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Glass Fibers

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GLASS FIBERS are among the most versatile industrial materials known today. They are readily produced from raw materials, which are available in virtually unlimited supply (Ref 1). All glass fibers described in this article are derived from compositions containing silica. They exhibit useful bulk properties such as hardness, transparency, resistance to chemical attack, stability, and inertness, as well as desirable fiber properties such as strength, flexibility, and stiffness (Ref 2). Glass fibers are used in the manufacture of structural composites, printed circuit boards and a wide range of special-purpose products (Ref 3).

Fiber Forming Processes. Glass melts are made by fusing (co-melting) silica with minerals, which contain the oxides needed to form a given composition. The molten mass is rapidly cooled to prevent crystallization and formed into glass fibers by a process also known as fiberization.

Nearly all continuous glass fibers are made by a direct draw process and formed by extruding molten glass through a platinum alloy bushing that may contain up to several thousand individual orifices, each being 0.793 to 3.175 mm (0.0312 to 0.125 in.) in diameter (Ref 1). While still highly viscous, the resulting fibers are rapidly drawn to a fine diameter and solidify. Typical fiber diameters range from 3 to 20 μm (118 to 787 μin.). Individual filaments are combined into multifilament strands, which are pulled by mechanical winders at velocities of up to 61 m/s (200 ft/s) and wound onto tubes or forming packages. This is the only process that is described in detail subsequently in the present article.

The marble melt process can be used to form special-purpose, for example, high-strength fibers. In this process, the raw materials are melted, and solid glass marbles, usually 2 to 3 cm (0.8 to 1.2 in.) in diameter, are formed from the melt. The marbles are remelted (at the same or at a different location) and formed into glass fibers. Glass fibers can also be down drawn from the surface of solid preforms. Although this is the only process used for manufacturing optical fibers, which are not discussed in this Volume, it is a specialty process for manufacturing structural glass fibers such as silica or quartz glass fibers. These and other specialty processes are highlighted wherever appropriate but not discussed in full. Additional details about fiber forming are provided in the section "Glass Melting and Fiber Forming" in this article.

Sizes and Binders. Glass filaments are highly abrasive to each other (Ref 4). "Size" coatings or binders are therefore applied before the strand is gathered to minimize degradation of filament strength that would otherwise be caused by filament-to-filament abrasion. Binders provide lubrication, protection, and/or coupling. The size may be temporary, as in the form of a starch-oil emulsion that is subsequently removed by heating and replaced with a glass-to-resin coupling agent known as a finish. On the other hand, the size may be a compatible treatment that performs several necessary functions during the subsequent forming operation and which, during impregnation, acts as a coupling agent to the resin being reinforced.

Glass Fiber Types

Glass fibers fall into two categories, low-cost general-purpose fibers and premium special-purpose fibers. Over 90% of all glass fibers are general-purpose products. These fibers are known by the designation E-glass and are subject to ASTM specifications (Ref 5). The remaining glass fibers are premium special-purpose products. Many, like E-glass, have letter designations implying special properties (Ref 6). Some have tradenames, but not all are subject to ASTM specifications. Specifically:

Letter designation	Property or characteristic
E, electrical	Low electrical conductivity
S, strength	High strength
C, chemical	High chemical durability
M, modulus	High stiffness
A, alkali	High alkali or soda lime glass
D, dielectric	Low dielectric constant

Table 1 gives compositions and Table 2 gives physical and mechanical properties of commercial glass fibers.

General-purpose glass fibers (E-glass variants) are discussed in the following section of this article, which provides an in-depth discussion of compositions, melt properties, fiber properties (Ref 12), methods of manufacture, and significant product types. An in-depth discussion of composite applications can be found in other articles in this Volume.

Glass fibers and fabrics are used in ever increasing varieties for a wide range of applications (Ref 13). A data book is available (Ref 14) that covers all commercially available E-glass fibers, whether employed for reinforcement, filtration, insulation, or other applications. It lists all manufacturers, their sales offices, agents, subsidiaries, and affiliates, complete with addresses, and telephone and fax numbers. And it tabulates key properties and relevant supply details of all E-glass fiber grades, that are available in the market today.

Special-Purpose Glass Fibers. S-glass, D-glass, A-glass, ECR-glass, ultrapure silica fibers, hollow fibers, and trilobal fibers are special-purpose glass fibers. Selected special-purpose glass fibers are discussed in the subsequent section of this article. That section reviews compositions, manufacture, properties, and applications to an extent commensurate with their commercial use (Ref 15).

A companion data book (Ref 16) is available that covers all commercially available high-strength glass fibers including S-glass and, all silica or quartz glass fibers, including Astroquartz and Quartzel. It also lists a wide range of woven fabrics, that are commercially available in the market of today, ranging from S-glass/aramid, S-glass/carbon, silica/aramid, and silica/carbon yarns to silica/boron yarns. In addition, it covers all commercially available carbon, ceramic, boron, and high-temperature polymer fibers and yarns. This data book also lists all yarn counts, fabric constructions, fabric weights, and commercial sources.

ASTM Test Methods. ASTM has published standard test methods for glass density (Ref 17), alternating current loss characteristics and dielectric constant (Ref 18), direct current conductance of insulating materials (Ref 19), dielectric breakdown voltage and dielectric strength (Ref 20), softening point of glass (Ref 21), annealing point and strain point of glass by fiber elongation (Ref 22), annealing point and strain point of glass by beam bending (Ref 23), viscosity (Ref 24), liquidus temperature (Ref 25), and coeffi-

Table 1 Compositions of commercial glass fibers

		Composition, wt%												
Fiber	Ref	SiO_2	B_2O_3	Al_2O_3	CaO	MgO	ZnO	TiO_2	Zr_2O_3	Na_2O	K_2O	Li_2O	Fe_2O_3	F_2
General-purpose fibers														
Boron-containing E-glass	1, 2	52–56	4–6	12–15	21–23	0.4–4	. . .	0.2–0.5	. . .	0–1	Trace	. . .	0.2–0.4	0.2–0.7
Boron-free E-glass	7	59.0	. . .	12.1	22.6	3.4	. . .	1.5	. . .	0.9	. . .	. . .	0.2	. . .
	8	60.1	. . .	13.2	22.1	3.1	. . .	0.5	. . .	0.6	0.2	. . .	0.2	0.1
Special-purpose fibers														
ECR-glass	1, 2	58.2	. . .	11.6	21.7	2.0	2.9	2.5	. . .	1.0	0.2	. . .	0.1	Trace
D-glass	1, 2	74.5	22.0	0.3	0.5	. . .	. . .	. . .	. . .	1.0	<1.3	. . .	. . .	. . .
	2	55.7	26.5	13.7	2.8	1.0	. . .	. . .	. . .	0.1	0.1	0.1	. . .	. . .
S-, R-, and Te-glass	1, 2	60–65.5	. . .	23–25	0–9	6–11	. . .	. . .	0–1	0–0.1	. . .	. . .	0–0.1	. . .
Silica/quartz	1, 2	99.9999	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .

cient of linear thermal expansion of plastics (Ref 26).

Some fiber properties (Ref 4), such as tensile strength, modulus, and chemical durability, are measured on the fibers directly. Other properties, such as relative permittivity, dissipation factor, dielectric strength, volume/surface resistivities, and thermal expansion, are measured on glass that has been formed into a bulk patty or block sample and annealed (heat treated) to relieve forming stresses. Properties such as density and refractive index are measured on both fibers and bulk samples, in annealed or unannealed form.

General-Purpose Glass Fibers

Types. Two generic types of E-glass (Ref 6) are known in the market today. The incumbent E-glass contains 5 to 6 wt% of boron oxide. Stringent environmental regulations require the addition of costly emission abatement systems to eliminate boron from the off-gases of boron-containing melts. Alternatively, the use of environmentally friendly boron-free E-glass is required. These melts do not contain, and therefore do not emit, boron into the environment during processing. As a result, a boron-free E-glass product was recently introduced into the market by Fiberglas (Owens Corning Corp., Toledo, OH) under the trademark Advantex.

Commercial boron-containing E-glass comes in two variants. One commercial variant is derived from the quaternary SiO_2-Al_2O_3-CaO-MgO (Ref 2, 4, 6, 27), and the other is derived from the ternary SiO_2-Al_2O_3-CaO phase diagram (Ref 2, 4, 6, 28). Commercial E-glasses in the ternary SiO_2-Al_2O_3-CaO system contain a small amount (<0.6 wt%) of MgO that is not deliberately added but obtained as by-product (or tramp) from other ingredients. On the other hand, commercially available boron-free E-glass is derived from the quaternary SiO_2-Al_2O_3-CaO-MgO phase diagram (Ref 2, 7, 8, 29).

ASTM standards for E-glass (Ref 5) cover all three commercial E-glass variants, distinguishing E-glasses by end use. Compositions containing 5 to 10 wt% by weight of boron oxide are certified for printed circuit board and aerospace applications. Compositions containing 0 to 10 wt% by weight of boron oxide are certified for general applications. According to these standards, E-glass compositions for either type of application may also contain 0 to 2 wt% alkali oxide and 0 to 1 wt% fluoride. The more recent boron-free E-glass variants may also be fluorine-free.

Oxide Compositions. E-glasses of any type are general-purpose fibers because they offer useful strength at low cost. Table 1 presents the oxide components and their ranges for the two types of E-glass fibers that are currently being produced and used in composites. A range is given for each with regard to its oxide components because each manufacturer, and even different manufacturing plants of the same company, may use slightly different compositions for

Table 2 Physical and mechanical properties of commercial glass fibers

	Log 3 forming temperature(a)		Liquidus temperature		Softening temperature		Annealing temperature		Straining temperature		
Fiber	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	Bulk density, annealed glass, g/cm^3
General-purpose fibers											
Boron-containing E-glass	1160–1196	2120–2185	1065–1077	1950–1970	830–860	1525–1580	657	1215	616	1140	2.54–2.55
Boron-free E-glass	1260	2300	1200	2190	916	1680	736	1355	691	1275	2.62
Special-purpose fibers											
ECR-glass	1213	2215	1159	2120	880	1615	728	1342	691	1275	2.66–2.68
D-glass	. . .	. . .	. . .	. . .	770	1420	. . .	. . .	475	885	2.16
S-glass	1565	2850	1500	2730	1056	1935	. . .	. . .	760	1400	2.48–2.49
Silica/quartz	>2300	>4170	1670	3038	. . .	. . .	. . .	. . .	. . .	. . .	2.15

								Tensile strength at 23 °C (73 °F)		Young's modulus		
Fiber	Coefficient of linear expansion, 10^{-6}/°C	Specific heat, cal/g/°C	Dielectric constant at room temperature and 1 MHz	Dielectric strength, kV/cm	Volume resistivity at room temperature $\log_{10}$ (Ω cm)	Refractive index (bulk)	Weight loss in 24 h in 10% H_2SO_4, %	MPa	ksi	GPa	10^6 psi	Filament elongation at break, %
General-purpose fibers												
Boron-containing E-glass	4.9–6.0	0.192	5.86–6.6	103	22.7–28.6	1.547	~41	3100–3800	450–551	76–78	11.0–11.3	4.5–4.9
Boron-free E-glass	6.0	. . .	7.0	102	28.1	1.560	~6	3100–3800	450–551	80–81	11.6–11.7	4.6
Special-purpose fibers												
ECR-glass	5.9	. . .	. . .	. . .	. . .	1.576	5	3100–3800	450–551	80–81	11.6–11.7	4.5–4.9
D-glass	3.1	0.175	3.56–3.62	. . .	. . .	1.47	. . .	2410	349	. . .	. . .	. . .
S-glass	2.9	0.176	4.53–4.6	130	. . .	1.523	. . .	4380–4590	635–666	88–91	12.8–13.2	5.4–5.8
Silica/quartz	0.54	. . .	3.78	. . .	. . .	1.4585	. . .	3400	493	69	10.0	5

(a) The log 3 forming temperature is the temperature of a melt at a reference viscosity of 100 Pa · s (1000 P). Source: Ref 2, 7–10, 11 the same glass. These variations result mainly from differences in the available glass batch (raw materials). Tight control is maintained within a given production facility to optimize compositional consistency and maximize production efficiencies.

As shown in Table 1, commercial, boron-containing E-glass compositions (Ref 1, 2, 4, 6, 12, 24) differ substantially from boron-free E-glass compositions. The silica content for commercial boron-containing E-glasses ranges from 52 to 56 wt% by weight, and for commercial boron-free E-glasses from 59 to 61 wt%. The alumina content generally ranges from 12 to 15 wt% for these boron-containing E-glasses and from 12 to 13.5 wt% for these boron-free E-glasses. The calcia content ranges from 21 to 23 wt% for these commercial boron-containing E-glasses and from 22 to 23 wt% for these boron-free E-glasses.

For commercial, boron-containing, ternary or quaternary E-glasses, the magnesia content ranges from 0.4 wt% (tramp only) to greater amounts if magnesia (dolomite) is deliberately added. For commercial boron-free E-glasses, it ranges from 3.1 to 3.4 wt% (see Table 1). The boron oxide content ranges from 5 to 6% for commercial boron-containing E-glasses, and it is zero for boron-free E-glasses. The titania content ranges from 0.4 to 0.6 wt% for commercial boron-containing E-glasses. For boron-free E-glasses, it ranges from 0.5 wt% (Ref 8) to 1.5 wt% (Ref 7) (see also Table 1).

Environmentally friendly E-glass melts are boron-free and fluorine-free. However, the log 3 fiber forming or fiberization temperature (T_F) of boron-free E-glass melts may be as much as 100 to 110 °C (180 to 200 °F) higher than that of boron-containing E-glass melts (Fig. 1). The log 3 forming temperature is the temperature of a melt at a reference viscosity of 100 Pa · s (1000 P). In addition, the softening point of boron-free E-glass is 60 to 90 °C (110 to 160 °F) higher also than that of a boron-containing E-glass. The higher process temperature requires more process energy, but the higher softening point facilitates higher use temperatures.

Melt Properties. According to Table 2, the log 3 forming temperature, T_F, of boron-containing E-glasses ranges from 1140 to 1185 °C (2085 to 2165 °F). The liquidus temperature (T_L) is the temperature below which solid (crystals) will form. It ranges form 1050 to 1064 °C (1920 to 1945 °F). The difference between forming and liquidus temperature (ΔT) ranges from 81 to 90 °C (146 to 162 °F). In contrast, the log 3 fiber forming temperature of boron-free E-glasses ranges from 1250 to 1264 °C (2280 to 2307 °F), the liquidus temperature from 1146 to 1180 °C (2095 to 2155 °F), and the difference between forming and liquidus temperature (ΔT) from 86 to 104 °C (155 to 187 °F) (Ref 7–10). Finally, the softening point of boron-containing E-glasses ranges from 830 to 860 °C (1525 to 1580 °F); that of boron-free E-glasses is about 916 °C (1680 °F).

Mechanical Properties. Table 2 also compares the mechanical properties of the boron-free and boron-containing E-glasses. Elastic modulus (or fiber stiffness) of boron-free E-glasses is about 5% higher than that of boron-containing E-glasses, while pristine, virgin, or single-filament tensile strength is said to be about the same for both types of E-glasses when both are tested at room temperature (Ref 8, 9).

Physical Properties. In addition, Table 2 compares the physical properties of the boron-free and boron-containing E-glasses. Most importantly, the corrosion resistance of boron-free E-glasses was found to be seven times higher than that of boron-containing E-glasses when tested at room temperature for 24 h in 10% sulfuric acid. It approaches that of ECR glass fibers (Ref 9, 10).

Boron-free E-glasses have a slightly higher density (2.62 g/cm^3) than boron-containing E-glasses (2.55 g/cm^3), but the density of both fibers is lower than that of ECR glass (2.66 to 2.68 g/cm^3), a corrosion-resistant special-purpose fiber. Boron-free E-glasses have a higher refractive index and linear expansion coefficient than boron-containing E-glass fibers. The refractive index of both E-glasses is lower than that of ECR glass. The linear expansion coefficient of ECR glass fibers is midway between that of the two E-glasses.

Boron-free E-glasses have a slightly higher dielectric constant (7.0) than boron-containing E-glasses (5.9 to 6.6) when measured at room temperature and at a frequency of 1 MHz. As a result, boron-containing, but not boron-free, E-glass fibers are needed for electronic circuit boards and aerospace applications. On the other hand, boron-free and boron-containing E-glass fibers are used in structural composites where the dielectric constant is of no concern. Composite and laminate uses of all glass fibers are discussed in other articles in this Volume.

Special-Purpose Glass Fibers

Types. Special-purpose fibers, which are of commercial significance in the market today, include glass fibers with high corrosion resistance (ECR-glass), high strength (S-, R-, and Te-glass), with low dielectric constants (D-glass), high strength fibers, and pure silica or quartz fibers, which can be used at ultrahigh temperatures. These fibers will be discussed in the following paragraphs. Others special-purpose fibers include A-glass, C-glass, hollow fibers, bicomponent fibers, and trilobal fibers. These special-purpose glass fibers have recently been reviewed in detail (Ref 2).

ECR-Glass. The corrosion resistance of glass fibers is determined by their chemical structure. It has already been noted in the preceding section on general-purpose glass fibers that boron-free E-glass fibers derived from the quaternary SiO_2-Al_2O_3-CaO-MgO phase diagram have higher acid resistance than E-glass fibers that are derived from the ternary SiO_2-Al_2O_3-CaO phase diagram but have high boron levels. The ECR glass fibers offer enhanced long-term acid resistance and short-term alkali resistance (Ref 27).

The addition of high levels of ZnO and TiO_2 to the boron-free quaternary E-glass system further enhances the corrosion resistance of the resulting ECR glass fibers while at the same time reducing the log 3 forming temperature. The product and process advantage are obtained at a cost penalty. About 2% ZnO and two additional percent TiO_2 are required, and both materials are known to be costly batch ingredients.

S-Glass, R-Glass, and Te-Glass. The tensile strength of glass fibers is determined by the structure connectivity of the silicate network, notably, by the absence of alkali oxides, which are not readily integrated into the structure. The structure of boron oxide, though being a part of the network, is weaker than that of silicon oxide, and therefore, boron oxide serves as a flux. Several high-strength glass fibers are known, including S-glass, Te-glass, and R-glass (Ref 2). All offer 10 to 15% higher strength than E-glass at room temperature, but their real value is their ability to withstand higher in-use temperatures than E-glass. These fibers are used in military applications. Stringent quality-control procedures are necessary to meet military specifications.

S-glass and Te-glass are derivatives of the ternary SiO_2-Al_2O_3-CaO system. R-glass is a derivative of the quaternary SiO_2-Al_2O_3-CaO-MgO system. S-glass and S-2 glass fibers, a product variant, have the same glass composition (Ref 2) but different coatings. While internal structural uniformity (high strength) is achieved with these boron-free and alkali-free compositions, their forming temperatures are higher than that of E-glass. Attainment of high in-use temperatures is a definite product advantage, but

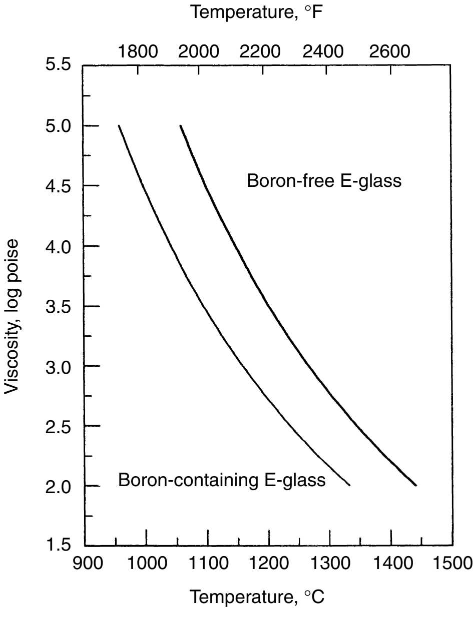

Fig. 1 Viscosity of boron-free and boron-containing E-glass

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higher melt temperatures, more process energy, and more costly bushing alloys are required.

Silica/Quartz Fibers. Glass fibers with increasing SiO_2 levels can be used in applications requiring increasingly high in-use temperatures. High-silica fibers (95% SiO_2) are amorphous glass fibers. They are obtained by acid leaching of borosilicate E-glass fabrics, which are, in turn, used as insulation blankets at temperatures up to 1040 °C (1900 °F). Pure silica fibers (99% SiO_2) are made by dry spinning from aqueous waterglass solutions. They are known by the tradename "Silfa" and mostly are used as yarns, for example, for wire insulation at temperatures up to 1090 °C (1990 °F). For details see Ref 2. They are not used in composite applications and are therefore not shown in Table 2.

Ultrapure silica glass fibers or quartz fibers (99.99% SiO_2), which are down-drawn from preforms (Ref 2) in a containerless process, are also amorphous, despite the fact that the trivial name "quartz" or trade names Quartzel and Astroquartz would imply the presence of the hexagonal crystal structure of quartz. Ultrapure silica (quartz) fibers combine superior high-temperature resistance with superior transparency to ultraviolet (UV) and longer wavelength radiation. For example, in a composite radome on the nose of an aircraft, they protect delicate radar equipment from flying objects, lightning and static discharge (Ref 30). The purest of all commercial silica glass or quartz fibers (99.999% SiO_2) are obtained by dry-spinning of a reagent grade tetraethylorthosilicate sol-gel (Ref 2).

All ultrapure silica glass or quartz fibers are used in yarn and in composite applications and are, therefore, shown in Table 2. Ultrapure and pure silica yarns and fabrics can be used at temperatures up to 1090 °C (1990 °F), high silica fabrics at up to 1040 °C (1900 °F), and S-glass, Te-glass, and R-glass yarns and fabrics at up to 815 °C (1500 °F) (for process and product details see Ref 2).

D-Glass. The electrical properties of glass fibers are determined by their volume resistivity, surface conductivity, dielectric constant and loss tangent (Ref 2). E-glass with its relatively high dielectric constant is the major reinforcing fiber for printed circuit board (PCB) laminates in the market today, but miniaturization drives the industry toward specialty fibers with lower dielectric constants and lower dielectric loss tangents.

Several low D-glass variants are known. All have very high B_2O_3 levels (20 to 26%) and, therefore, much lower dielectric constants than E-glass (4.10 to 3.56 versus 6.86 to 7.00). Those D-glass variants having low dielectric loss tangents as well (Ref 8) are said to offer the highest value in-use when used to reinforce PCB laminates. Because of their high cost, however, any D-glass version will remain a low volume specialty fiber. The very high boron-oxide levels, which are needed and in part emitted from the melt, may require an entirely different specialty process (see Ref 2 for details).

For very different reasons, ultrapure silica fibers, hollow E-glass fibers, S-glass, and other high-temperature fibers have lower dielectric constants than solid E-glass. They, too, can and are being used to reinforce printed circuit board (PCB) laminates. However, silica fibers have a low modulus and are, therefore, less effective as reinforcing fibers. Hollow fibers, although initially effective because of their low dielectric constant, lose their dielectric properties if moisture can seep into the laminate structure.

Glass Melting and Fiber Forming

A glass is an amorphous solid obtained by cooling a melt (i.e., liquid phase) sufficiently fast that crystallization (devitrification) cannot occur. When the melt is cooled slowly, crystallization can occur at the liquidus temperature, T_L, where crystals and melt are in equilibrium, or below. Glass fibers are therefore obtained at high cooling rates. Chemically, a glass consists of a silica network. Other oxides facilitate melting, homogenizing, removal of gaseous inclusions, and fiber formation at optimum temperatures. This section addresses the generic glass-melting and fiber-forming process, including the viscosity versus temperature profile that is required for general-purpose E-glass glass fibers and, more specifically, for E-glass fibers containing 5 to 6% boron oxide (see Ref 1 for details).

Depending on fiber diameter, optimum fiber formation is achieved with melts having a viscosity ranging from log 2.5 to log 3 P. The generic melting and forming process that is required for boron-free E-glass is the same as that required for boron-containing E-glass, but the viscosity/temperature profile differs. The relative forming temperatures can be deduced from the Fulcher curves shown in Fig. 1. They will be proportionately higher for boron-free E-glass at equal melt viscosities between log 2.5 to log 3.0 P. This section does not address the glass melting and fiber forming processes required for the special-purpose glass fibers, that is, ECR-glass, S-glass, ultrapure silica fibers, and D-glass (see Ref 2).

Batch Mixing and Melting. The glass melting process begins with the weighing and blending of selected raw materials. In modern fiberglass plants, this process is highly automated, with computerized weighing units and enclosed material transport systems. The individual components are weighed and delivered to a blending station where the batch ingredients are thoroughly mixed before being transported to the furnace.

Fiberglass furnaces generally are divided into three distinct sections (Fig. 2). Batch is delivered into the furnace section for melting, removal of gaseous inclusions, and homogenization. Then, the molten glass flows into the refiner section, where the temperature of the glass is lowered from 1370 °C (2500 °F) to about 1260 °C (2300 °F). The molten glass next goes to the forehearth section located directly above the fiber-forming stations. The temperatures throughout this process are prescribed by the viscosity characteristics of the particular glass. In addition, the physical layout of the furnace can vary widely, depending on the space constraints of the plant.

Fiberizing and Sizing. The conversion of molten glass in the forehearth into continuous glass fibers is basically an attenuation process (Fig. 3). The molten glass flows through a platinum-rhodium alloy bushing with a large number of holes or tips (400 to 8000, in typical production). The bushing is heated electrically, and the heat is controlled very precisely to maintain a constant glass viscosity. The fibers are drawn down and cooled rapidly as they exit the bushing.

A sizing is then applied to the surface of the fibers by passing them over an applicator that continually rotates through the sizing bath to maintain a thin film through which the glass filaments pass. It is this step, in addition to the original glass composition, which primarily differentiates one fiberglass product from another.

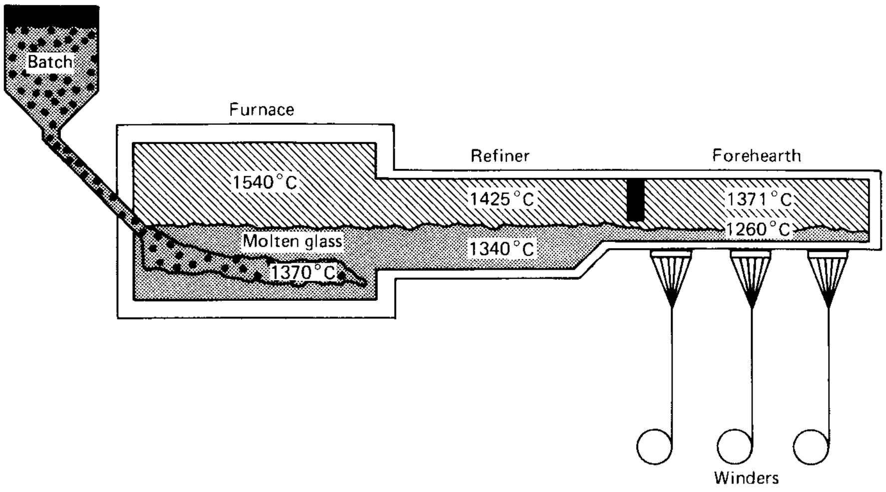

Fig. 2 Furnace for glass melting

The components of the sizing impart strand integrity, lubricity, resin compatibility, and adhesion properties to the final product, thus tailoring the fiber properties to the specific end-use requirements. After applying the sizing, the filaments are gathered into a strand before approaching the take-up device. If small bundles of filaments (split strands) are needed, multiple gathering devices (often called shoes) are used.

Fiber Diameters. The attenuation rate, and therefore the final filament diameter, is controlled by the take-up device. Fiber diameter is also affected by bushing temperature, glass viscosity, and the pressure head over the bushing. The most widely used take-up device is the forming winder, which employs a rotating collet and a traverse mechanism to distribute the strand in a random manner as the forming package grows in diameter. This facilitates strand removal from the package in subsequent processing steps, such as roving or chopping. The forming packages are dried and transferred to the specific fabrication area for conversion into the finished fiberglass roving, mat, chopped strand, or other product.

In recent years, processes have been developed to produce finished roving or chopped products directly during forming, thus leading to the term *direct draw roving* or *direct chopped strand*. Special winders and choppers designed to perform in the wet-forming environment are used in these cases (Fig. 4).

Yarn Nomenclature. It is standard practice in the fiberglass industry to refer to a specific filament diameter by a specific alphabet designation, as listed in Table 3. Fine fibers, which are used in textile applications, range from D through G. One reason for using fine fibers is to provide enough flexibility to the yarn to enable it to be processed in high-speed twisting and weaving operations. Conventional plastics reinforcement, however, uses filament diameters that range from G to T.

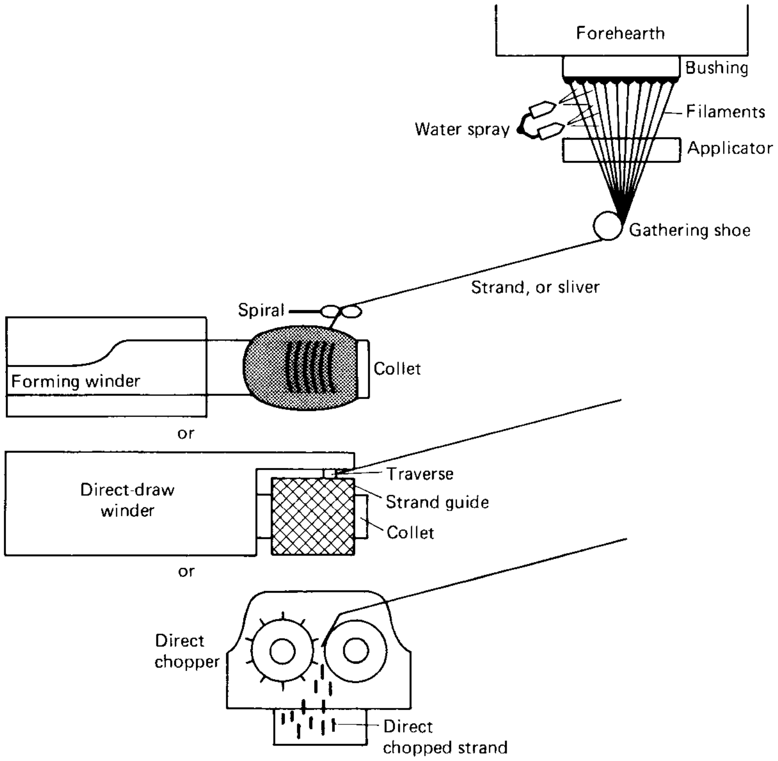

Fig. 3 Fiberglass forming process

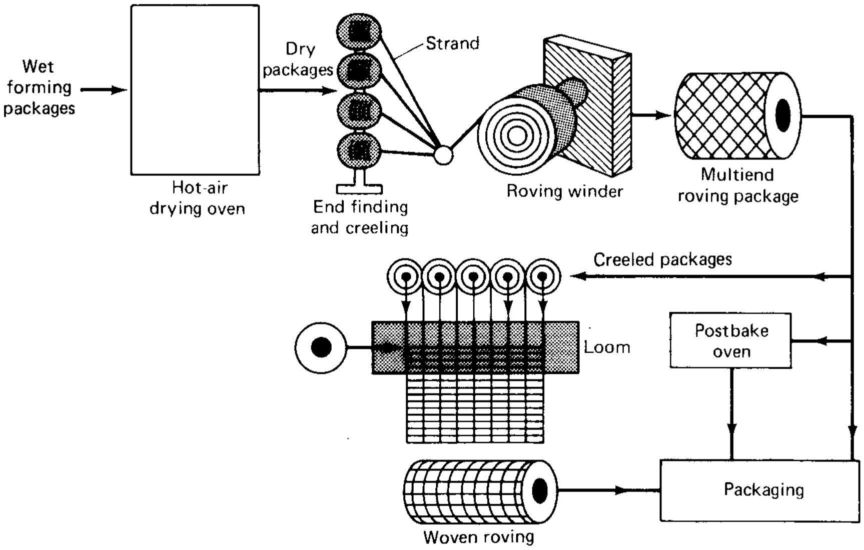

Fig. 4 Multiend roving process production

Important Commercial Products

Once the continuous glass fibers have been produced they must be converted into a suitable product form for their intended composite application. The major finished forms for E-glass fibers are continuous roving, woven roving, fiberglass mat, chopped strand, and yarns for textile applications.

Fiberglass roving is produced by collecting a bundle of strands into a single large strand, which is wound into a stable, cylindrical package. This is called a multiend roving process. The process begins by placing a number of oven-dried forming packages into a creel. The ends are then gathered together under tension and collected on a precision roving winder that has a constant traverse-to-winding ratio, and is called the waywind. This ratio has a significant effect on package stability, strand characteristics, and ease of payout in subsequent operations. The yield (meter per kilogram, or yard per pound) of the finished roving is determined by the number of input ends and the yield of the input strand or sliver. Final package weight and dimensions can be made to vary widely, depending upon the required end-use. Figure 4 shows the entire process.

Rovings are used in many applications. When used in a spray-up fabrication process, the roving is chopped with an air-powered gun that propels the chopped-glass strands to a mold while simultaneously applying resin and catalyst in the compact ratio. This process is commonly used for bath tubs, shower stalls, and many marine applications. In another important process, the production of sheet molding compound (SMC), the roving is chopped onto a bed of formulated polyester resin and compacted into a sheet, which thickens with time. This sheet is then placed in a press and molded into parts. Many fiber-reinforced plastic (FRP) automotive body panels are made by this process.

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Filament winding and pultrusion are processes that use single-end rovings in continuous form. Applications include pipes, tanks, leaf springs, and many other structural composites. In these processes the roving is passed through a liquid resin bath and then shaped into a part by winding the resin-impregnated roving onto a mandrel or by pulling it through a heated die. Because of a property called *catenary* (the presence of some strands that have a tendency to sag within a bundle of strands), multiend rovings sometimes do not process efficiently. Catenary is caused by uneven tension in the roving process that results in poor strand integrity.

While providing desirable entanglement for transverse strength in pultrusion, the looser ends in the roving may eventually cause loops and breakouts in close-tolerance orifices, making reinforced plastics processing difficult. Consequently, the process of direct forming single-end rovings was developed by using very large bushings and a precision winder specially designed to operate in the severe forming environment. No subsequent step other than drying is required. Single-end rovings have become the preferred product for many filament-winding and pultrusion applications.

Woven roving is produced by weaving fiberglass rovings into a fabric form. This yields a coarse product that is used in many hand lay-up and panel molding processes to produce FRPs. Many weave configurations are available, depending on the requirements of the laminate. Plain or twill weaves provide strength in both directions, while a unidirectionally stitched or knitted fabric provides strength primarily in one dimension. Many novel fabrics are currently available, including biaxial, double-bias, and triaxial weaves for special applications.

Fiberglass mats may be produced as either continuous- or chopped-strand mats. A chopped-strand mat is formed by randomly depositing chopped fibers onto a belt or chain and binding them with a chemical binder, usually a thermoplastic resin with a styrene solubility ranging from low to high, depending on the application. For example, hand lay-up processes used to moderate corrosion-resistant liners or boat hulls require high solubility, whereas closed-mold processes such as cold press or compression molding require low solubility to prevent washing in the mold during curing.

Table 3 Filament diameter nomenclature

	Filament diameter	
Alphabet	μm	10^{-4} in.
AA	0.8–1.2	0.3–0.5
A	1.2–2.5	0.5–1.0
B	2.5–3.8	1.0–1.5
C	3.8–5.0	1.5–2.0
D	5.0–6.4	2.0–2.5
E	6.4–7.6	2.5–3.0
F	7.6–9.0	3.0–3.5
G	9.0–10.2	3.5–4.0
H	10.2–11.4	4.0–4.5
J	11.4–12.7	4.5–5.0
K	12.7–14.0	5.0–5.5
L	14.0–15.2	5.5–6.0
M	15.2–16.5	6.0–6.5
N	16.5–17.8	6.5–7.0
P	17.8–19.0	7.0–7.5
Q	19.0–20.3	7.5–8.0
R	20.3–21.6	8.0–8.5
S	21.6–22.9	8.5–9.0
T	22.9–24.1	9.0–9.5
U	24.1–25.4	9.5–10

Continuous-strand mat is formed in a similar manner but without chopping, and, usually, less binder is required because of increased mechanical entanglement, which provides some inherent integrity. Continuous-strand mat may be used in closed mold processes and as a supplemental product in unidirectional processes such as pultrusion, where some transverse strength is required. A number of specialty mats are also produced. Surfacing veil made with C-glass is used to make corrosion-resistant liners for pipes and tanks. Surfacing veils made from other glass compositions are used to provide a smooth finished surface in some applications. Glass tissue is used in some vinyl flooring products.

Combinations of a mat and woven roving have been developed for specific products in recent years. In many lay-up processes the laminate is constructed from alternate layers of fiberglass mat and woven roving. Fiberglass producers thus began to provide products that make this process more efficient. The appropriate weights of fiberglass mat (usually chopped-strand mat) and woven roving are either bound together with a chemical binder or mechanically knit or stitched together. This product can then be used as a significant labor saver by the fabricators.

Chopped strand products are produced by two major processes. In the first process, dried forming packages are used as a glass source. A number of strand ends are fed into a chopper, which chops them into the correct length, typically 3.2 to 12.7 mm ($\frac{1}{8}$ to $\frac{1}{2}$ in.). The product is then screened to remove fuzz and contamination and boxed for shipment (Fig. 5). The second process, used in recent years to produce many chopped-strand products, is the direct-chop process. In this process, large bushings are used in forming, and the strands are chopped in a wet state directly after sizing is applied. The wet, chopped strands are then transported to an area where they are dried, screened, and packaged. The direct-chop process has provided the industry with a wide variety of chopped reinforcements for compounding with resins.

Chopped glass is widely used as a reinforcement in the injection molding industry. The glass and resin may be dry blended or extrusion compounded in a preliminary step before molding, or the glass may be fed directly into the molding machine with the plastic resin. Hundreds of different parts for many applications are made in this manner. Chopped glass may also be used as a reinforcement in some thermosetting applications, such as bulk molding compounds.

Milled fibers are prepared by hammer milling chopped or sawed continuous strand glass fibers, followed by chemically sizing for some specific applications and by screening to length. Fiber lengths typically vary from particulates to screen opening dimensions for the reported nominal length (0.79 to 6.4 mm, or $\frac{1}{32}$ to $\frac{1}{4}$ in.). As such, milled fibers have a relatively low aspect ratio (length to diameter). They provide some increased stiffness and dimensional stability to plastics but minimal strength. Their use is primarily in phenolics, reaction-injection molded urethanes, fluorocarbons, and potting compounds.

Fiberglass paper is the reinforcing element for fiberglass roofing shingles. Chopped strands of 25 to 50 mm (1 to 2 in.) length are usually used in making fiberglass paper or a thin fiberglass mat. In this process, chopped fibers are dispersed in water to form a dilute solution. The fiberglass strands filamentize during the mixing and dispersion process. The solution is pumped onto a continuously moving chain, where most of the water is removed by vacuum, leaving behind a uniformly distributed, thin fiberglass mat. A binding resin is added on-line, followed by drying and curing, to form the fiberglass paper. This paper is then combined with the appropriate resin system to form roofing shingles.

Textile yarns are fine-fiber strands of yarn from the forming operation that are air dried on the forming tubes to provide sufficient integrity to undergo a twisting operation. Twist provides additional integrity to yarn before it is subjected to the weaving process, a typical twist consisting

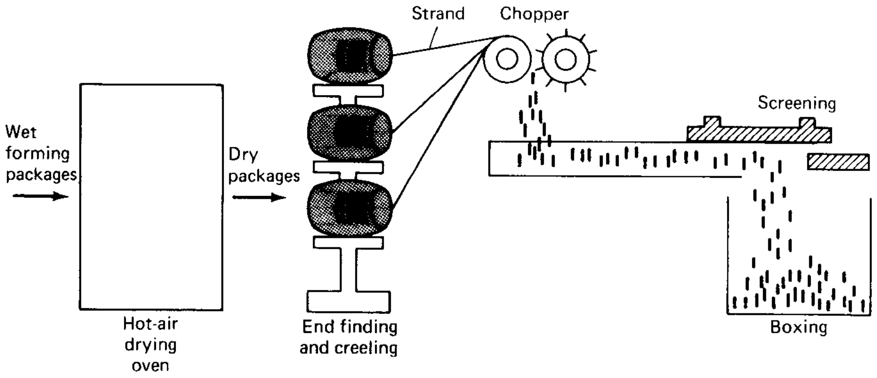

Fig. 5 Chopped-strand production

of up to one turn per inch. The twisting operation is shown in Fig 6. In many instances, heavier yarns are needed for the weaving operation. This is normally accomplished by twisting together two or more single strands, followed by a plying operation. Plying essentially involves retwisting the twisted strands in the opposite direction from the original twist. The two types of twist normally used are known as S and Z, which indicate the direction in which the twisting is done. Usually, two or more strands twisted together with an S twist are plied with a Z twist in order to give a balanced yarn. Thus, the yarn properties, such as strength, bundle diameter, and yield, can be manipulated by the twisting and plying operations.

The yarn nomenclature for fiberglass yarns consists of both letters of the alphabet and numbers. For instance, in ECG 75 2/4:

- The first letter specifies the glass composition, in this case, E-glass.
- The second letter specifies the filament type (staple, continuous, texturized) (in the case, of ECG 75 2/4, continuous).
- The third letter specifies the filament diameter (in this case, G).
- The next series of numbers represents the basic strand yield in terms of $\frac{1}{100}$ th of the yield (in this case, 75 means 7500 yd/lb).
- The fraction represents the number of strands twisted together (numerator) to form a single end and the number of such ends plied together (denominator) to form the final yarn. In the above case, 2/4 means two basic strands are twisted together to form a single end, and four such ends are plied together (usually in the opposite direction) to form the final yarn.

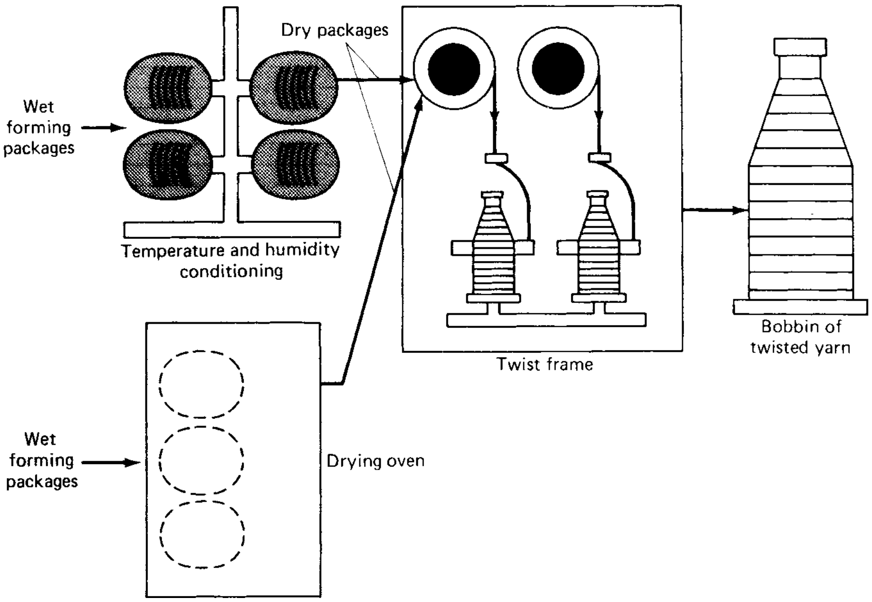

Fig. 6 Twisting

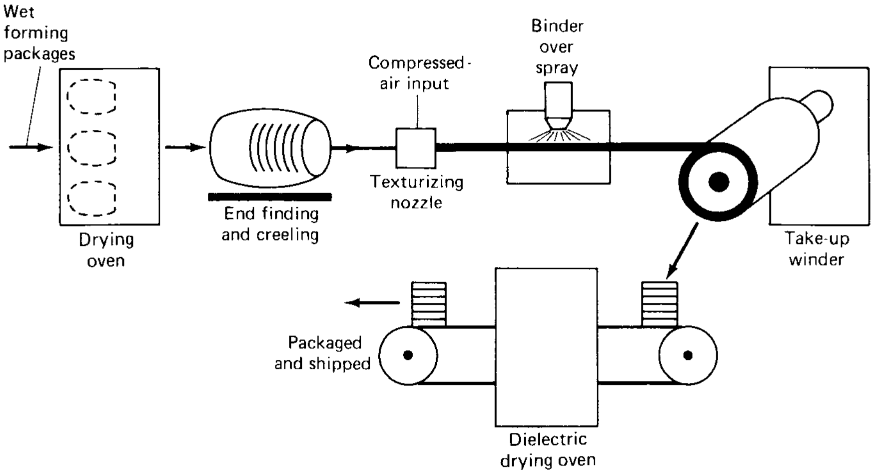

Fig. 7 Texturizing

The product brochures from various weavers as well as to Ref 4 should be consulted for details on commercially available fabrics. The *Glass-Fibre Dictionary and Databook* (Ref 14) should be consulted for even greater detail and/or for a summary of all commercially available yarns.

Fiberglass Fabric. Fiberglass yarns are converted to fabric form by conventional weaving operations. Looms of various kinds are used in the industry, but the air jet loom is the most popular. The major characteristics of a fabric include its style or weave pattern, fabric count, and the construction of warp yarn and fill yarn. Together, these characteristics determine fabric properties such as drapability and performance in the final composite. The fabric count identifies the number of warp and fill yarns per inch. Warp yarns run parallel to the machine direction, and fill yarns are perpendicular.

There are basically four weave patterns: plain, basket, twill, and satin. Plain weave is the simplest form, in which one warp yarn interlaces over and under one fill yarn. Basket weave has two or more warp yarns interlacing over and under two or more fill yarns. Twill weave has one or more warp yarns floating over at least two fill yarns. Satin weave (crowfoot) consists of one warp yarn interfacing over three and under one fill yarn to give an irregular pattern in the fabric. The eight-harness satin weave is a special case, in which one warp yarn interlaces over seven and under one fill yarn to give an irregular pattern. In fabricating a composite part, the satin weave gives the best conformity to complex contours, followed in descending order by twill, basket, and plain weaves.

Texturized Yarn. Texturizing is a process in which the textile yarn is subjected to an air jet that impinges on its surface to make the yarn "fluffy" (Fig. 7). The air jet causes the surface filaments to break at random, giving the yarn a bulkier appearance. The extent to which this occurs can be controlled by the velocity of the air jet and the yarn feed rate. The texturizing process allows the resin-to-glass ratio to be increased in the final composite. One of the major applications of texturized yarns is as an asbestos replacement.

Carded Glass Fibers. Carding is a process that makes a staple fiberglass yarn from continuous yarn. The continuous yarn is chopped into 38 to 50 mm (1.5 to 2.0 in.) lengths, and then aligned in one direction in a mat form. It is finally converted to a staple yarn. The yarn produced by this process can absorb much more resin than texturized yarn. Carded glass fibers are also used as an asbestos replacement in friction applications, such as automotive brake linings.

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