fibers. Optical properties of fibers also provide a convenient measure of many structural characteristics, especially the molecular orientation. Chapter 20 discusses the practical aspects of the optical properties of fibers.

CHAPTER 20

Optical Properties of Fibers

When light encounters a fiber, it is either transmitted, reflected or absorbed, depending on the structure of the fiber and the wavelength of the light. The transmission, reflection and absorption of light determine the visual appearance of an individual fiber. The appearance of fiber assembles then is the result of the combined effects of individual fibers, and also is affected by the arrangements of fibers. In addition, optical properties of fibers provide a convenient measure of many structural characteristics, especially the molecular orientation. Theoretical treatment of optical properties of fibers is complex. This chapter discusses the practical aspects of the optical properties of fibers.

20.1 POLARIZATION AND LIGHT

Polarization refers to the separation of charge, either momentarily or permanently. There are four mechanisms of polarization (Figure 20.1).

- Electronic polarization arises from the temporary distortion of electron clouds with respect to the nuclei with which they are associated, upon the application of an external electric field. Electronic polarization can occur to all materials and also is called atom or atomic polarization. Electronic polarization induces dipole moments.
- Ionic polarization occurs in materials that have ionic characteristic. These ionic materials have internal dipoles, but these built-in dipoles cancel each other and are unable to rotate by themselves. During ionic polarization, the external electric field displaces the cations and anions in opposite directions, leading to net dipole moments.

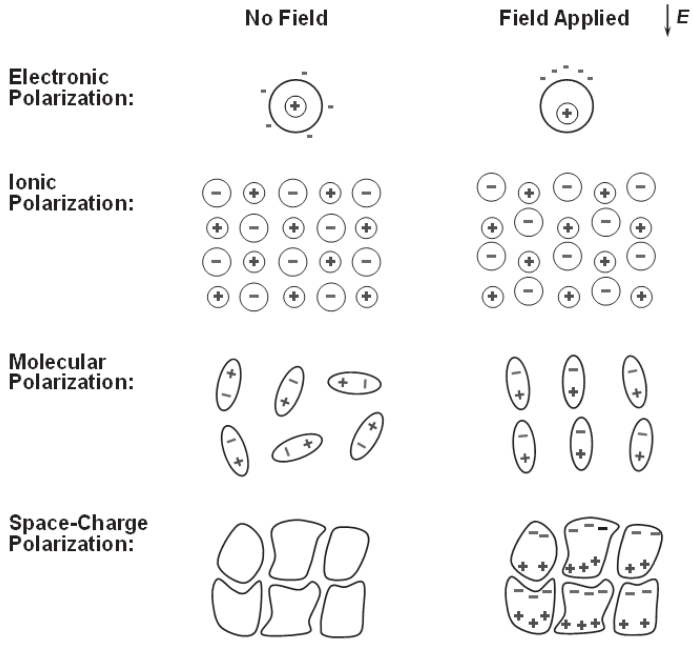

Figure 20.1. Schematic of electric, ionic, molecular and space-charge mechanisms.

- Molecular polarization occurs in polar molecules that can rotate freely. In thermal equilibrium, these natural dipoles are randomly oriented. The external electric field aligns the dipoles to some extent and induces a polarization of the material.
- Space-charge polarization, also known as interface polarization, involves the redistribution of ionically charged layers. In many cases, surfaces, grain boundaries, interphase boundaries of materials may be charged. The charged layers contain dipoles that may become oriented to some degree in an external electric field and leads to the polarization.

Light basically is an electromagnetic wave, which attempts to polarize the material as it passes through. When light travels, it typically propagates as a transverse wave, i.e., the electric field of the wave is perpendicular to the wave's direction of travel. Since the frequency of the waves of visual light is very high (400–790 trillion Hz), only the polarization of the electron clouds around the nuclei of atoms is fast enough to respond to the electric field of the light. As a result, the optical properties of materials are determined by the electronic polarization mechanism. The polarization of larger-scale charges, such as the permanent dipoles, cannot take place fast enough, and hence ionic, molecular and space-charge polarization mechanisms are not activated when light passes the materials.

20.2 REFRACTIVE INDEX AND BIREFRINGENCE

20.2.1 Refractive Index

The velocity of light often changes with the medium through which the light is transmitting. This property can be used to give the most fundamental definition of refractive index (n), which is the ratio of the velocity of light in a vacuum (v_{vacuum}) to the velocity of light in the medium (v_{medium}):

$$n = \frac{v_{vacuum}}{v_{medium}} \tag{20.1}$$

Since light travels slower in a medium than in a vacuum, the refractive index typically is greater than 1. One consequence is the direction of light is refracted or bent while passing from one medium to another (Figure 20.2). As a result, an alternative definition of refractive index is:

$$n = \frac{\sin\theta_i}{\sin\theta_r} \tag{20.2}$$

where θ_i is the angle of incidence, and θ_r the angle of refraction.

Refractive index is a basic optical property of fibers that is directly related to other optical properties. In general, the refractive index of fibers varies with temperature and wavelength. The standard conditions for refractive index measurement involve the use of specific wavelength (589 nm) at a specific temperature (20°C).

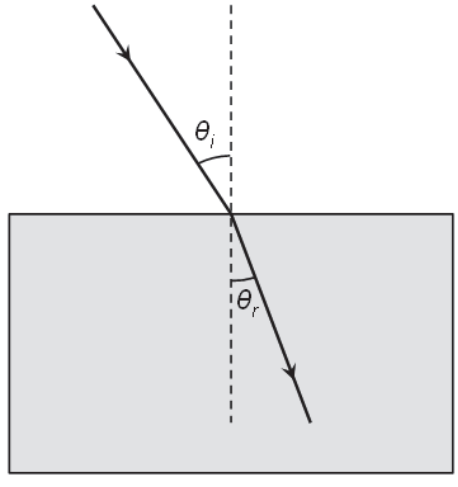

Figure 20.2. Refraction of light in a medium.

The refractive index of fibers also is affected by the fiber density. This is because electronic polarizability increases when the number of electrons per unit volume increases. For many fibers, the relationship between refractive index and fiber density (ρ) can be expressed by Gladstone and Dale's law:

$$\frac{n-1}{\rho} = constant \tag{20.3}$$

Most fibers are anisotropic and the refractive index value is directional. When the average refractive index is used, the constant in Equation 20.3 is around 0.3570.

A similar relationship can be obtained between the refractive index (n_m) and volume (v_m) of a mixture of different components:

$$v_m\left(n_m-1\right) = v_1\left(n_1-1\right) + v_2\left(n_2-1\right) + v_3\left(n_3-1\right) + \ldots \tag{20.4}$$

where v_1, v_2, v_3, … and n_1, n_2, n_3, … are the refractive indices and volumes of the individual components. This relationship can be used to describe the effect of moisture on the refractive index of fibers. The refractive index of water is 1.333, and hence the effect of moisture on the refractive index can be described by:

$$v_{MR}\left(n_{MR}-1\right) = v_0\left(n_0-1\right) + 0.333MR \tag{20.5}$$

where v_0 is the volume of 1 gram of dry fiber, v_{MR} the volume of the sample fiber at a fractional moisture regain of MR, and n_0 and n_{MR} the refractive indices of the same fiber when it is dry and moisturized, respectively. The refractive index values of most fibers are greater than that of water, and hence they decrease with increase in moisture regain. Figure 20.3 shows schematically the effect of moisture on the average refractive index of fibers. For some fibers, an increase in refractive index is observed at low moisture regains and this probably is caused by the filling up of voids or defects in the fibers by water.

20.2.2 Birefringence

When light is transmitted through a fiber, the change of velocity is associated with the electronic polarization. In general, the electrons in the inner shells are not easily displaced, and hence only the outer electrons, which are involved in the covalent bonds, are affected by light waves. Figure 20.4 shows the electronic polarization process while the electric field is applied on a covalent bond through different directions. The electronic polarization is the greatest when the electric field is applied along the direction of the covalent bond. In isotropic polymer materials, the covalent bonds are arranged randomly in all directions, and hence the refractive index is identical in all directions and is the sum of the polarizabilities

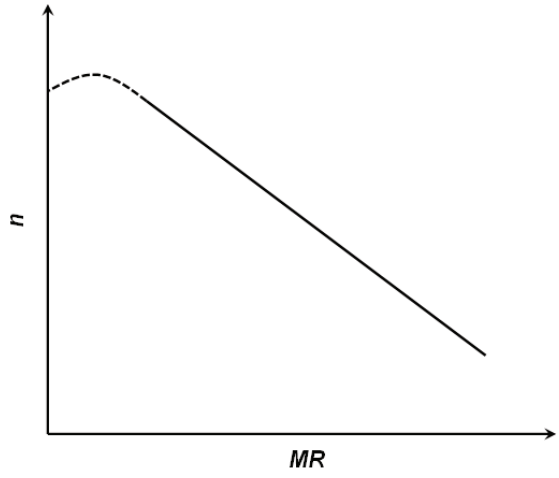

Figure 20.3. Effect of moisture regain on the refractive index of fibers.

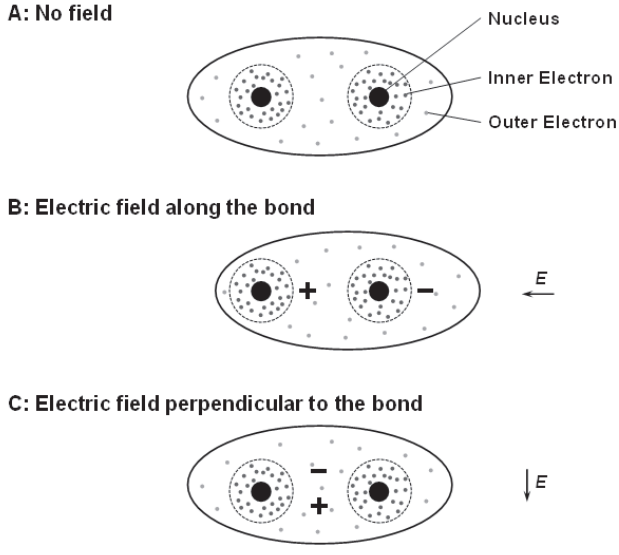

Figure 20.4. Schematic of electronic polarization of two atoms linked by a covalent bond. (A) Electron distribution around the atoms without the presence of electric field, (B) polarization while applying an electric field along the covalent bond, and (C) polarization while applying an electric field perpendicular to the covalent bond.

of all covalent bonds. However, polymer fibers are anisotropic and the polymer chains are largely aligned along the fiber axial direction. As a result, the refractive index of oriented polymer fibers is directional.

Most oriented fibers can be characterized by two principal refractive indices, one parallel to the fiber axis, $n_{\parallel}$, and one perpendicular to the fiber axis, $n_{\perp}$. Here, the subscripts $\parallel$ and $\perp$ indicate the vibration direction of the light waves. The two two principle refractive indices obey the conversation law:

$$n_{iso} = \frac{n_{\parallel} + 2n_{\perp}}{3} \tag{20.6}$$

where n_{iso} is the refractive index of the unoriented, isotropic sample made from the same material.

The birefringence (Δn) of a fiber then can be defined as the difference between the two principal refractive indices:

$$\Delta n = n_{\parallel} - n_{\perp} \tag{20.7}$$

Table 20.1 shows the two principal refractive indices and birefringence values of fibers. The values given in Table 20.1 are only typical examples. For example, both the refractive indices and birefringence of fibers change with increase in molecular orientation. Table 20.2 shows the effect of drawing on the refractive indices and birefringence values of polypropylene fibers. With increase in draw ratio, the birefringence of polypropylene fibers increases due to the increased molecular orientation. In practice, the measurement of birefringence is an important method for studying the molecular orientation in polymer fibers.

The birefringence of polymer fibers is associated to the orientation of the crystal axes in the crystalline phase and the orientation of the individual polymer chains or chain segments in the amorphous phase. As a result, the birefringence of a polymer fiber can be described as:

$$\Delta n = V_c \Delta n_c + \left(1 - V_c\right) \Delta n_a \tag{20.8}$$

where Δn_c is the birefringence of the crystalline phase, Δn_a the birefringence of the amorphous phase, and V_c the volumetric degree of crystallinity. The birefringence of crystalline and amorphous phases can be written as:

$$\Delta n_c = \Delta n_{c,intri} f_c \tag{20.9}$$

and

$$\Delta n_a = \Delta n_{a,intri} f_a \tag{20.10}$$

where $\Delta n_{c,intri}$ is the intrinsic, or maximum possible, birefringence of the crystalline phase when all polymer chains are perfectly oriented along the filament axis, $\Delta n_{a,intri}$ the intrinsic, or maximum possible, birefringence of the amorphous phase,

Table 20.1. Refractive indices and birefringence of fibers.

Fiber	$n_{\parallel}$	$n_{\perp}$	Δn
Synthetic Polymer Fibers			
Polyethylene	1.550	1.510	0.040
Polypropylene	1.526	1.490	0.036
Nylon	1.582	1.519	0.063
Polyester	1.720	1.540	0.180
Acrylic (Orlon®)	1.500	1.500	0.000
Acrylic (Terylene®)	1.520	1.524	–0.004
Kevlar	2.267	1.606	0.662
Natural Polymer Fibers (including regenerated fibers)			
Cotton	1.578	1.532	0.046
Ramie	1.596	1.528	0.068
Flax	1.596	1.528	0.068
Wool	1.553	1.542	0.010
Silk	1.591	1.538	0.053
Rayon	1.539	1.519	0.020
Acetate	1.476	1.470	0.006
Triacetate	1.474	1.479	–0.005
Non-Polymer Fibers			
Glass	1.547	1.547	0.000

Source: Hamza, A.A., et. al., *Journal of Optics A: Pure and Applied Optics*, 9, 820–827, 2007.; Heyn, A.N.J., *Textile Research Journal*, 22, 513–522, 1952.; Kumar, S., *Indian Journal of Fiber and Textile Research*, 16, 52–64, 1991.; Preston, J.M., *Modern Textile Microscopy*, Emmott, 1933.; Preston, J.M., *Transactions of the Faraday Society*, 29, 65–71, 1933.

Table 20.2. Refractive indices and birefringence of polypropylene fibers prepared with different draw ratios.

Draw Ratio	$n_{\parallel}$	$n_{\perp}$	Δn
6:1	1.518	1.494	0.024
7:1	1.521	1.493	0.028
8:1	1.523	1.492	0.031
9:1	1.524	1.491	0.033
10:1	1.526	1.490	0.036
11:1	1.527	1.489	0.038

Source: Hamza, A.A., et. al., *Journal of Optics A: Pure and Applied Optics*, 9, 820–827, 2007.

f_c the orientation factor of the crystalline phase, and f_a the orientation factor of the amorphous phase. Substituting Equations 20.9 and 20.10 into Equation 20.8 gives:

$$\Delta n = V_c \Delta n_{c,intri} f_c + (1 - V_c) \Delta n_{a,intri} f_a \tag{20.11}$$

In this equation, the Δn, V_c, $\Delta n_{c,intri}$, $\Delta n_{a,intri}$ and f_c values can be either measured experimentally or calculated theoretically. Only the f_a value is difficult to measure directly or calculate by other means. Therefore, Equation 20.11 often is used to calculate the f_a value, which is an important property of fibers. High f_a is beneficial for improving some of the mechanical properties, but it could cause large thermal shrinkage and poor dye penetration.

Both Equations 20.8 and 20.11 work for dry fibers. When fibers absorb a large amount of moisture, the birefringence may be greater than the value given by these two equations. This is because these two equations only consider the orientation of polymer chains in the crystalline and amorphous phases. Research has shown that when non-spherical particles are dispersed with a preferred orientation in a medium of different refractive index, a birefringence of greater than zero can be observed even if both the particles and the medium are isotropic. This is called form birefringence. For dry fibers, the difference between the refractive indices of the crystalline and amorphous phases is relatively small and the contribution of form birefringence is negligible. When fibers absorb moisture, the water molecules mainly enter the amorphous phase and change its refractive index. Therefore, in wet fibers, the refractive index difference between the crystalline and amorphous phases become larger and the form birefringence starts to make contribution to the total fiber birefringence. The effect of form birefringence become significant only when the moisture regain is large, e.g., greater than 15%.

20.3 REFLECTION AND LUSTER

When the light falls on a fiber, part of the light is reflected. The amount of light reflected and how it is reflected are important optical properties of fibers. The amount of light reflected can be estimated by:

$$R = \left(\frac{n-1}{n+1} \right)^2 \tag{20.12}$$

where R is the reflectivity or the fraction of light reflected, and n the refractive index. Figure 20.5 shows three major types of surface reflection. Light may be reflected specularly, leaving the surface with an angle $\theta_r = \theta_i$ (Figure 20.5A), or reflected diffusively, with equal intensity in all directions (Figure 20.5B). Most real surfaces show a combination of specular and diffuse reflections (Figure 20.5C).

The luster of a single fiber is determined by total visual appearance of these reflections from the fiber surface.

The reflection of flight from a fiber surface is affected by how it is incident upon the fiber. Figure 20.6 shows the surface reflection when the light falls on a smooth, cylinder-shape fiber along two different directions. When the light is incident upon the fiber along the longitudinal direction, it can be predominantly reflected at a constant angle as long as the fiber surface is sufficiently smooth. However, when the light falls across the fiber on the transverse direction, it is reflected at various angles. This is an important feature of the surface reflection on fibers. However, many fibers do not have smooth surface or circular cross-section. Rough surface and irregular cross-sectional shapes increase the diffuse reflection. Fibers with rough or irregular cross-sectional shapes, such as wool and cotton, are not lustrous even when the light is incident along the fiber longitudinal direction. Lustrous fibers are those with smooth surface and regular cross-sectional shape, such as silk and some synthetic polymer fibers.

In addition to the primary reflection from the outer surface of the fiber, light can reflected from the internal surfaces. Figure 20.7 shows the primary and secondary reflections from a cylinder-shape fiber. When light falls on the surface of the fiber, some of it is transmitted through the fiber. A portion of the transmitted

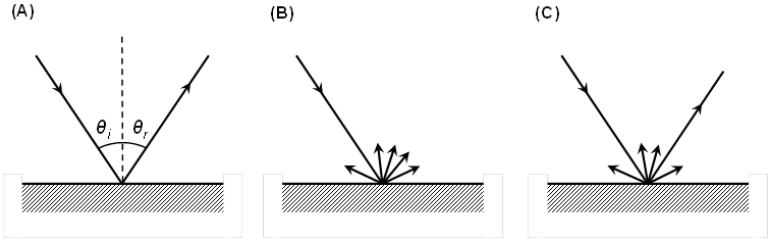

Figure 20.5. Types of surface reflection. (A) Specular reflection, (B) diffuse reflection, and (C) combination of specular and diffuse reflections.

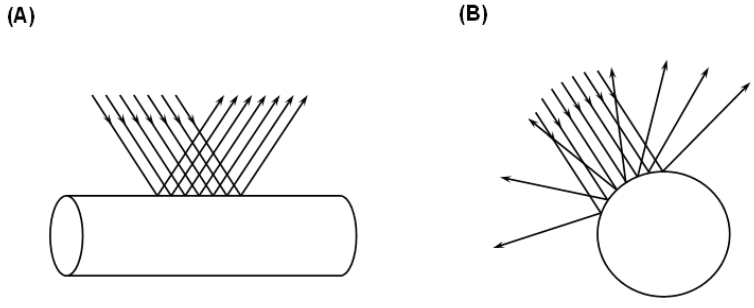

Figure 20.6. Reflection of light from the surface of a smooth, cylinder-shape fiber. Light is incident upon the fiber along: (A) the longitudinal direction, and (B) the transverse direction.

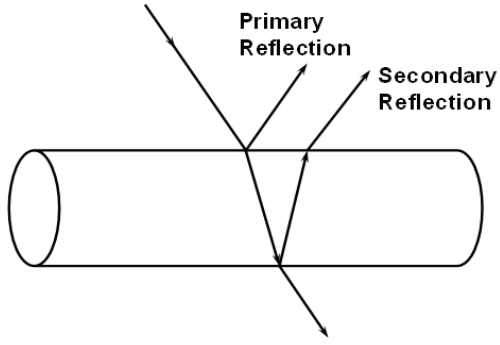

Figure 20.7. Primary and secondary reflections.

light can be reflected from the internal surfaces and join the light reflected from the outer surface. This is called secondary reflection. The secondary reflection is enhanced in fibers that have hollow tunnels (e.g., lumen), cavities or particulate fillers (e.g., TiO_2). Figure 20.8 shows the secondary reflection on these fibers. Hollow tunnels, cavities and particulate fillers scatter the transmitted light and cause apparent diffuse reflection. This effect masks the specular reflection and can be used to produce delustered fibers.

20.4 ABSORPTION AND DICHROISM

When light falls on a fiber, it is transmitted, reflected, or absorbed. Sections 20.2 and 3 discussed the transmission and reflection of light, respectively. This section addresses the absorption of light by fibers.

The absorption of light is the result of the interaction between the electromagnetic waves and the electron clouds in the fiber. The color of a fiber is determined by the selective absorption of light wavelengths (or frequencies). For example, a yellow, opaque fiber has a yellow color because it absorbs all wavelengths in the visual spectrum except yellow, and the yellow light is reflected. A yellow, transparent (or translucent) fiber is yellow when viewed in transmission because it allows yellow light to be transmitted while absorbing other wavelengths in the spectrum.

The absorption of light in a fiber obeys the Lambert's law:

$$I = I_0 \exp(-kx) \tag{20.13}$$

where I is the intensity of light after passing for a distance x through a fiber, I_0 the intensity of the incident light, and k the absorption coefficient.

Polymer fibers are semicrystalline, and they typically are translucent. Most of them are either colorless or slightly colored in neutral shades. In order to produce color, fibers often are dyed. The absorption coefficient k of a dyed fiber is

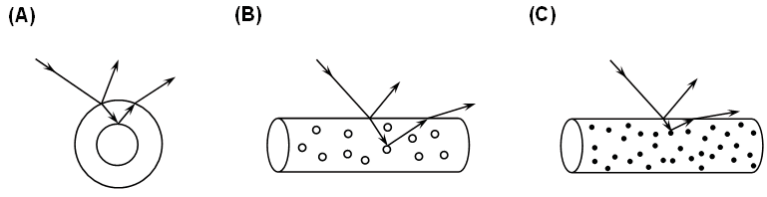

Figure 20.8. Secondary reflection on fibers with (A) hollow tunnel, (B) cavities, or (C) particulate fillers.

proportional to the density or concentration of the dye molecules added to the fiber. The Lambert's law then can be rewritten to give the Beer-Lambert equation:

$$I = I_0 \exp\left(-ck'x\right) \tag{20.14}$$

where c is the concentration of dye molecules, and k' the extinction coefficient or absorption per unit of dye concentration.

For a dyed fiber, the absorption of light by dye molecules may vary with the direction of polarization of the light. This effect is called dichroism and it often leads to differences in the depth of shade or even in actual color. For dichroism to occur in a dyed fiber, the dye molecules must have an asymmetrical structure so that the absorption of light can vary with the direction of polarization. In addition, the dye molecules must be absorbed onto polymer chains with a particular angle and the polymer chains need be oriented. When polarized light is used to examine a dyed fiber that exhibits dichroism, the following intensity ratio often is assessed:

$$\frac{\log\left(I_{\parallel} / I_0\right)}{\log\left(I_{\perp} / I_0\right)} = \frac{k_{\parallel}}{k_{\perp}} = \theta \equiv \text{dichroic ratio} \tag{20.15}$$

where $I_{\parallel}$ and $I_{\perp}$ are the intensities of the light polarized along the longitudinal and transverse directions of the fiber, respectively, and $k_{\parallel}$ and $k_{\perp}$ are the corresponding absorption coefficients. The dichroic ratio, θ, is independent of the concentration of dye molecules and can be used to assess the orientation in fibers. In general, the dichroic ratio increases with increasing orientation in fibers.

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PROBLEMS

(1) What type of polarization mechanism is involved when the light encounters a fiber? Why?

(2) What is refractive index? How does the fiber density affect the refractive index of a fiber?

(3) What is birefringence? Why is birefringence so important in fiber science?

(4) Compare specular reflection with diffuse reflection.

(5) What are the possible approaches to produce delustered fibers?

(6) What is dichroism?

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