TEXTILES

1. Introduction

Textile materials have a wide variety of applications in modern society. They provide shelter and protection in the form of apparel, as well as comfort and decoration in the form of household textiles, eg, sheets upholstery, carpeting, and wall coverings. In addition, technical textiles serve a variety of industrial functions, eg, tyre reinforcement, conveyor belts, seat belts, filter media, heat resistant fabrics, and reinforcement media in various composite materials. Yet another class are the "smart" or "intelligent" textile materials that are capable of sensing and responding to their environment. Textiles that can conduct electricity, sense human physiological condition, gases, moisture, radiation, pressure etc, are finding applications in areas, eg, personal protective equipment, health monitoring, and high performance sportswear.

Textiles are manufactured from staple fibers (qv) that have finite lengths, and filaments, and are continuous, by a variety of processes to form woven, knitted, and nonwoven fabrics. For the manufacture of woven and knitted fabrics, the textile fibers and filaments are first formed into continuous-length yarns, which are then either interlaced by weaving or interloped by knitting into planar, flexible sheet-like structures known as fabrics. For applications in the reinforcement of composites, three-dimensional (3D) structures are woven. Nonwoven fabrics (qv) are formed directly from fibers and filaments by chemically or physically bonding or interlocking fibers that have been arranged in a planar configuration.

2. Characteristics of Fiber-forming Polymers

The primary characteristic feature of textile fibers is that they are very long in relation to their width and this is an essential requirement of textile fibers. Most synthetic fibers typically have aspect ratios of $\sim 100:1$, the most widely used of the natural fibers, cotton and wool, each have aspect ratios of $> 1000:1$. This essential characteristic is also a requirement of their molecules and all fibers are composed of long, mostly linear polymers. The cellulose molecule of cotton is comprised of up to 10,000 glucose residues, corresponding to a molecular weight of > 1.0 million. In the case of synthetic fibers the molecular weights are very much less than that of cotton, but nevertheless are still high, of the order of $\sim 12{,}000-20{,}000$ for regular nylon. Typically, fiber filaments have diameters of $\sim 10-50\,\mu\text{m}$. The diameters of natural fibers, eg, wool and cotton, vary according to source. The diameters of the synthetic fibers can be varied according to the end-use requirements. Thus microfibers have diameters of $< 10\,\mu\text{m}$ and their fineness (~ 1 dtex), which gives them a soft handle and elegant draping properties, has led to their wide adoption in fashionable outerwear. A relatively new class of fibers are the nanofibers, which, as their name suggests, have diameters ranging from $0.1\,\mu\text{m}$ to as low as $0.001\,\mu\text{m}$ (1 nm). Nanofibers are the fibers of the future and have considerable potential applications (see the Section Technical Textiles).

Within the fiber filaments, the polymer molecules are aligned almost parallel to the longitudinal axis. Within the filaments, regions exist where the molecules align parallel and very close to each other, in what are termed "crystalline" regions. Within these regions strong intermolecular forces of attraction exist between the adjacent polymer molecules. In other regions, the molecules are aligned more randomly in what are termed "amorphous" regions. From these structural features, the concepts of orientation (of the crystalline regions to the longitudinal axis) and crystallinity (the proportion of the polymer that lies within highly ordered "crystalline" regions) emerge. Orientation and crystallinity are two important physical parameters that influence both the physical and chemical properties of textile fibers. For example fibers with high crystallinity and orientation possess higher strength, and are generally more brittle and more chemically resistant. It is less easy for attacking molecules to penetrate such fibers, so generally dyeability is poorer. Orientation and crystallinity are two properties of synthetic fibers that can be modified during the manufacturing process, enabling fibers of differing grades, for different end-uses, to be produced.

3. Classification of Textile Fibers

Textile fibers may be classified in the first instance as either natural or manufactured. Within each of these groups there are a number of subgroups:

3.1. Naturally Occurring Fibers

- Vegetable (based on cellulose): cotton (qv), linen, hemp, jute, ramie.
- Animal (based on proteins): wool (qv), silk, mohair, vicuna, other animal hairs.
- Mineral: asbestos (qv).

3.2. Manufactured Fibers. Manufactured fibers comprise the regenerated, synthetic organic, and the inorganic fibers.

Regenerated Fibers. These fibers are manufactured from naturally occurring materials comprising organic polymers, the polymers being subjected to chemical processing to both extract the fiber-forming polymer and to impart novel characteristics to the resulting fibers.

- Rayon: regenerated cellulose (viscose, cuprammonium rayon and lyocell).
- Acetate: partially acetylated cellulose derivative (also called secondary acetate).
- Triacetate: fully acetylated cellulose derivative.
- Azlon: regenerated protein.

Synthetic Organic Fibers

- Polyamide: aliphatic polyamides (nylons) and aromatic polyamides (aramids).
- Polyesters.

- Acrylics.
- Polyolefins (polyethylene and polypropylene).
- Polyurethane (elastomeric fibers).
- Carbon–graphite (derived from polyacrilonitrile, rayon, or pitch).
- Specialty fibers, eg, those based on poly(phenylene sulfide), polyetheretherketone (PEEK), polyimides, etc.

Inorganic Fibers

- Glass (qv).
- Metallic.
- Ceramic.

4. Fiber Production Trends

For centuries, the textile industry was comprised exclusively of the natural fibers, particularly cotton, wool, and silk. With the commercialization of manufactured fibers, beginning with the regenerated fibers based on natural polymers (chiefly cellulosic) toward the end of the nineteenth century, followed by those based on synthetic polymers in the 1930s, the textile industry had undergone a true revolution. In the period since the emergence of the first synthetic polymers, the nylons and polyesters, considerable development of this class of fibers has taken place, with the aim of producing fibers of very high technical specifications.

The 2004 total world production of textile fibers amounted to ~ 67 million tonnes, distributed among the principal types of fibers as shown in Table 1 (1). The total world production has grown steadily by some 20 million tonnes over the last 10 years, as populations have risen and general standards of living have increased. Over this period, consumption of textiles has risen from 7.5 to 9.7 kg/capita. In the early 1990s, roughly equal amounts of natural and synthetic fibers were produced, but now a greater proportion of synthetic fiber is produced, mainly due to a rapid increase in the demand for polyester. It is noteworthy that nearly all of the regions of the world are involved in fiber production, though over the last decade especially a considerable amount of synthetic fiber production has shifted to the Asian countries, especially to China (Table 2). Whereas in 1994, 13.5% of world synthetic fiber production was in China, by 2004 that proportion had increased to 41%. Over the same period, the proportion manufactured in the United States decreased from 17.7 to 8.9%.

5. Natural Fibers

Natural fibers are those derived directly from animal, vegetable, or mineral sources. With the exception of silk (qv), which is extruded by the silkworm as a continuous filament, natural fibers are of finite length and are used directly in textile manufacturing operations after preliminary cleaning. These fibers are known as staple fibers, and an estimate of their average length is referred to as their staple length. Other quality factors that affect the utility of natural fibers for textile purposes are fineness, presence of foreign matter, color, and spinability. The latter term denotes the ability of a fiber to be spun economically into yarns by conventional textile processing procedures. Chemical properties, eg, ability to absorb dyes, thermal- and photostability, and resistance to attack by chemical reagents, are also important.

The influence of orientation and crystallinity is exemplified by a comparison between cotton and flax. Both are composed of cellulose of about the same molecular weight and purity, but in flax the degree of orientation and crystallinity are much higher than in cotton. Consequently, while cotton has a tenacity of ~2.2–2.6 N/dtex, the value for flax is ~4.8–5.3 N/dtex.

6. Manufactured Fibers

6.1. Manufactured Fibers Produced from Natural Organic Polymers. These types of fibers are classed either as regenerated fibers or as derivative fibers. The regenerated fibers are those formed when a natural polymer or its chemical derivative is dissolved and extruded as a continuous filament, and the fundamental nature of the natural polymer is either retained or regenerated after the fiber-formation process. However, the chemical processes to which the polymer is subjected usually results in fibers in which the component polymers have reduced relative molecular mass, which in turn influences their physical and chemical properties.

The newest class of fibers in this group are the Lyocell fibers, produced by an environmentally friendly process from wood pulp. The fibers possess the characteristics of cotton, but in addition they can be fibrillated, whereby the single fibers are split into microfibers of between 1 and 4 μm in diameter. The microfibers generated can be used to create a variety of interesting touch and feel aesthetics, eg, a peach skin effect. Viscose, especially high tenacity viscose, is an important fiber for the manufacture of run-flat tyres.

Derivative fibers are formed when a chemical derivative of the natural polymer is prepared, dissolved, and extruded as a continuous filament. The chemical (and physical) nature of the final fiber is different from that of the original polymer. For example, the secondary and tertiary acetate fibers (acetylated forms of cellulose) are more hydrophobic than natural cellulose fibers. Increasingly, acetate fibers are being replaced by synthetics in apparel applications, eg, jacket linings.

6.2. Manufactured Fibers Based on Synthetic Organic Polymers. These types of fibers are often referred to as “synthetic” fibers. The generic names of synthetic fibers are defined and controlled by the Federal Trade Commission in the United States and are also defined by ISO 2076:1999. The production of synthetic fibers is based on three principal methods of fiber spinning. In the context of synthetic fiber formation, the term *spinning* refers to the overall process of polymer liquefaction (dissolution or melting) and extrusion into fibers. The three principal methods of fiber spinning are melt, dry, and wet spinning, though there are many variations and combinations of these basic processes. (The term *spinning* is otherwise customarily reserved for that textile manufacturing operation wherein staple fibers are formed into continuous textile yarns by several consecutive attenuating and twisting steps. A yarn so formed from natural or manufactured staple fibers is referred to as a staple or spun yarn).

In melt spinning, the polymer in the form of chips or granules is heated above its melting point and the molten polymer is forced through a spinneret. A spinneret is a die with many small orifices that may be varied in their number, diameter, and shape. The jet of molten polymer emerging from each orifice of the spinneret is guided to a cooling zone (usually cold air), where the polymer solidifies as a continuous fiber.

In dry spinning, the polymer is dissolved in a suitable solvent and the resultant solution is extruded through a spinneret. The jet of polymer solution is guided to a heating zone, where the solvent evaporates to leave the fiber filaments.

In wet spinning, the polymer is also dissolved in a suitable solvent and the solution is forced through a spinneret that is submerged in a coagulating bath containing a liquid in which the polymer is insoluble (usually water). As the polymer emerges from the spinneret orifices in the coagulating bath, the fibers are formed by precipitation.

Typical of the variations on these three principal spinning techniques for manufactured fiber formation are dry-jet wet spinning and sol–gel spinning, for the manufacture of high performance fibers.

In most instances, the filaments formed directly by melt, dry, or wet spinning are not suitable for textile fibers because they possess only low strength. Therefore, after extrusion the fibers are subjected to one or more successive drawing operations. Drawing is the hot or cold stretching of the fiber filaments, a process that develops an ordered fine structure and induces molecular orientation with respect to the fiber axis. This fine structure with a high degree of order is generally characterized by a high degree of crystallinity and by an orientation of the crystalline regions. The drawing process is achieved by passing the fiber filaments over two (usually heated) rollers, the second of the rollers rotating at a faster speed than the first, so that typically the fiber stretches by a factor of 6–10. The two-step process of spinning (extrusion) and drawing (structure development) can be combined in a single, high speed spinning process. In high speed spinning, where wind-up speeds of the order of 6000 m/min are possible, orientation and crystallinity are developed immediately. In some cases, however, for specialist fiber requirements, it can be advantageous to store the as-spun fibers on take-up rollers for a few hours, prior to subjecting them to a hot drawing process.

The fine structure and physical properties of manufactured textile fibers are frequently further modified by a variety of thermomechanical annealing treatments, notably heat setting, to provide dimensional stability. A widely used process is that of texturing, which provides crimp to the filaments, and thereby imparts bulk and softness to the textile products manufactured from them.

Bicomponent manufactured fibers, where two different polymers are extruded simultaneously in either side-by-side or skin-core configurations, are also an important category of fibers. Microfibers, generally defined as fibers with linear densities of < 1 dtex/filament, are widely used in apparel, eg, polyester fleeces and sportswear.

In the production of manufactured fibers the filaments are obtained in continuous form. Usually, the spinneret contains many orifices, producing several such filaments that are combined together and slightly twisted to maintain integrity. The resulting yarn is referred to as a multifilament yarn and will typically comprise ~ 100 individual filaments. For some applications, single filament yarns are extruded, though these are considerably larger in diameter than the individual filaments of multifilament yarns. Such yarns are often referred to as monofilament yarns.

In the spinning of synthetic fibers, it is possible to vary the cross-sectional shape by extruding the molten polymer or polymer solution through a spinneret in which the orifice has a special shape. Thus by appropriate design of the orifice shape, fibers with cross-sections that are, eg, circular, triangular, or star-shaped, can be produced. Even hollow fibers can be produced, and such fibers have applications in thermal resistance clothing and potentially in medical applications, eg, slow-release drug delivery.

Frequently, it is desired to obtain manufactured fibers in finite lengths for subsequent processing into spun yarns by conventional textile spinning operations. Thousands of continuous filaments are collected together into a continuous rope of parallelized filaments called a tow. The tow is converted into staple-length fiber by cutting it into specified lengths. The staple length that is produced in this conversion process depends on the system of yarn processing that is to be used. The cotton yarn processing system requires lengths of ~ 35 mm (1.5 in.), whereas the woollen or worsted systems require much longer lengths of between 75 and 125 mm (3 and 5 in.). When manufactured fibers are produced in staple form for blending with natural fibers, dimensional properties, eg, length and fineness, are matched to the natural fiber that is to be used in the blend.

6.3. Inorganic Fibers. Glass fibers are used in applications, eg, insulation, where the entrapped air between the fibers provides the insulating properties, filtration, reinforcement in polymer resins, and for optical fibers (2). Optical fibers made from inorganic glasses have become especially important for the transmission of digital data as an electromagnetic wave. Metallic fibers are not extensively used for textile materials, but they are incorporated into some yarns for an aesthetic function. Increasingly, metallic fibers are being used in the construction of “textrodes”, which are textile-based electrodes for monitoring the human physiological condition. Ceramic fibers have been developed in response to a need for reinforcing fibers capable of withstanding very high temperatures and corrosive environments, in which organic and glass fibers are unstable. These fibers are based on silicon carbide, alumina, or other non-oxide materials, eg, boron nitride (3).

7. Physical Characteristics of Textile Fibers

A measure of the fineness of a yarn (or filament) is given by the denier, the weight in grams of 9000 m of it. Another unit often used is tex, which is the weight in grams of 1000 m. The tensile strength, or tenacity, of a fiber is given in various units, eg, g/denier, or N/tex. For example, if a load of 500 g will just break a yarn of 100 den, the tenacity is 5 g/den (equivalent to 0.44 N/tex). Some other important properties are elongation at break (a measure of the brittleness of a fiber), elasticity (a measure of the extent to which a fiber will recover its original length after being stretched), and Young's modulus (a measure of the stiffness of a fiber). Additionally, moisture regain (the percentage weight of moisture in a fiber measured at 65% R.H. and 21°C, calculated on its oven-dry weight) is an important property of fibers for apparel, since it is related to comfort in wear and electrostatic characteristics of garments.

8. Types of Textile Materials

Textile yarns are produced from staple (finite length) fibers by a sequence of processing steps, referred to collectively as yarn spinning (4). After preliminary fiber alignment by carding, the fibers are locked together by twisting the structure to form the spun yarn, which is continuous in length and remarkably strong and uniform. Depending on the specific processing conditions, the degree of fiber parallelization and surface hairiness can vary over a considerable range, which strongly influences yarn physical properties. Sorption properties in particular are strongly affected by the fiber organization in spun yarn.

Textile yarns are also produced from continuous manufactured filaments. Such multifilament yarns are characterized by nearly complete filament alignment and parallelization with respect to the yarn axis. The degree of twist introduced into a multifilament yarn is usually quite low and just adequate to produce some level of interfilament cohesion. Such yarns are quite compact and smooth in appearance. A variety of processes have been developed to introduce bulk and texture into multifilament yarns. These processes are designed to disrupt the high degree of filament alignment and parallelization and to produce yarns with properties generally associated with spun yarns.

Yarns are used principally in the formation of textile fabrics either by weaving or knitting process (5). In a woven fabric, two systems of yarns, known as the warp and the weft, are interlaced at right angles to each other in various patterns. There are three basic weave structures, plain, twill, and satin weave, and within each type there are different variations. The woven fabric can be viewed as a planar, sheet-like material with pores or holes created by the interlacing pattern. The dimensions of the fabric pores are determined by the yarn structure, by the weave structure and by the density of the woven cloth. The physical properties of woven fabrics are strongly dependent on the test direction. In recent years various devices have been patented for the production of three-dimensional (3D) woven materials. These structures serve as preforms in the manufacture of high strength composite materials for uses in construction.

Knitted fabrics are produced from one set of yarns by looping and interlocking processes to form a planar structure. The pores in knitted fabrics are usually not uniform in size and shape, and again depend on yarn dimensions and on the numerous variables of the knitting process. Knitted fabrics are normally quite deformable, but they will recover from a stretch. There are two basic knitted structures. In weft knitting, the fabric is made from a single yarn and the loops are made horizontally across the fabric. In warp knitting, at least one yarn is supplied to each needle and the yarns formed into loops that run lengthwise in the fabric. Warp knitting can produce open fabrics for lace and nets and the technique is especially useful for the manufacture of technical textile materials that have complex shapes.

Nonwovens are a very important class of materials and in 2004 $>$ 5.5 million tonnes were produced, most of which were of synthetic fibers. They are widely used for hygiene products, eg, wipes, sanitary towels, and baby diapers, for home textiles, eg, furniture, bedding, and carpets, and for industrial purposes, eg, geotextiles and automobiles. They are manufactured by processing the fibers directly into a planar, sheet-like structure, without first spinning the fibers into yarns. Dimensional stability is imparted to structure by various means, eg, chemical bonding, thermal bonding, or mechanical interlocking (6,7). Typically, staple-length fibers are dispersed in a fluid (liquid in the wet-laid process, or air in the dry-laid process of manufacture) and deposited in sheet-like planar form on a support base prior to bonding or interlocking. Carding of staple fibers is frequently the basis of dry-laid nonwoven manufacture. The spunbond process differs from the dry- and wet-laid processes in that continuous length filaments are extruded, collected in a randomized planer network, and bonded together to form the final product. Spunbonded nonwovens are generally thin, strong, and almost film-like in appearance.

Within the plane of a nonwoven material the fibers may be either completely isotropic or in a preferred orientation or alignment, usually with respect to the processing direction. In the case of thicker, dry-laid nonwovens, fiber orientation may be developed in the third dimension, which is that dimension perpendicular to the plane of the fabric, by a process known as needle punching (8). This process serves to bind the fibers in the nonwoven structure by mechanical interlocking. Hydroentangling is an alternative to needle punching (9).

9. Dyeing and Printing

Colored effects in textiles are produced by dyeing, whereby dyes diffuse monomolecularly into the interior of the fibers. Dyes are applied to fibers from aqueous solution though some dye application classes, eg, vat dyes and azoic dyes are actually insoluble in water. During dyeing of vat dyes, the parent dye is chemically reduced to a water-soluble form and on completion of the exhaustion stage, an oxidizing agent is carried out to regenerate the insoluble parent form, trapped within the fiber polymer matrix. The application of azoic dyes actually involves the formation of the azoic dye molecules within the fiber from soluble starting materials. Disperse dyes are so-called because they are only partially soluble in water and form very fine dispersions. However, their solubility increases substantially at the high temperatures used for dyeing (10).

Dyeing can be carried out at any of the stages of the textile manufacturing process (eg, loose fiber, yarn, fabric, garment), the particular stage selected depending on various factors, probably the most important of which are cost and fashion considerations. In recent years, there has been a noticeable shift toward late-stage dyeing, to enable manufacturers to respond quickly to repeat orders for the most popular colors. For this reason, garment dyeing has become especially important. Levelness requirements also have to be considered and for those dyes that are difficult to apply in terms of levelness (usually acid dyes of high wash-fastness for wool) it is better to apply them early in the manufacturing sequence, so that any unlevelness can be randomized during subsequent carding and spinning of the fibers.

During the dyeing process, dye molecules transfer from the aqueous phase to the surface of solid fiber phase and then diffuse into the interior of the fibers. The dye molecules are held in the fiber by primary (ionic and covalent) and secondary forces (eg, van der Waals, hydrogen bonding, etc). The nature of the forces that operate between the dye and fiber molecules depends on the particular dye/fiber combination. For example, while ionic dye–fiber bonds bind acid dyes to protein fibers, disperse dyes are bound to polyester fibers by hydrogen bonding and dipolar forces.

In order to achieve reasonable rates of dyeing, commercial dyeing is normally conducted at 100°C. However, there are variations. In the case of polyester the glass transition temperature is $> 100^\circ$C, so that the boil diffusion of dye into the fibers is very slow. Dyeings are therefore conducted under pressure to allow temperatures of $\sim 130^\circ$C to be used. For acrylic fibers, the T_g is well below 100°C, and to dye at the boil causes the dye to adsorb onto the fiber at such a fast rate that unlevelness results. Application of basic dyes to acrylics is usually carried out at $\sim 80^\circ$C, with very careful control of the rate of temperature rise. The application of reactive dyes to cotton is usually carried out at $\sim 80^\circ$C also, the optimum temperature for covalent bond formation, though the precise temperature used depends on the precise nature of the fiber-reactive group.

While dye molecules can be classified according to chemical composition (eg, azo, anthraquinone, carbonyl, nitro, phthalocyanine, etc) they can be classified also according to their characteristics in dyeing the various fiber types. Some commonly used application classes and the fibers types to which they are most usually applied are shown in Table 3.

The selection of which dye application class or particular dye within a given application class to use depends on the fiber type, the fastness properties required, the cost, and the end-use of the fiber or fabric.

Printing is used to achieve multicolored patterned effects (11). The process is much more rapid and less energy intensive than dyeing. The print paste containing the dye is forced through a screen, sometimes referred to as a “silk” screen, that contains the pattern for the color to be printed. A separate screen is therefore required for each color in the print design. The screen can be either flat or cylindrical, the latter (rotary screen printing) giving very high production rates of > 60 m/min. After printing, the fabric is dried, steamed (to enable diffusion of the dye into the fibers) then washed. If pigments are being printed, the print paste will contain a binder that forms a hard, durable film that entraps the pigment particles on the fiber surface. Increasingly ink-jet printing (12) is being used for small print runs of fabric and in 2004 some 30 bn m^2 of fabric were printed worldwide. At present, production rates are low (between 26 and

150 m^2/h, at print definitions of between 50 and 720 dpi, depending on the sophistication of the machine) so the process is used for low volume, specialized applications, eg, T-shirts and flags. Digital printing using ink-jet technologies offers considerable advantages, especially for “just-in-time” production, in that there are no screens to prepare or store, there is no restriction on the range of colors in the design, and it is very suitability for short runs. It is a method that will become increasingly important as developments in the technology permit faster printing speeds consistent with high quality.

10. Finishing

After the fabric formation process, textiles are generally subjected to a variety of mechanical and chemical finishing operations.

Mechanical finishing is designed primarily to produce special fabric surface effects. Typical operations in this category are napping, shearing, embossing, and calendaring. Chemical finishing may involve either the addition of functional chemicals or the chemical modification of some or all of the fibers comprising the fabric. The primary purpose of chemical finishing is to confer special functional properties to the fabric, eg: dimensional stability, crease-resistance, noniron, durable press characteristics, soiling resistance, water repellence, and flame retardance (13).

Chemical finishing procedures are performed principally on those fabrics that are composed either entirely, or in part, of cellulose fibers (ie, cotton and rayon). These fibers have chemically reactive sites (−OH groups) that lend themselves to chemical modification and additive chemical treatments. Of particular importance in this regard are treatments of cotton and rayon containing fabrics with difunctional reagents that are capable of chemically cross-linking cellulose chains, such as dimethyloldihydroxy ethylene urea (DMDHEU) and similar chemicals. Such reactions improve fiber resilience, thereby enhancing fabric smoothness appearance, crease resistance, and crease recovery. The same reactions can be used to impart wash-and-wear and durable press characteristics.

An important chemical finishing process for cotton yarns and fabrics is that of mercerization, which improves strength, luster, and dyeability. Mercerization involves the treatment of the yarn (or fabric) under tension with concentrated (20–25 wt%) NaOH solution (14). The treatment causes the cotton fibers to become more circular in cross-section and smoother in surface appearance, which increases their luster. At the molecular level, mercerization causes a modification of the crystalline structure of the cellulose, but there is an overall decrease in the degree of crystallinity. Biopolishing is a relatively new treatment of cotton fabrics, involving cellulase enzymes, to produce special surface effects (15).

Fabrics containing wool are also subjected to functional chemical finishing. The main purpose of these treatments is to control felting shrinkage, which occurs when wool fabrics are subjected to mechanical agitation at elevated temperatures in the wet state, conditions typical of normal washing procedures. Felting shrinkage arises from the unique scalar surface structure of wool and other animal fibers that causes the frictional coefficient to be significantly higher in the "against-scale" direction than in the "with-scale" direction. The chemical finishing treatments, eg, chlorination, oxidation, polymer deposition, and combinations of them (14), are designed to minimize this differential friction by "smoothing" the scale edges. Wool fabrics can also be chemically after-treated to impart wash-and-wear and durable press properties.

Fabrics composed of synthetic organic polymer fibers are frequently subjected to heat-setting operations. Because of the thermoplastic nature of these fibers, eg, polyester, nylon, polyolefins, and triacetate, it is possible to set such fabrics into desired configurations. These heat treatments bring about recrystallization processes at the molecular level and thus are permanent unless the fabrics are exposed to thermal conditions more severe than those used in the heat-setting process.

A technique that is rapidly developing and can be considered to be a chemical finishing process for textiles is that of microencapsulation treatments. The technique involves the production of microcapsules of a functional chemical (called the active ingredient) by depositing a thin polymer coating on the chemical in the form of small particles, liquid droplets, or a dispersion of the solid in a liquid (16). The active ingredient is released from the microcapsule by erosion of the polymer wall, rupture of the polymer wall by pressure, by diffusion through the polymer wall, by dissolution, or biodegradation of the polymer wall. Typical of the types of active ingredients that can be incorporated in microcapsules are oils for skin care (cosmeto-textiles), fragrances (aromatherapy), antimicrobial, and deodorizing finishes. The gradual, slow release of the active ingredient on to the fiber surface offers opportunities for applications in the medical field. Not all microcapsules are required to breakdown, and there are applications for microcapsules that retain the active ingredients, eg, chemicals for thermoregulation [called phase-change materials (PCMs)] or flame retardancy. Additionally the application of microencapsulated thermochromic or photochromic dyes can be used to produce color change textiles that respond to changes in temperature or light. Textiles treated with microencapsulated compounds possess enhanced functionality and can be included in the class of smart, or intelligent textiles, which are discussed in greater detail below.

11. Technical Textiles

Technical textiles are textiles that are produced primarily for their technical properties and performance, rather than for their appearance or other aesthetic qualities. The applications of these types of textile materials are mainly in the industrial sector (in the United States they are referred to as "industrial textiles"), but the applications spread to nonindustrial applications, eg, those items of apparel or home textiles, where high technical performance is required. The range of applications of technical textiles is extremely wide, covering areas, eg, agriculture, civil engineering, transport, medical products, personal protective equipment, and sports equipment. Even within one area, the range of products is wide. For example, in cars they are used for tyre cord, thermal and sound insulation, safety belts, airbags, seats, and other internal fittings.

The demand for textiles fibers of enhanced technical performance, eg, strength, chemical, and thermal resistance has led to the development of what are called high performance textiles. Yet another class of fibers now being developed are the superfibers, which have properties superior even to those of the high performance fibers. The difference between these fibers classes lies principally in their superior tensile strength and Young's modulus properties (17). The natural fibers, eg, cotton, wool, and silk, have tenacities typically in the range of 1.0–4.0 N/dtex. The synthetic fibers for apparel uses, eg, nylon and polyester, have tensile strengths of $\sim 4.0–5.7$ N/dtex. The grades for industrial uses have tensile strengths of $\sim 5.7–8.8$ N/dtex. The superfibers have tensile strengths of > 18 N/dtex. In terms of tensile strength per unit cross-sectional area, these superfibers are stronger than metal. They are synthetic organic fibers, so they are light, and together with their superior strength, heat and chemical resistance are finding applications in areas not previously considered possible. Second generation superfibers, with tensile strengths of > 35 N/dtex and moduli of > 800 N/dtex, are now being developed. The main superfibers developed so far are based on aramids, polybenzoxazole (PBO), polyethylene, and carbon fibers. Their manufacture is technically complex, requiring the development of new spinning technologies, eg, liquid crystalline spinning and gel spinning.

Carbon fibers are a special class of technical textiles. Most commercial carbon fibers are produced from polyacrylonitrile (PAN) fibers by heating under tension at temperatures up to 2000°C or more. The fibers are characterized by very high strength and low weight, making them suitable for use in composites for aircraft construction and in the blades of wind turbines. Carbon fibers are also used in sports equipment, eg, golf club shafts, tennis racquets, and skis. Since their discovery in 1991, carbon nanofibers are now being developed that are extremely interesting due to their high electrical conductivity and high strength and stiffness. These fibers are essentially carbon nanotubes with well-defined walls, either single wall (SWCNT) or multiwall (MWCNT), depending on the method of formation used (18).

Conventional fibers generally have diameters of $\sim 10–50\,\mu m$. Nanofibers can be classed as those fibers with diameters in the range 1–1000 nm. These fibers are very fine indeed and because of their high surface area per unit weight, show properties quite different from conventional fibers. For example, their absorbency is considerably higher (by a factor of 2–3 times for nylon) than with conventional fibers. The very fine nature of these fibers makes them suitable as highly effective filters. They cannot be produced by conventional spinning technologies and typically they are produced by an electrospinning technique. Commercial production of nanofibers has still to be achieved and considerable research effort is being made to develop new nanofibers and production methods for them (19).

12. Smart (Intelligent) Textiles

A new breed of textile fibers and materials based on them is being developed that is classed as "smart" or "intelligent". These fibers are engineered to possess a high degree of functionality. They are capable of sensing their environment and responding to it (20). In this sense, conventional textiles can be regarded as passive materials because they do not change their characteristics in use.

Smart textiles represent the next stage of development from the so-called "technical" or "high performance" textiles, which despite how high tech they may be, cannot be considered as intelligent. The *degree of intelligence* can be divided into three subgroups (21): (*1*) *Passive smart textiles* that can only sense the environment: they are sensors. (*2*) *Active smart textiles* that can sense the stimuli from the environment and also react to them: besides the sensor function, they also have an actuator function. (*3*) *Very smart textiles* that go one step further, having the ability to adapt their behavior or characteristics to the circumstances.

Intelligent textile-based systems can be used in health monitoring, acting as sensors, eg, to temperature (body temperature and external temperature), heart rate, breathing rate, perspiration and both transmit the measured data to remote monitoring sites, and provide a response, eg, absorbing–releasing heat or the controlled release of medicines. Fiber-based piezoelectric devices are used to make flexible switches for keypads in garments and flexible display screens are being developed also, using optical fibers. This is possible because textile materials are extremely diverse in nature, with a wide choice of materials, structures, and designs being available.

Such textiles can be used for intelligent clothing, for personal protective equipment for ensuring the safety of personnel in conducting hazardous industrial activities, in the military or police forces. They are used for health monitoring (people at risk, eg, the elderly, first responders in emergency situations), and for monitoring structural components in, eg, bridges and aircraft. The development of such novel textile materials is currently the subject of intensive research effort, directed toward producing electrically conducting fibers, shape-memory fiber polymers, chemically responsive fibers, photosensitive fibers, color change materials, and mechanoresponsive textile materials, to name only a few. The next few years will see many novel textiles and garments in this field being commercialized.

13. Conclusions

This article has attempted to give an understanding of the fundamentals of textile chemistry and the processes by which textile fibers are converted into useful products. It should be obvious that the applications of textile fibers are very widespread, and are not limited solely to apparel. Indeed the modern textile industry is very much focused toward the nonapparel uses, especially uses for which textiles have not been previously considered. The next decade will also see more developments in smart and intelligent textiles and clothing systems with functional characteristics that will be of significant benefit to the well-being of society.

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Table 1. **Worldwide Fiber Demand**[a]

Synthetic fibers		Regenerated fibers		Natural fibers	
polyester	24,401	cellulosics	3096	cotton	21,974
polyamide	4,076			wool	1,219
acrylic	2,727			silk	115
polypropylene	6,302			jute	3,179
spandex	485			linen	751
aramid	40			ramie	269
carbon	20				
totals	*38,051*		*3096*		*27,507*

[a] Thousand metric tonnes, 2004 (1).

Table 2. **Top 10 Producing Countries of Synthetic Fiber in 2004**[a]

Country	Percentage share of global production
China	40.6
Taiwan	9.4
United States	8.9
South Korea	6.9
Western Europe	6.0
India	6.0
Indonesia	3.4
Japan	3.1
Thailand	2.9
Turkey	2.6

[a] See Ref. 1.

Table 3. **Application Classes of Dyes for Various Fiber Types**

Cellulose	Protein	Cellulose acetates	Nylon	Acrylic	Polyester
direct sulfur azoic vat reactive	acid reactive premetallized	disperse	disperse acid premetallized	basic	disperse