FIBERS, OLEFIN

1. Introduction

Olefin fibers, also called polyolefin fibers, are defined as manufactured fibers in which the fiber-forming substance is a synthetic polymer of at least 85 wt% ethylene, propylene, or other olefin units (1). Several olefin polymers are capable of forming fibers, but only polypropylene [9003-07-0] (PP) and, to a much lesser extent, polyethylene [9002-88-4] (PE) are of practical importance. Olefin polymers are hydrophobic and resistant to most solvents. These properties impart resistance to staining, but cause the polymers to be essentially undyeable in an unmodified form.

The first commercial application of olefin fibers was for automobile seat covers in the late 1940s. These fibers, made from low density polyethylene (LDPE) by melt extrusion, were not very successful. They lacked dimensional stability, abrasion resistance, resilience, and light stability. The success of olefin fibers began when high density polyethylene (HDPE) was introduced in the late 1950s. Yarns made from this highly crystalline, linear polyethylene have higher tenacity than yarns made from the less crystalline, branched form (LDPE). Markets were developed for HDPE fiber in marine rope where water resistance and buoyancy are important. However, the fibers also possess a low melting point, lack resilience, and have poor light stability. These traits caused the polyethylene fibers to have limited applications.

Isotactic polypropylene, based on the stereospecific polymerization catalysts discovered by Ziegler and Natta, was introduced commercially in the United States in 1957. Commercial polypropylene fibers followed in 1961. The first market of significance, contract carpet, was based on a three-ply, crimper-textured yarn. It competed favorably against wool and rayon–wool blends because of its lighter weight, longer wear, and lower cost. In the mid-1960s, the discovery of improved light stabilizers led to the development of outdoor carpeting based on polypropylene. In 1967, woven carpet backing based on a film warp and fine-filament fill was produced. In the early 1970s, a bulked-continuous-filament (BCF) yarn was introduced for woven, texturized upholstery. In the mid-1970s, further improvement in light stabilization of polypropylene led to a staple product for automotive interiors and nonwoven velours for floor and wall carpet tiles. In the early 1980s, polypropylene was introduced as a fine-filament staple for thermal bonded nonwovens.

The growth of polyolefin fibers continues. Advances in olefin polymerization provide a wide range of polymer properties to the fiber producer. Inroads into new markets are being made through improvements in stabilization, and new and improved methods of extrusion and production, including multicomponent extrusion and spunbonded and meltblown nonwovens.

2. Properties

2.1. Physical Properties. Table 1 (2) shows that olefin fibers differ from other synthetic fibers in two important respects: (*1*) olefin fibers have very low moisture absorption and thus excellent stain resistance and almost equal wet and dry properties, and (*2*) the low density of olefin fibers allows a much lighter weight product at a specified size or coverage. Thus one kilogram of polypropylene fiber can produce a fabric, carpet, etc, with much more fiber per unit area than a kilogram of most other fibers.

2.2. Tensile Strength. Tensile properties of all polymers are a function of molecular weight, morphology, and testing conditions. The effect of temperature on the tensile properties of a typical polypropylene fiber is shown in Figure 1 (3). Tensile properties are also affected by strain rate, as shown in Figure 2 (3). Lower temperature and higher strain rate result in higher breaking stresses at lower elongations, consistent with the general viscoelastic behavior of polymeric materials. Similar effects are observed on other fiber tensile properties, such as

Table 1. **Physical Properties of Commercial Fibers**[a]

Polymer	Standard tenacity, GPa[b]	Breaking elongation, %	Modulus, GPa[b]	Density, kg/m^3	Moisture regain[c]
olefin	0.16–0.44	20–200	0.24–3.22	910	0.01
polyester	0.37–0.73	13–40	2.1–3.7	1380	0.4
carbon	3.1	1	227	1730	
nylon	0.23–0.60	25–65	0.5–2.4	1130	4–5
rayon	0.25–0.42	8–30	0.8–5.3	1500	11–13
acetate	0.14–0.16	25–45	0.41–0.64	1320	6
acrylic	0.22–0.27	35–55	0.51–1.02	1160	1.5
glass	4.6	5.3–5.7	89	2490	
aramid	2.8	2.5–4.0	113	1440	4.5–7
fluorocarbon	0.18–0.74	5–140	0.18–1.48	2100	
polybenzimidazole	0.33–0.38	25–30	1.14–1.52	1430	15

[a] Ref. 2.

[b] To convert GPa to psi, multiply by 145,000.

[c] At 21°C and 65% rh.

tenacity or stress at break, energy to rupture, and extension at break (4). Under the same spinning, processing, and testing conditions, higher molecular weight results in higher tensile strength. The effect of molecular weight distribution on tensile properties is complex because of the interaction with spinning conditions (4,5). In general, narrower molecular weight distributions result in higher breaking tenacity and lower elongation (4,6). The variation of tenacity and elongation with draw ratio for a given spun yarn correlates well with amorphous orientation (7,8). However, when different spun yarns are compared, neither average nor

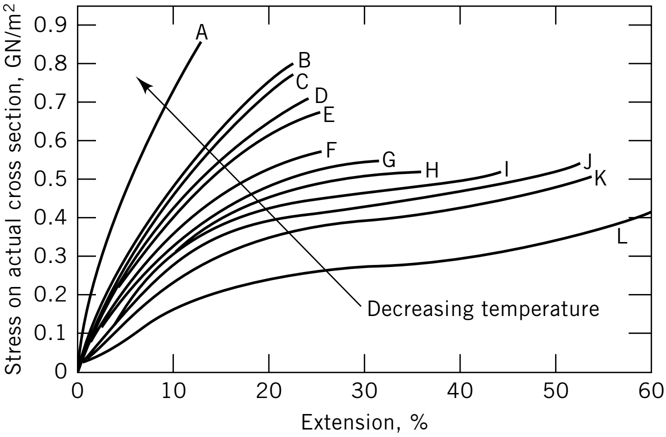

Fig. 1. Effect of temperature on tensile properties of polypropylene (3); strain rate = 6.47×10^{-4} s^{-1}. In degrees Kelvin: A, 90; B, 200; C, 213; D, 227; E, 243; F, 257; G, 266; H, 273; I, 278; J, 283; K, 293; and L, 308 (broken at 74.8% extension, 4.84×10^8 N/m^2 stress). To convert GN/m^2 to dyne/cm^2, multiply by 10^{10}.

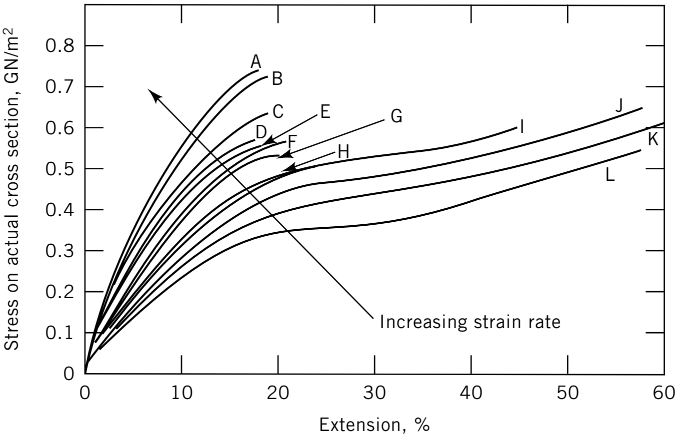

Fig. 2. Effect of strain rate on tensile properties of polypropylene at 20°C (3). In s^{-1}: A, 4.9×10^2; B, 2.48×10^2; C, 1.26×10^2; D, 6.3×10^1; E, 3.2×10^1; F, 2.87×10^1; G, 2.3×10^{-1}; H, 3.3×10^{-2}; I, 1.33×10^{-2}; J, 4.17×10^{-3}; K, 1.67×10^{-3}; and L, 3.3×10^{-4}. To convert GN/m^2 to dyne/cm^2, multiply by 10^{10}.

amorphous orientation completely explains these variations (9–11). Theory suggests that the number of tie molecules, both from molecules traversing the interlamellar region and especially those resulting from entanglements in the interlamellar region, defines the range of tensile properties achievable using draw-induced orientation (12,13). Increased entanglements (more ties) result in higher tenacity and lower elongation.

2.3. Creep, Stress Relaxation, Elastic Recovery. Olefin fibers exhibit creep, or time-dependent deformation under load, and undergo stress relaxation, or the spontaneous relief of internal stress. Because of the variety of molecular sizes and morphological states present in semicrystalline polymers, the creep and stress relaxation properties for materials such as polypropylene cannot be represented in one curve by using time–temperature superposition principles (14). However, given a spun yarn and thus a given structural state, curves for creep fracture (time to break under variable load) can be developed for different draw ratios, as shown in Figure 3 (15), indicating the importance of spun-yarn structure in a crystallizable polyolefin fiber. The same superposition can be carried out up to 110°C, where substantial reordering of polymer crystalline structure occurs (16).

High molecular weight and high orientation reduce creep. At a fixed molecular weight, the stress-relaxation modulus is higher for a highly crystalline sample prepared by slow cooling than for a smectic sample prepared by rapid quench (14). Annealing the smectic sample raises the relaxation modulus slightly, but not to the degree present in the fiber prepared by slow cooling.

Elastic recovery or resilience is the recovery of length upon release of stress after extension or compression. A fiber, fabric, or carpet must possess this property in order to spring back to its original shape after being crushed or wrinkled. Polyolefin fibers have poorer resilience than nylon; this is thought to be partially related to the creep properties of the polyolefins. Recovery from small strain

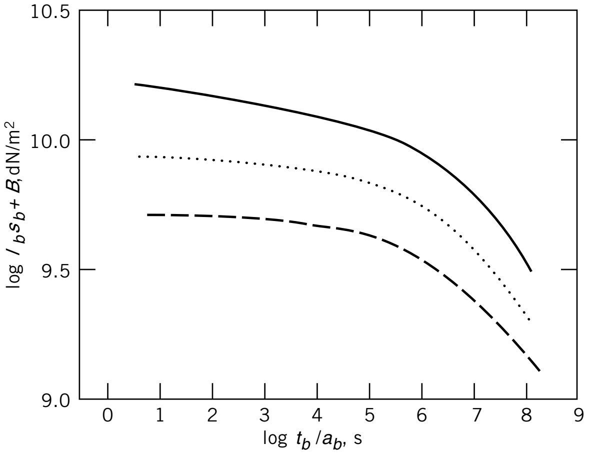

Fig. 3. Composite curve of true stress at break $\lambda_b\sigma_b$ at 40°C vs reduced time to break t_b/a_b for polypropylene fibers of three draw ratios (15): (—), 2.7 × draw, $B = 0$; (. . .), 3.5 ×draw, $B = 0.2$; (–), 4.5 × draw, $B = 0.4$. Values of B are arbitrary.

cyclic loading is a function of temperature, as shown in Figure 4, and found to be a minimum for polypropylene at 10°C, near the glass-transition temperature, T_g (17). The minimum for polyethylene is at 30°C, higher than the amorphous T_g. This minimum is thought to be associated with motions in the crystalline phase of the highly oriented crystalline structure (17).

2.4. Chemical Properties. The hydrocarbon nature of olefin fibers, lacking any polarity, imparts high hydrophobicity and consequently resistance to soiling or staining by polar materials, a property important in carpet and

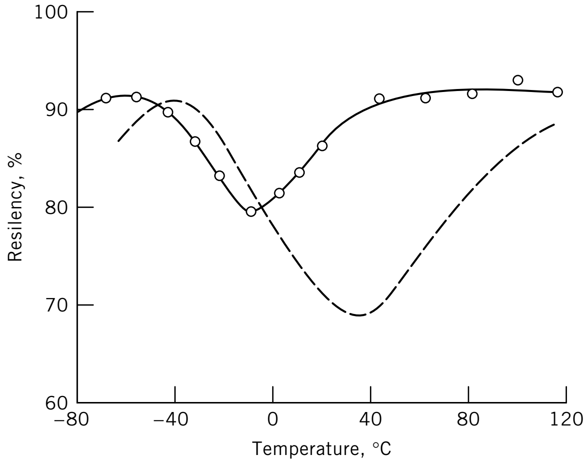

Fig. 4. Resiliency of polypropylene, (—○—), and polyethylene, (———), multifilament yarns as a function of temperature (17).

Table 2. **Thermal Properties of Olefins and Other Fiber-Forming Polymers**

Polymer[a]	T_g,°C	T_m,°C	Softening temperature,°C	Thermal degradation temperature,°C
high density polyethylene (HDPE)	−120	130	125	
i-polypropylene (PP)	−20	170	165	290
i-poly(1-butene)	−25	128		
i-poly(3-methyl-1-butene)		315		
i-poly(4-methyl-1-pentene)	18	250	244	
poly(ethylene terephthalate) (PET)	70	265	235	400
nylon-6,6	50	264	248	360

[a] i = isotactic.

upholstery applications. Unlike the condensation polymer fibers, such as polyester and nylon, olefin fibers are resistant to acids and bases. At room temperature, polyolefins are resistant to most organic solvents, except for some swelling in chlorinated hydrocarbon solvents. At higher temperatures, polyolefins dissolve in aromatic or chlorinated aromatic solvents, and show some solubility in high boiling hydrocarbon solvents. At high temperatures, polyolefins are degraded by strong oxidizing acids.

2.5. Thermal and Oxidative Stability. The thermal transitions of several polyolefins are compared to other polymers in Table 2. In general, polyolefins undergo thermal transitions at much lower temperatures than condensation polymers, thus the thermal and oxidative stability of polyolefin fibers are comparatively poor (18). They are highly sensitive to oxygen, which must be carefully controlled in all processing. The tertiary hydrogen in polypropylene imparts sensitivity to oxidative degradation by chain scission resulting in molecular weight degradation. Polyolefins are stabilized by hindered phenols or phosphites. Hindered phenol stabilizers provide moderate melt stability and good long-term heat aging, but undergo gas yellowing, which is a chemical reaction of phenolic compounds and nitrous oxide gases producing yellow-colored compounds. Typical sources of nitrous oxides are gas-fired heaters, dryers, and tenters, and propane-fueled lift trucks used in warehouses. Phosphites are good melt stabilizers, do not gas yellow, but have poor long-term heat aging. Preferred stabilizers are highly substituted phenols such as Cyanox 1790 and Irganox 1010, or phosphites such as Ultranox 626 and Irgafos 168 (see ANTIOXIDANTS, POLYMERS; HEAT STABILIZERS).

2.6. Ultraviolet Degradation. Polyolefins are subject to light-induced degradation (19); polyethylene is more resistant than polypropylene. Although the mechanism of uv degradation is different from thermal degradation, the resulting chain scission and molecular weight degradation is similar. In fiber applications, stabilization against light is necessary to prevent loss of properties. The stabilizer must be compatible, have low volatility, be resistant to light and thermal degradation itself, and must last over the lifetime of the fiber. Chemical and physical interactions with other additives must be avoided. Minimal odor

Table 3. **Stabilization of Polypropylene Fiber by Polymeric HALS**[a]

HALS	Manufacturer	Carbon arc T50,h[b]	Florida T50, kJ/m^2[c,d]
none		70	<105
Chimassorb 944	CIBA-GEIGY Corp.	300	293–418
Cyasorb 3346	American Cyanamid Co.	320	418
Spinuvex A-36	Montedison Corp.	370–400	293

[a] Test specimens were 0.5 tex (4.5 den) filaments containing 0.25% specified HALS (22).

[b] Hours to 50% retention of initial tensile strength under carbon arc exposure.

[c] kJ/m^2 to 50% retention of tensile strength; Florida under glass exposure.

[d] To convert kJ/m^2 to Langley, multiply by 239.

and toxicity, colorlessness, resistance to gas yellowing, and low cost are additional requirements.

Stabilizers that act as uv screens or energy quenchers are usually ineffective by themselves. Because polyolefins readily form hydroperoxides, the more effective light stabilizers are radical scavengers. Hindered amine light stabilizers (HALS) are favored, especially high molecular weight and polymeric amines that have lower mobility and less tendency to migrate to the surface of the fiber (20,21). This migration is commonly called bloom. Test results for some typical stabilizers are given in Table 3 (22).

2.7. Flammability. Flammability of polymeric materials is measured by many methods, most commonly by the limiting-oxygen-index test (ASTM D2863), which defines the minimum oxygen concentration necessary to support combustion, or the UL 94 vertical-burn test, which measures the burn length of a fabric. Most polyolefins can be made fire retardant using a stabilizer, usually a bromine-containing organic compound, and a synergist such as antimony oxide (23). However, the required loadings are usually too high for fibers to be spun. Fire-retardant polypropylene fibers exhibit reduced light and thermal resistance. Commercial fire-retardant polyolefin fibers have just recently been introduced, but as expected the fibers have limited light stability and poor luster. Where applications require fire retardancy it is usually conferred by fabric finishes or incorporation of fire retardants in a latex, such as in latex-bonded nonwovens and latex-coated wovens.

2.8. Dyeing Properties. Because of their nonionic chemical nature, olefin fibers are difficult to dye. Oil-soluble dispersed dyes diffuse into polypropylene but readily bloom and rub off. In the first commercial dyeing of olefin fibers, nickel dyes such as UV-1084, also a light stabilizer, were used. The dyed fibers were colorfast but dull and hazy. A broad variety of polymeric dyesites have been blended with polypropylene; nitrogen-containing copolymers are the most favored (24–26). A commercial acid-dyeable polypropylene fiber is prepared by blending the polypropylene with a basic amino-polyamide terpolymer (27). In apparel applications where dyeing is important, dyeable blends are expensive and create problems in spinning fine denier fibers. Hence, olefin fibers are usually colored by pigment blending during manufacture, called solution dying in the trade.

3. Manufacture and Processing

Olefin fibers are manufactured commercially by melt spinning, similar to the methods employed for polyester and polyamide fibers. The basic process of melt spinning is illustrated in Figure 5. The polymer resin and ingredients, primarily stabilizers, pigments, and rheological modifiers, are fed into a screw extruder, melted, and extruded through fine diameter holes. The plate containing the holes is commonly called a spinneret. A metering pump and a mixing device are usually installed in front of the spinneret to ensure uniform delivery and mixing to facilitate uniform drawdown at high speeds. In the traditional or long spinning process, the fiber is pulled through a long cooling stack-type quench chamber by a take-up device at speeds in the range of 50–2000 m/min and discontinuously routed to downstream finishing operations. In the short spinning process, filaments are cooled within a few centimeters of the spinneret at speeds of 50–150 m/min. Because of the lower speeds, fiber can be continuously routed to downstream finishing operations in a one-step process (28). Finishing operations include drawing the fiber to as much as six times its original length, heat treatment to relieve internal stresses, and texturizing processes, which are combinations of deformational and heat treatments. These treatments were developed to impart specific characteristics to the olefin fiber dependent on its end use. Commercial olefin fibers are produced in a broad range of linear densities, from 0.1 to 12 tex (1.1–110 den), to fit a variety of applications, as shown in Figure 6 (29).

3.1. Extrusion. Polymer resin and additives are melted and pumped through an extruder into a spinning pump. The pump meters the molten polymer through a filter system which removes particles from the molten polymer stream that might clog the capillaries of the spinneret or cause discontinuities

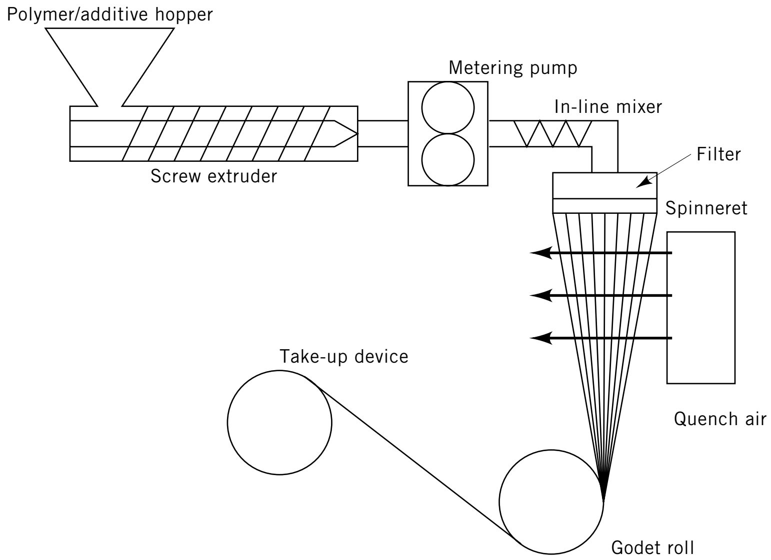

Fig. 5. Melt spinning process.

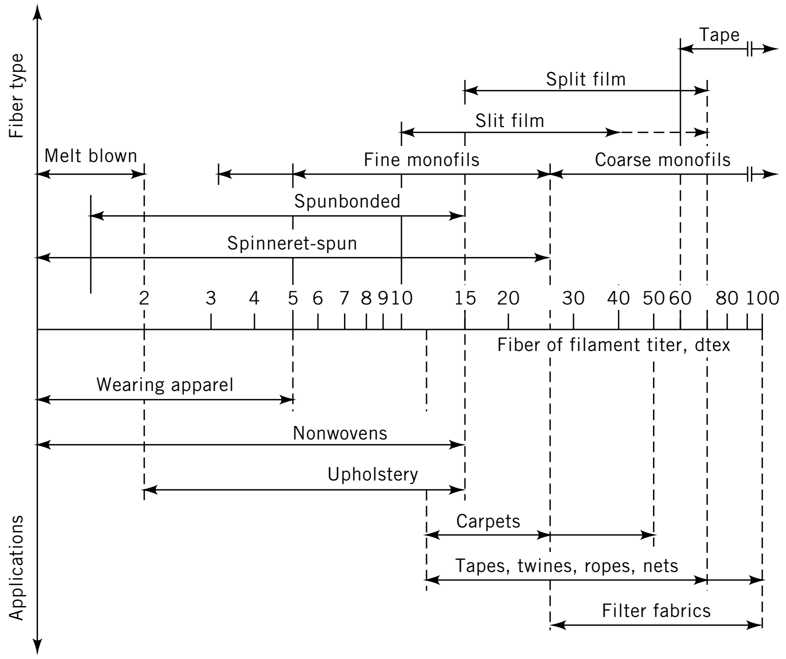

Fig. 6. Linear density of olefin fibers in various applications (29); dtex = 1.1 den.

in fine diameter fiber. These filters are typically either sand packs or metal screens. The polymer continues to a spinneret where it is extruded through holes under pressure. These holes or capillaries define the size and shape of the extruded fiber. A spinneret may contain up to several thousand capillaries, typically 0.3 to 0.5 mm in diameter. The length of the capillary is sized to the melt viscosity of the polymer. Typical length-to-diameter ratios of spinneret capillaries are 2:1 to 8:1. The spinneret holes can be arranged in a variety of hole spacings and patterns including rectangular, round, and annular. Considerations include throughput rate, heat transfer required to quench the fiber, and fiber diameter.

The extrusion of olefin fibers is largely controlled by the polymer. Polyolefin melts are strongly viscoelastic, and melt extrusion of polyolefin fibers differs from that of polyesters and polyamides. Polyolefins are manufactured in a broad range of molecular weights and ratios of weight-average to number-average molecular weight (M_w/M_n). Unlike the condensation polymers, which typically have molecular weights of 10,000–15,000 and M_w/M_n of approximately 2, polyolefins have weight-average molecular weights ranging from 50,000 to 1,000,000 and, as polymerized, M_w/M_n ranges from 4 to 15. Further control of molecular weight and distribution is obtained by chemical or thermal degradation. The full range of molecular weights used in olefin fiber manufacture is above 20,000, and M_w/M_n varies from 2 to 15. As molecular weight increases and molecular weight distribution broadens, the polymer melt becomes more pseudoplastic as indicated in Table 4 and shown in Figure 7 (30). In the sizing of extrusion equipment for olefin fiber production, the wide range of shear viscosities and thinning effects

Table 4. **Molecular Weight Characterization Data for Polypropylene Samples**[a,b]

Code[c]	Melt flow rate[d]	$M_w \times 10^{-5}$	M_w/M_n	M_z/M_w	$M_v \times 10^{-5}$
High molecular weight polypropylene					
○ narrow	4.2	2.84	6.4	2.59	2.40
△ regular-broad	5.0	3.03	9.0	3.57	2.42
□ broad-regular	3.7	3.39	7.7	3.54	2.71
Middle molecular weight polypropylene					
∘ narrow	11.6	2.32	4.7	2.81	1.92
regular	12.4	2.79	7.8	4.82	2.13
◫ broad	11.0	2.68	9.0	4.46	2.07
Low molecular weight polypropylene					
• narrow	25.0	1.79	4.6	2.47	1.52
◑ regular-narrow	23.0	2.02	6.7	3.18	1.66

[a] Ref. 30.
[b] Figures 7–9.
[c] Narrow, regular, and broad refer to molecular weight distribution.
[d] ASTM D1238 (Condition L; 230/2.16).

must be considered because these affect both power requirements and mixing efficiencies.

Fiber spinning is a uniaxial extension process, and the elongational viscosity behavior, which is the stress-strain relationship in uniaxial extension, is more important than the shear viscosity behavior. The narrower molecular weight distributions tend to be less thinning, and as shown in Figure 8 (30), elongational viscosity increases at higher extension rates. This leads to higher melt orientation, which in turn is reflected in higher spun fiber orientation, higher tenacity, and lower extensibility. In contrast, the broad molecular weight distributions tend to be more thinning and hence more prone to necking and fracture at

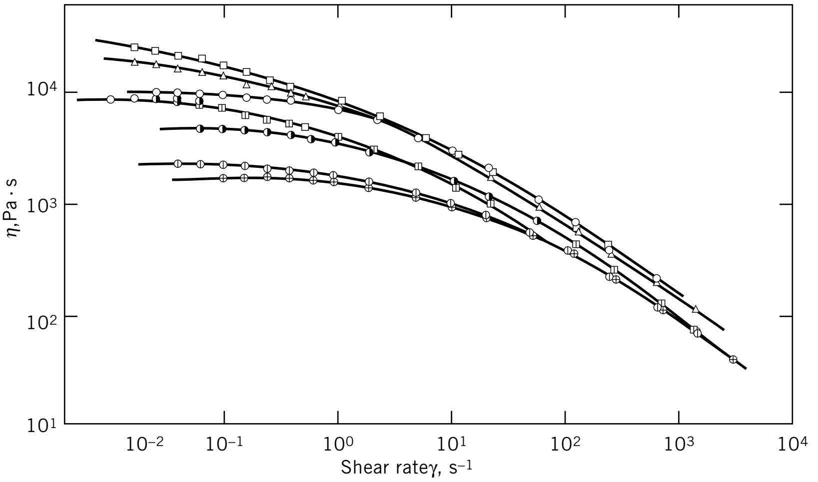

Fig. 7. Shear viscosity at 180°C of polypropylene of different molecular weight and distribution vs shear rate (30); see Table 4 for key. Pa · s = 0.1 P.

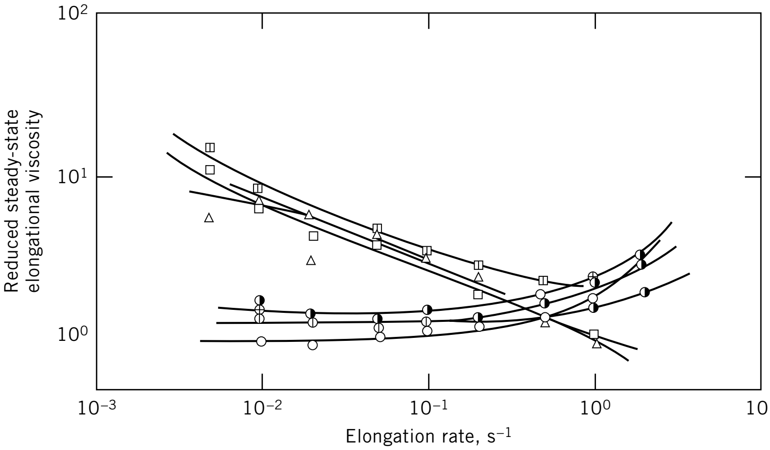

Fig. 8. Elongational viscosity at 180°C of polypropylene of different molecular weight and distribution (30); see Table 4 for key.

high spinning speeds (30,31), but yield a less oriented, higher elongation spun fiber. The choice of an optimum molecular weight and molecular weight distribution is determined by the desired properties of the fiber and the process continuity on available equipment.

Because of the high melt viscosity of polyolefins, normal spinning melt temperatures are 240–310°C, which is 80–150°C above the crystalline melting point. Because of the high melt temperatures used for polyolefin fiber spinning, thermal stabilizers such as substituted hindered phenols are added. In the presence of pigments, the melt temperature must be carefully controlled to prevent color degradation and to obtain uniform color dispersion.

Polyolefin melts have a high degree of viscoelastic memory or elasticity. First normal stress differences of polyolefins, a rheological measure of melt elasticity, are shown in Figure 9 (30). At a fixed molecular weight and shear rate, the first normal stress difference increases as M_w/M_n increases. The high shear rate obtained in fine capillaries, typically on the order of 10^3–10^4 s^{-1}, coupled with the viscoelastic memory, causes the filament to swell (die swell or extrudate swell) upon leaving the capillary. On a molecular scale, the residence time in the region of die swell is sufficient to allow relaxation of any shear induced orientation. However, high die swell significantly affects the drawdown or extension rate, leading to threadline breaks. Die swell can be reduced by lower molecular weight, narrower molecular weight distribution, or higher melt temperature.

3.2. Quench. Attempts have been made to model this nonisothermal process (32–35), but the complexity of the actual system makes quench design an art. Arrangements include straight-through, and outside-in and inside-out radial patterns (36). The optimum configuration depends on spinneret size, hole pattern, filament size, quench-chamber dimensions, take-up rate, and desired physical properties. Process continuity and final fiber properties are governed by the temperature profile and extension rate.

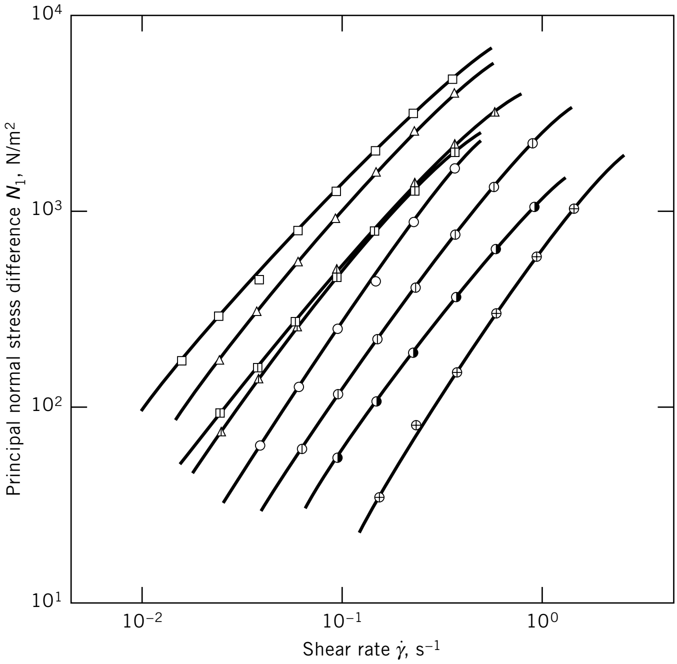

Fig. 9. First normal stress differences of polypropylene of different molecular weight and distribution (30); see Table 4 for key. To convert N/m^2 to dyne/cm^2, multiply by 10.

Polypropylene and other linear polyolefins crystallize more rapidly than most other crystallizable polymers. Unlike polyester, which is normally amorphous as spun, the fiber morphology of polyolefins is fixed in the spinning process; this limits the range of properties in subsequent drawing and annealing operations. In a low crystallinity state, sometimes called the paracrystalline or smectic form, a large degree of local order still exists. It can be reached by extruding low molecular weight polyolefins, processing at low draw ratio, or by a rapid quench such as by using a cold water bath (37).

Quench is more commonly practiced commercially by a controlled air quench in which the rate of cooling is controlled by the velocity and temperature of the air. During normal cooling, crystallization occurs in the threadline. In-line x-ray scattering studies demonstrate that crystallization is extremely rapid; the full crystalline structure is almost completely developed in fractions of a second (38).Fiber spinning is an extensional process during which significant molecular orientation occurs. Under rapid crystallization, this orientation is fixed during the spinning process. Small-angle neutron-scattering studies of quiescent polypropylene crystallization show that the chain dimensions in both melt and crystallized forms are comparable (39). Although there may be significant relaxation of the amorphous region after spinning, the primary structure of the fiber is fixed during spinning and controls subsequent drawing and texturizing of the fiber. For fixed extrusion and take-up rates, a more rapid quench reduces the average melt-deformation temperature, increases relaxation times, and gives a more entangled melt when crystallization begins. The rapidly quenched fiber usually gives lower elongation and higher tenacity during subsequent draw (40). Using a very rapid quench, the melt may not be able to relax fast enough to sustain drawdown, resulting in melt fracture. Under conditions of a slow quench, the melt may totally relax, leading to ductile failure of the threadline.

A common measurement useful in predicting threadline behavior is fiber tension, frequently misnamed spinline stress. It is normally measured after the crystallization point in the threadline when the steady state is reached and the threadline is no longer deformed. Fiber tension increases as take-up velocity increases (38) and molecular weight increases. Tension decreases as temperature increases (41). Crystallinity increases slightly as fiber tension is increased (38). At low tension, the birefringence increases as tension is increased, leveling off at a spinline tension of 10 MPa (1450 psi) (38).

3.3. Take-Up. Take-up devices attenuate the spinline to the desired linear density and collect the spun yarn in a form suitable for further processing. A godet wheel is typically used to control the take-up velocity which varies from 1–2 m/s for heavy monofilaments to 10–33 m/s for fine yarns. The yarn can be stacked in cans, taken up on bobbins, or directly transferred to drawing and texturizing equipment.

In the spunbond process (Fig. 10), an aspiratory is used to draw the fibers in spinning and directly deposit them as a web of continuous, randomly oriented

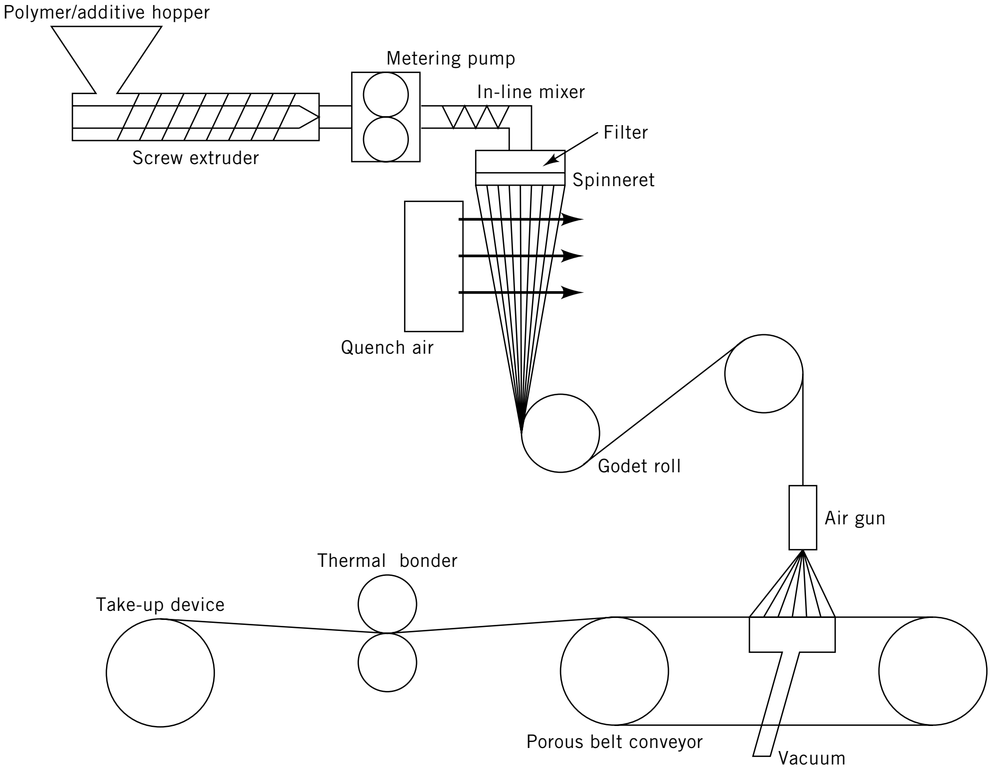

Fig. 10. Flow sheet for typical spunbond fabric manufacture.

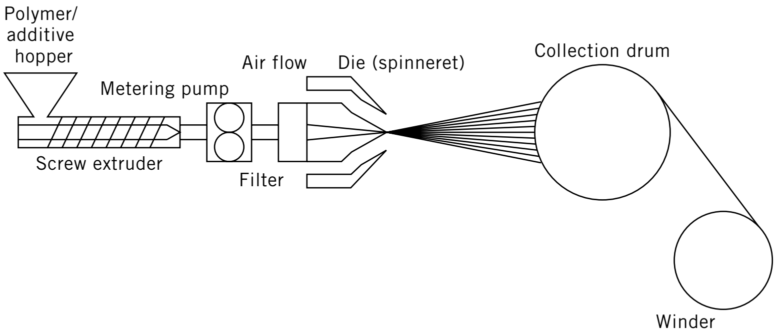

Fig. 11. Flow sheet for typical meltblown fabric manufacture.

filaments onto a moving conveyor belt. In the meltblown process (Fig. 11), high velocity air is used to draw the extruded melt into fine-denier fibers that are laid down in a continuous web on a collector drum.

3.4. Draw. Polyolefin fibers are usually drawn to increase orientation and further modify the physical properties of the fiber. Linear density, necessary to control the textile properties, is more easily reduced during drawing than in spinning. The draw step can be accomplished in-line with spinning in a continuous spin–draw–texturing process (36,42) or in a second processing step. This second processing step allows simultaneous mixing of colors in a multi-ply continuous filament yarn for textiles. For staple fiber production, large bundles or tows consisting of up to a million or more filaments are stretched, texturized (crimped), and cut.

In secondary drawing operations, the aging properties of the spun yarn must be considered. Because polypropylene fibers have a low T_g,, the spun yarn is restructured between spinning and drawing; this is more important as the smectic content is increased (43). The aging process depends on whether the yarn is stored on bobbins under tension or coiled in cans with no tension on the fiber. The aging of quick-quenched (smectic) polypropylene films has been studied (43). Stored at room temperature, the increase in yield stress is 5% in 24 hours. Similar data on polypropylene spun fibers have not been published, but aging effects are similar. Drawn fiber properties, such as density, stress relaxation modulus, and heat of fusion, age because of collapse of excess free volume in the noncrystalline fraction (44).

The crystalline structure of the spun yarn affects the draw process. Monoclinic yarns tend to exhibit higher tenacity and lower elongation at low draw ratios than smectic yarns (6). They exhibit lower maximum draw ratios, undergo brittle fracture, and form microvoids (45) at significantly lower draw temperatures, which creates a chalky appearance. Studies of the effect of spun-yarn structure on drawing behavior show that the as-spun orientation and morphology determine fiber properties at a given draw ratio, as shown in Figure 12 (9,45,46). However, final fiber properties can be correlated with birefringence, a measure of the average orientation, as shown in Figure 13 (9,45). Fiber properties and amorphous orientation show good correlation in some studies

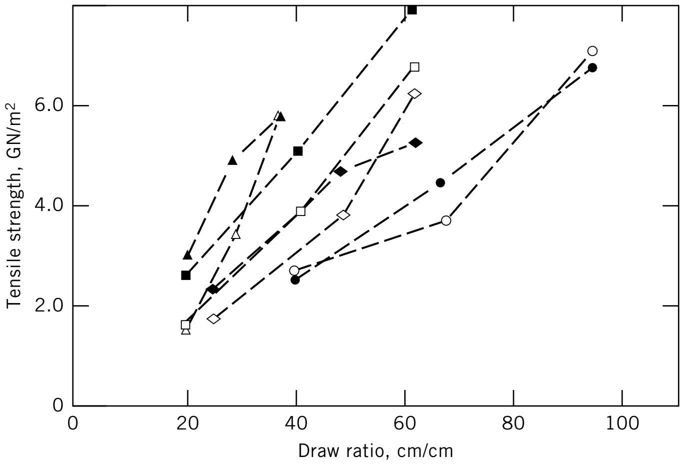

Fig. 12. Tensile strength vs draw ratio (6): 0.42 melt index spun at 50 m/min, ■, □; and 500 m/min, ▲, △; 12.0 melt index spun at 100 m/min, •, ○; and 500 m/min, ◆, ◇. Open symbols = cold drawn and annealed at 140°C; filled symbols = drawn at 140°C. To convert GN/m^2 to dyne/cm^2, multiply by 10^{10}.

(Fig. 14) (7,8), but in most studies the range of spun-yarn properties is limited. Such studies suggest that the deformation during draw primarily affects the interlamellar amorphous region at low draw ratio. At higher draw ratio, the crystalline structure is substantially disrupted.

3.5. Texturing. The final step in olefin fiber production is texturing; the method depends primarily on the application. For carpet and upholstery, the fiber is usually bulked, a procedure in which fiber is deformed by hot air or steam jet turbulence in a nozzle and deposited on a moving screen to cool. The

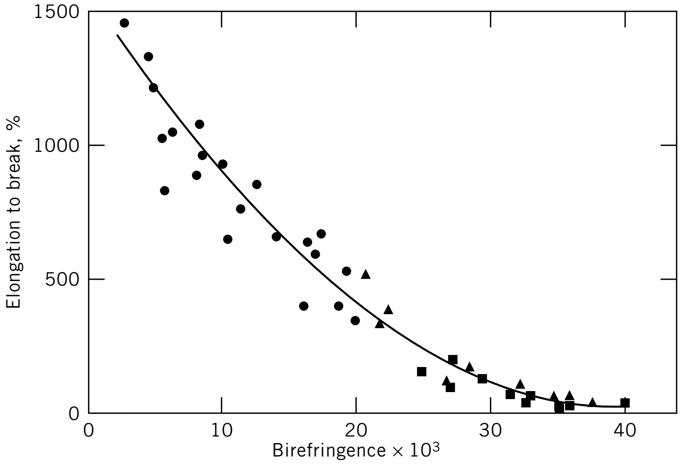

Fig. 13. Elongation to break as a function of birefringence for undrawn, hot-drawn, and cold-drawn annealed fibers (6): •, undrawn; ▲, cold-drawn, annealed at 140°C; ■, hot-drawn at 140°C.

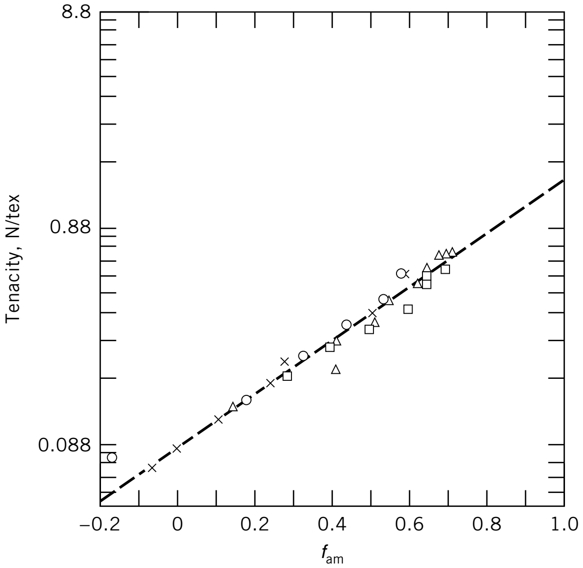

Fig. 14. Tenacity as a function of amorphous orientation (f_{am}) for polypropylene fibers and films (7). Film drawn at: ○, 135°C; ×, 110°C; □, 90°C. △, Heat-set fiber. To convert N/tex to gf/den, multiply by 11.3. $\text{Tenacity}_{max} = 1.3$ N/tex (15 gf/den).

fiber takes on a three-dimensional crimp that aids in developing bulk and coverage in the final fabric. Stuffer box crimping, a process in which heated tow is overfed into a restricted outlet box, imparts a two-dimensional sawtooth crimp commonly found in olefin staple used in carded nonwovens and upholstery yarns.

3.6. Slit-Film Fiber. A substantial volume of olefin fiber is produced by slit-film or film-to-fiber technology (29). For producing filaments with high linear density, above 0.7 tex (6.6 den), the production economics are more favorable than monofilament spinning (29). The fibers are used primarily for carpet backing and rope or cordage applications. The processes used to make slit-film fibers are versatile and economical.

The equipment for the slit-film fiber process is shown in Figure 15 (29). An olefin film is cast, and as in melt spinning, the morphology and composition of the film determine the processing characteristics. Fibers may be produced by cutting or slitting the film, or by chemomechanical fibrillation. The film is fibrillated mechanically by rubbing or brushing. Immiscible polymers, such as polyethylene or polystyrene (PS), may be added to polypropylene to promote fibrillation. Many common fiber-texturing techniques such as stuffer-box, false-twist, or knife-edge treatments improve the textile characteristics of slit-film fibers.

Several more recent variations of the film-to-fiber approach result in direct conversion of film to fabric. The film may be embossed in a controlled pattern and subsequently drawn uniaxially or biaxially to produce a variety of nonwoven products (47). Addition of chemical blowing agents to the film causes fibrillation upon extrusion. Nonwovens can be formed directly from blown film using a unique radial die and control of the biaxial draw ratio (48) (see Nonwoven Fabrics, Staple Fibers).

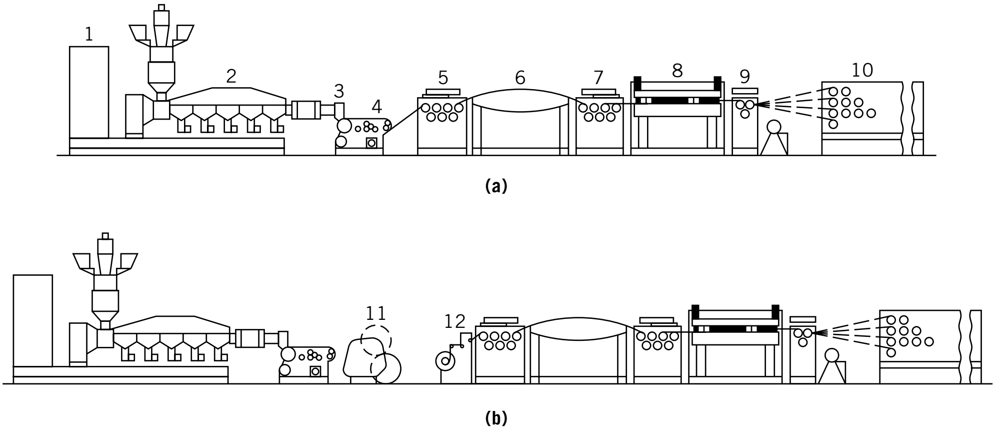

Fig. 15. Production lines for stretched film tape (29): (a) continuous production line for film tape; (b) discontinuous production lines for film and film tape. 1, Control cabinet; 2, extruder; 3, flat die; 4, chill roll; 5, septet (seven rolls); 6, hot plate; 7, septet (seven rolls) 8, heat-setting oven; 9, trio (three rolls); 10, bobbin winder; 11, film winder; and 12, film-unrolling stand.

3.7. Bicomponent Fibers. Polypropylene fibers have made substantial inroads into nonwoven markets because they are easily thermal bonded. Further enhancement in thermal bonding is obtained using bicomponent fibers (49). In these fibers, two incompatible polymers, such as polypropylene and polyethylene, polyester and polyethylene, or polyester and polypropylene, are spun together to give a fiber with a side-by-side or core–sheath arrangement of the two materials. The lower melting polymer can melt and form adhesive bonds to other fibers; the higher melting component causes the fiber to retain some of its textile characteristics.

Bicomponent fibers have also provided a route to self-texturing (self-crimping) fibers. The crimp results from the length differential developed during processing caused by differential shrinkage in the two polymers in side-by-side or eccentric core–sheath configurations (50).

Conventional spinning technology is limited in the production of very fine denier filaments because of spinning and mass uniformity problems as the melt drawdown is increased. Ultrafine filaments (microfibers) can be produced through bicomponent technology by extruding two or more components together as a single fiber and later separating the components through chemical or mechanical processes. Fibers of 0.1 to 0.001 tex (~1–0.01 den) per filament can be produced (50,51).

3.8. Meltblown, Spunbond, and Spurted Fibers. A variety of directly formed nonwovens exhibiting excellent filtration characteristics are made by meltblown processes (52), producing very fine, submicrometer filaments. A simple schematic of the die is shown in Figure 11. A stream of high velocity hot air is directed on the molten polymer filaments as they are extruded from a spinneret. This air attenuates, entangles, and transports the fiber to a collection device. Because the fiber cannot be separated and wound for subsequent processing, a

Table 5. **Theoretical and Actual Strengths of Commercial Fibers**[a]

Polymer	Density, kg/m^3	Molecular area, nm^2	Theoretical strength, GPa[b]	Strength of commercial fiber, GPa[b]
polyethylene	960	0.193	31.6	0.76
polypropylene	910	0.348	17.6	0.72
nylon-6	1140	0.192	31.9	0.96
polyoxymethylene	1410	0.185	32.9	
poly(vinyl alcohol)	1280	0.228	26.7	1.08
poly(*p*-benzamide)	1430	0.205	29.7	3.16
poly(ethylene terephthalate)	1370	0.217	28.1	1.15
poly(vinyl chloride)	1390	0.294	20.8	0.49
rayon	1500	0.346	17.7	0.69
poly(methyl methacrylate)	1190	0.667	9.2	

[a] Ref. 56.
[b] To convert GPa to psi, multiply by 145,000.

nonwoven web is directly formed. Mechanical integrity of the web is usually obtained by thermal bonding or needling, although other methods, such as latex bonding, can be used. Meltblown fabrics are made commercially from polypropylene and polyethylene. The webs are soft, breathable, and drapable (53–55).

In the spunbond process, the fiber is spun similarly to conventional melt spinning, but the fibers are attenuated by air drag applied at a distance from the spinneret. This allows a reasonably high level of filament orientation to be developed. The fibers are directly deposited onto a moving conveyor belt as a web of continuous randomly oriented filaments. As with meltblown webs, the fibers are usually thermal bonded or needled (53).

Pulp-like olefin fibers are produced by a high pressure spurting process developed by Hercules Inc. and Solvay, Inc. Polypropylene or polyethylene is dissolved in volatile solvents at high temperature and pressure. After the solution is released, the solvent is volatilized, and the polymer expands into a highly fluffed, pulp-like product. Additives are included to modify the surface characteristics of the pulp. Uses include felted fabrics, substitution in whole or in part for wood pulp in papermaking, and replacement of asbestos in reinforcing applications (56).

3.9. High Strength Fibers. The properties of commercial olefin fibers are far inferior to those theoretically attainable. Theoretical and actual strengths of common commercial fibers are listed in Table 5 (57). A number of methods, including superdrawing (58), high pressure extrusion (59), spinning of liquid crystalline polymers or solutions (60), gel spinning (61–65), and hot drawing (66) produce higher strengths than those given in Table 5 for commercial fibers, but these methods are tedious and uneconomical for olefin fibers. A high modulus commercial polyethylene fiber with properties approaching those of aramid and graphite fibers (Table 6) (67) is prepared by gel spinning (68). Although most of these techniques produce substantial increases in modulus, higher tensile strengths are currently available only from gel spinning or dilute fibrillar crystal

Table 6. **Properties of Commercial High Strength Fibers**[a]

Fiber	Density, kg/m^3	Strength, GPa[b]	Modulus, GPa[b]	Elongation to break, %	Filament diameter, mm
polyethylene	970	2.6	117	3.5	0.038
aramid	1440	2.8	113	2.8	0.012
S-glass	2490	4.6	89	5.4	0.009
graphite	1730	3.1	227	1.2	0.006
steel whiskers	7860	2.3	207	1.3	0.250

[a] Ref. 66.

[b] To convert GPa to psi, multiply by 145,000.

growth. Even using these techniques, the maximum strengths observed to date are only a fraction of the theoretical strengths.

3.10. Hard-Elastic Fibers. Hard-elastic fibers are prepared by annealing a moderately oriented spun yarn at high temperature under tension. They are prepared from a variety of olefin polymers, acetal copolymers, and polypivalolactone (69,70). Whereas the strengths observed are comparable to those of highly drawn commercial fiber, in the range 0.52–0.61 N/tex (6–7 gf/den), the recovery from elongation is substantially better. Hard-elastic fibers typically exhibit 90% recovery from 50% elongation, whereas highly drawn, high tenacity commercial fibers exhibit only 50–75% recovery from 5% elongation. The mechanism of elastic recovery differs from the entropic models normally used to explain plastic properties. The hard elastic fibers are thought to deform through opening of the lamellae stacked structure, resulting in void formations; recovery is controlled by energy considerations. Although there are potential uses in applications involving substantial deformation, products such as stretch fabrics and hard-elastic fibers are not yet used commercially.

4. Economic Aspects

Polyolefin fiber (from polypropylene or ethylene polymers) has continued to be one of the fastest growing segments of the synthetic fiber industry. Worldwide production has been increasing at an annual rate of 6% since 1996 and reached 5.5 million tons in 1999. Polyolefin fibers account for 18% of the worldwide synthetic fibers market. Polypropylene fibers predominate and account for 89–95% of the polyolefin production in Western Europe and the United States. The remainder is manufactured from polyethylene. Polypropylene fibers account for 80% usage in Japan (71).

The principal use for polyolefin fibers is in consumer products. The primary use is the production of carpets and rugs, and includes backings. Polyolefins in the form of nonwoven fabrics is the second largest use.

Nonwoven fabrics continue to be the largest growing segment in the textile industry. In 2001, worldwide consumption was 3.5 billion tons valued at over $14 billion. Between 1997 and 2001, world consumption grew at a rate of 11.2%/yr. For much of the past decade solid growth has occurred in industrialized nations. Double digit growth is now seen in developing nations (primarily

Asia). In 2001, developing countries consumed 39% of all nonwovens produced. Consumption is up from 11% in 1988. Use should continue to grow at the rate of 10–12% through 2006 (72).

Demand for nonwoven roll goods currently exceeds local capacity by 50%. Growth, particularly in China, has seen expansion of local manufacturing capabilities. In North America, Western Europe, and Japan, demand for nonwovens is expected to increase at 3–5%/yr through 2006.

Industrial applications of polyolefin fibers include woven and nonwoven geotextiles, agricultural fabrics, construction sheeting, automobile fabrics, filtration media, rope/twine, woven bags, narrow-woven web and tapes, tents, and tarpaulins. Geosynthetic fabrics will continue to be a growing market for polypropylene nonwovens.

5. Applications

Olefin fibers are used for a variety of purposes from home furnishings to industrial applications. These include carpets, upholstery, drapery, rope, geotextiles, and both disposable and nondisposable nonwovens. Fiber mechanical properties, relative chemical inertness, low moisture absorption, and low density contribute to desirable product properties. Olefin fiber use in apparel has been restricted by low melting temperatures, which make machine drying and ironing of polyethylene and polypropylene fabrics difficult or impossible. However, this market is increasing as manufacturers take advantage of the wicking properties (moisture transport) as in lightweight sportswear (73).

Polypropylene fibers are used in every aspect of carpet construction from face fiber to primary and secondary backings. Polypropylene's advantages over jute as carpet backing are dimensional stability and minimal moisture absorption. Drawbacks include difficulty in dyeing and higher cost. Bulked-continuous-filament (BCF) carpet yarns provide face fiber with improved crimp and elasticity. BCF carpet yarns are especially important in contract carpets, characterized by low dense loops, where easy cleaning is an advantage.

Olefin fiber is an important material for nonwovens (74). The geotextile market is still small, despite expectations that polypropylene is to be the principal fiber in such applications. Disposable nonwoven applications include hygienic coverstock, sanitary wipes, and medical roll goods. The two competing processes for the coverstock market are thermal-bonded carded staple and spunbond, both of which have displaced latex-bonded polyester because of improved strength, softness, and inertness.

A special use for meltblown olefin fiber is in filtration media such as surgical masks and industrial filters (75). The high surface area of these ultrafine filament fibers permits preparation of nonwoven filters with effective pore sizes as small as 0.5 μm.

Other applications, including rope, cordage, outdoor furniture webbing, bags, and synthetic turf, make up the remaining segments of the olefin fiber market. Spunbond polyethylene is used in packaging applications requiring high strength and low weight. Specialty olefin fibers are employed in asphalt and concrete reinforcement (76–79). Hollow fibers have been tested in several filtration applications (80,81). Ultrafine fibers are used in synthetic leather, silk-like fabrics, and special filters (50,51). These fibers are also used in sports outerwear, where the tight weaves produce fabrics that are windproof and waterproof but still are able to pass vapors from perspiration and thus keep the wearer cool and dry (51). If the economics of the high modulus olefin fibers becomes more favorable, substantial markets could be developed in reinforced composites such as boat hulls (67).

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