12 Glassworking

Chapter Contents

Glass products are commercially manufactured in an almost unlimited variety of shapes. Many are produced in very large quantities, such as light bulbs, beverage bottles, and window glass. Others, such as giant telescope lenses, are made individually.

Glass is one of three basic types of ceramics (Chapter 7). It is distinguished by its noncrystalline (vitreous) structure, whereas the other ceramic materials have a crystalline structure. The methods by which glass is shaped into useful products are quite different from those used for the other types. In glassworking, the principal starting material is silica (SiO_2); this is usually combined with other oxide ceramics that form glasses. The starting material is heated to transform it from a hard solid into a viscous liquid; it is then shaped into the desired geometry while in this highly plastic or fluid condition. When cooled and hard, the material remains in the glassy state rather than crystallizing.

The typical manufacturing sequence in glassworking consists of the steps pictured in Figure 12.1. Shaping is accomplished by various processes, including casting, pressing-and-blowing (to produce bottles and other containers), and rolling (to make plate glass). A finishing step is required for certain products.

12.1 Raw Materials Preparation and Melting

The main component in nearly all glasses is silica, the primary source of which is natural quartz in sand. The sand must be washed and classified. Washing removes impurities such as clay and certain minerals that would cause undesirable coloring of the glass. ***Classifying*** the sand means grouping the grains according to size. The most desirable particle size for glassmaking is in the range of 0.1 to 0.6 mm (0.004–0.025 in) [3]. The various other components, such as soda ash (source of Na_2O), limestone (source of CaO), aluminum oxide, potash

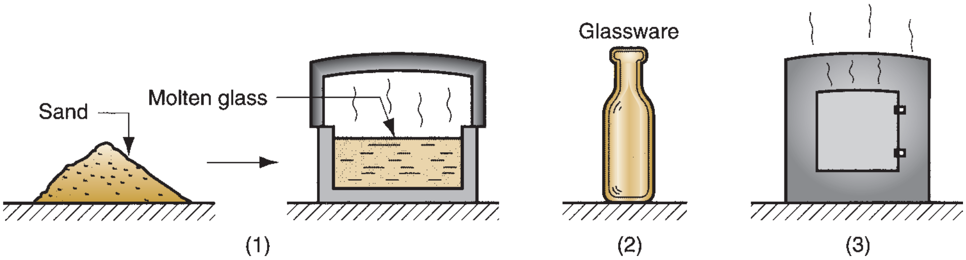

FIGURE 12.1 The typical process sequence in glassworking: (1) preparation of raw materials and melting, (2) shaping, and (3) heat treatment.

(source of K_2O), and other minerals are added in the proper proportions to achieve the desired composition. The mixing is usually done in batches, in amounts that are compatible with the capacities of available melting furnaces.

Recycled glass is usually added to the mixture in modern practice. In addition to preserving the environment, recycled glass facilitates melting. Depending on the amount of waste glass available and the specifications of the final composition, the proportion of recycled glass may be up to 100%.

The batch of starting materials to be melted is referred to as a ***charge***, and the procedure of loading it into the melting furnace is called ***charging*** the furnace. Glass-melting furnaces can be divided into the following types [3]: (1) ***pot furnaces***—ceramic pots of limited capacity in which melting occurs by heating the walls of the pot; (2) ***day tanks***—larger capacity vessels for batch production in which heating is done by burning fuels above the charge; (3) ***continuous tank furnaces***—long tank furnaces in which raw materials are fed in one end, and melted as they move to the other end where molten glass is drawn out for high production; and (4) ***electric furnaces*** of various designs for a wide range of production rates.

Glass melting is generally carried out at temperatures around 1500°C to 1600°C (2700°F–2900°F). The melting cycle for a typical charge takes 24 to 48 hours. This is the time required for all of the sand grains to become a clear liquid and for the molten glass to be refined and cooled to the appropriate temperature for working. Molten glass is a viscous liquid, the viscosity being inversely related to temperature. Because the shaping operation immediately follows the melting cycle, the temperature at which the glass is tapped from the furnace depends on the viscosity required for the subsequent process.

2.2 Shaping Processes in Glassworking

The major categories of glass products were identified in Section 7.4.2 as window glass, containers, light bulbs, laboratory glassware, glass fibers, and optical glass. Despite the variety represented by this list, the shaping processes to fabricate these products can be grouped into only three categories: (1) discrete processes for piece ware, which includes bottles, light bulbs, and other individual items; (2) continuous processes for making flat glass (sheet and plate glass for windows) and tubing (for laboratory ware and fluorescent lights); and (3) fiber-making processes to produce fibers for insulation, fiberglass composite materials, and fiber optics.

12.2.1 SHAPING OF PIECE WARE

The ancient methods of hand-working glass, such as glass blowing, were briefly described in Historical Note 7.3. Handicraft methods are still employed today for making glassware items of high value in small quantities. Most of the processes

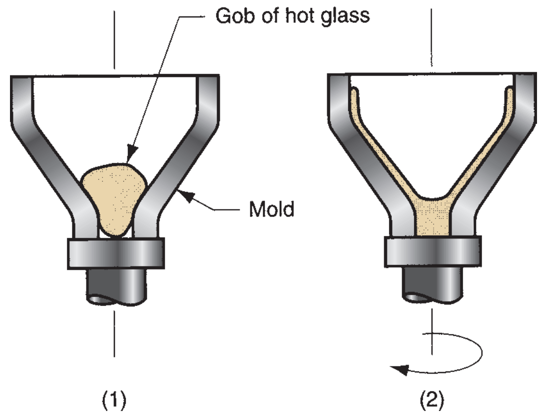

FIGURE 12.2 Spinning of funnel-shaped glass parts: (1) gob of glass dropped into mold; and (2) rotation of mold to cause spreading of molten glass on mold surface.

discussed in this section are highly mechanized technologies for producing discrete pieces such as jars, bottles, and light bulbs in high quantities.

Spinning Glass spinning is similar to ***centrifugal casting*** of metals, and is also known by that name in glassworking. It is used to produce funnel-shaped components such as the back sections of cathode ray tubes for televisions and computer monitors. The setup is pictured in Figure 12.2. A gob of molten glass is dropped into a conical mold made of steel. The mold is rotated so that centrifugal force causes the glass to flow upward and spread itself on the mold surface. The faceplate (i.e., the front viewing screen) is later assembled to the funnel using a sealing glass of low melting point.

Pressing This is a widely used process for mass producing glass pieces such as dishes, bake ware, headlight lenses, TV tube faceplates, and similar items that are relatively flat. The process is illustrated and described in Figure 12.3. The large quantities of most pressed products justify a high level of automation in this production sequence.

Blowing Several shaping sequences include blowing as one or more of the steps. Instead of a manual operation, blowing is performed on highly automated equipment. The two sequences described here are the press-and-blow and blow-and-blow methods.

As the name indicates, the ***press-and-blow*** method is a pressing operation followed by a blowing operation, as portrayed in Figure 12.4. The process is suited to

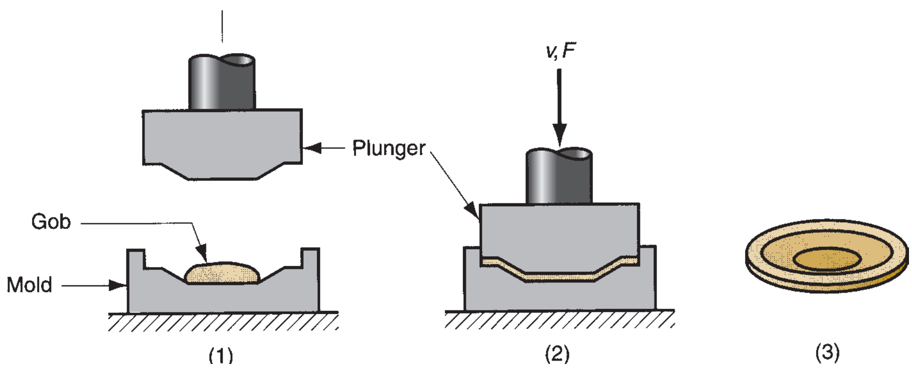

FIGURE 12.3 Pressing of a flat glass piece: (1) a gob of glass fed into mold from the furnace; (2) pressing into shape by plunger; and (3) plunger is retracted and the finished product is removed. Symbols v and F indicate motion (v = velocity) and applied force, respectively.

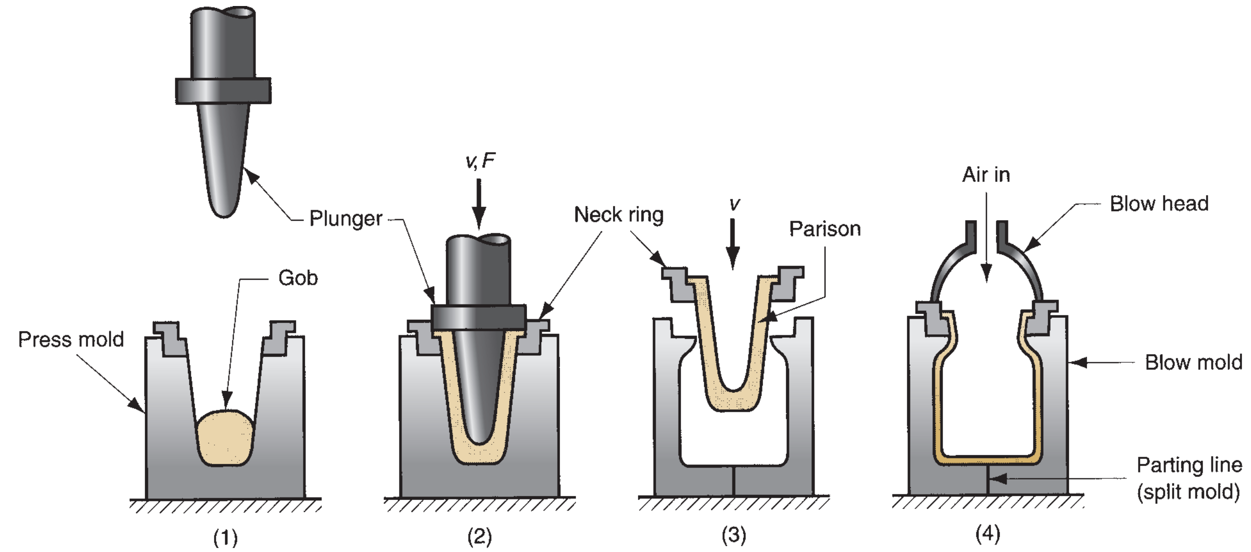

FIGURE 12.4 Press-and-blow forming sequence: (1) molten gob is fed into mold cavity; (2) pressing to form a ***parison***; (3) the partially formed parison, held in a neck ring, is transferred to the blow mold; and (4) blown into final shape. Symbols v and F indicate motion (v = velocity) and applied force, respectively.

the production of wide-mouth containers. A split mold is used in the blowing operation for part removal.

The ***blow-and-blow*** method is used to produce smaller-mouthed bottles. The sequence is similar to the preceding, except that two (or more) blowing operations are used rather than pressing and blowing. There are variations to the process, depending on the geometry of the product, with one possible sequence shown in Figure 12.5.

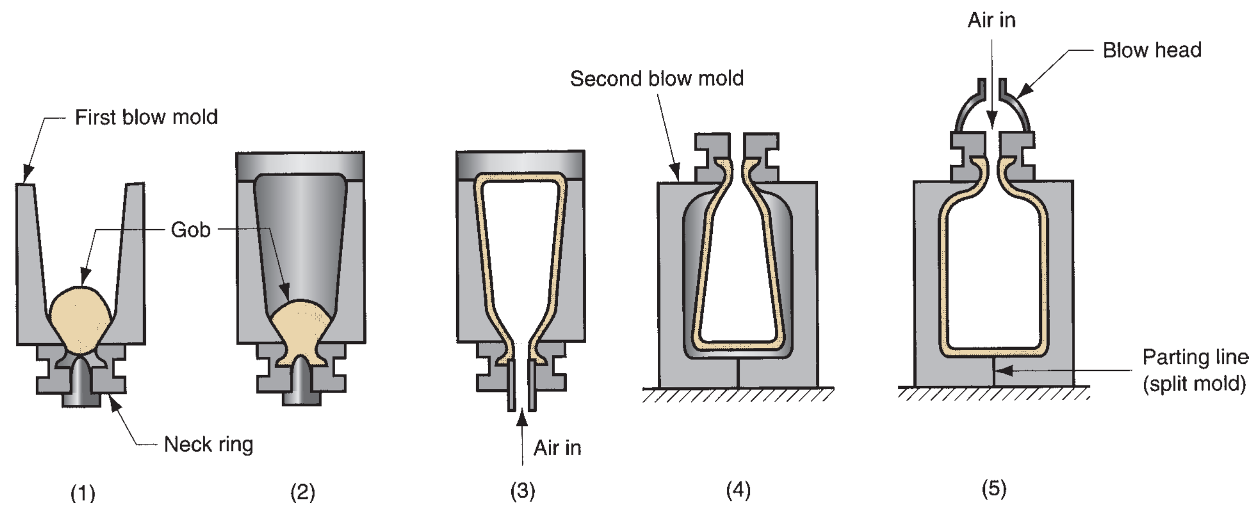

FIGURE 12.5 Blow-and-blow forming sequence: (1) gob is fed into inverted mold cavity; (2) mold is covered; (3) first blowing step; (4) partially formed piece is reoriented and transferred to second blow mold; and (5) blown to final shape.

Reheating is sometimes required between blowing steps. Duplicate and triplicate molds are sometimes used along with matching gob feeders to increase production rates. Press-and-blow and blow-and-blow methods are used to make jars, beverage bottles, incandescent light bulb enclosures, and similar geometries.

Casting If the molten glass is sufficiently fluid, it can be poured into a mold. Relatively massive objects, such as astronomical lenses and mirrors, are made by this method. These pieces must be cooled very slowly to avoid internal stresses and possible cracking owing to temperature gradients that would otherwise be set up in the glass. After cooling and solidifying, the piece must be finished by lapping and polishing. Casting is not much used in glassworking except for these kinds of special jobs. Not only is cooling and cracking a problem, but also molten glass is relatively viscous at normal working temperatures, and does not flow through small orifices or into small sections as well as molten metals or heated thermoplastics. Smaller lenses are usually made by pressing, discussed above.

12.2.2 SHAPING OF FLAT AND TUBULAR GLASS

Two methods for making plate glass and one method for producing tube stock are described here. They are continuous processes, in which long sections of flat window glass or glass tubing are made and later cut into appropriate sizes and lengths. They are modern technologies in contrast to the ancient method described in Historical Note 12.1.

Historical Note 12.1 *Ancient methods of making flat glass* (7)

Glass windows have been used in buildings for many centuries. The oldest process for making flat window glass was by manual glass blowing. The procedure consisted of the following: (1) a glass globe was blown on a blowpipe; (2) a portion of the globe was made to stick to the end of a "punty," a metal rod used by glassblowers, and then detached from the blowpipe; and (3) after reheating the glass, the punty was rotated with sufficient speed for centrifugal force to shape the open globe into a flat disk. The disk, whose maximum possible size was only about 1 m (3 ft), was later cut into small panes for windows.

At the center of the disk, where the glass was attached to the punty during the third step in the process, a lump would tend to form that had the appearance of a crown. The name "crown glass" was derived from this resemblance. Lenses for spectacles were ground from glass made by this method. Today, the name crown glass is still used for certain types of optical and ophthalmic glass, even though the ancient method has been replaced by modern production technology.

Rolling of Flat Plate Flat plate glass can be produced by rolling, as illustrated in Figure 12.6. The starting glass, in a suitably plastic condition from the furnace, is squeezed through opposing rolls whose separation determines the thickness of the sheet. The rolling operation is usually set up so that the flat glass is moved directly into an annealing furnace. The rolled glass sheet must later be ground and polished for parallelism and smoothness.

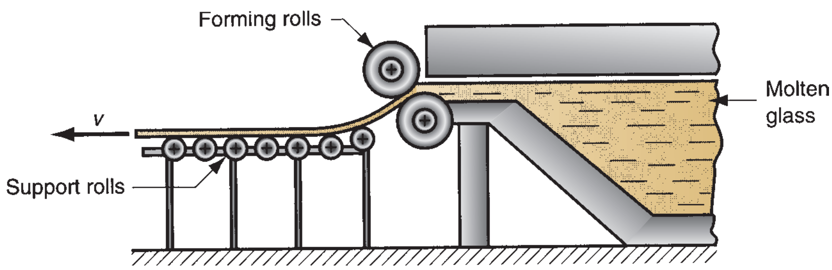

FIGURE 12.6 Rolling of flat glass.

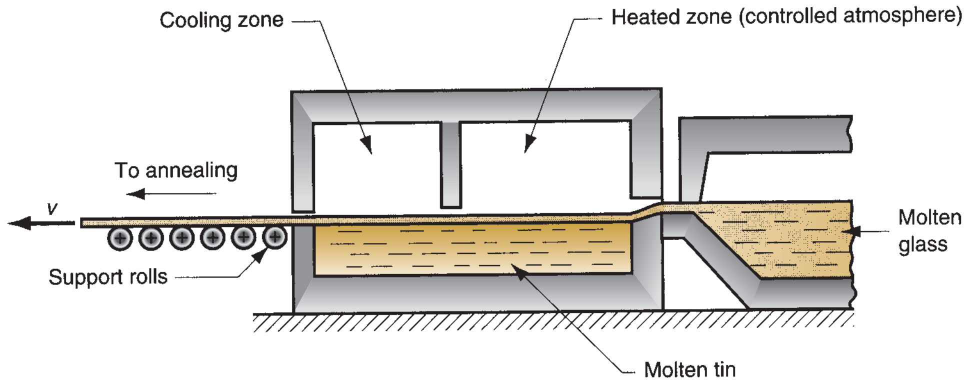

FIGURE 12.7 The float process for producing sheet glass.

Float Process This process was developed in the late 1950s. Its advantage over other methods such as rolling is that it obtains smooth surfaces that need no subsequent finishing. In the ***float process***, illustrated in Figure 12.7, the glass flows directly from its melting furnace onto the surface of a molten tin bath. The highly fluid glass spreads evenly across the molten tin surface, achieving a uniform thickness and smoothness. After moving into a cooler region of the bath, the glass hardens and travels through an annealing furnace, after which it is cut to size.

Drawing of Glass Tubes Glass tubing is manufactured by a drawing process known as the ***Danner process***, illustrated in Figure 12.8. Molten glass flows around a rotating hollow mandrel through which air is blown while the glass is being drawn. The air temperature and its volumetric flow rate, as well as the drawing velocity,

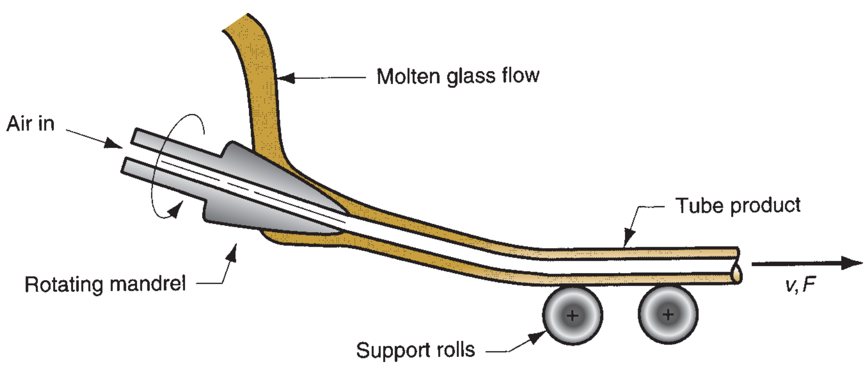

FIGURE 12.8 Drawing of glass tubes by the Danner process. Symbols v and F indicate motion (v = velocity) and applied force, respectively.

determine the diameter and wall thickness of the tubular cross section. During hardening, the glass tube is supported by a series of rollers extending about 30 m (100 ft) beyond the mandrel. The continuous tubing is then cut into standard lengths. Tubular glass products include laboratory glassware, fluorescent light tubes, and thermometers.

12.2.3 FORMING OF GLASS FIBERS

Glass fibers are used in applications ranging from insulation wool to fiber optics communications lines (Section 7.4.2). Glass fiber products can be divided into two categories [6]: (1) fibrous glass for thermal insulation, acoustical insulation, and air filtration, in which the fibers are in a random, wool-like condition; and (2) long, continuous filaments suitable for fiber-reinforced plastics, yarns and fabrics, and fiber optics. Different production methods are used for the two categories. Two methods are described in the following paragraphs, representing each of the product categories, respectively.

Centrifugal Spraying In a typical process for making glass wool, molten glass flows into a rotating bowl with many small orifices around its periphery. Centrifugal force causes the glass to flow through the holes to become a fibrous mass suitable for thermal and acoustical insulation.

Drawing of Continuous Filaments In this process, illustrated in Figure 12.9, continuous glass fibers of small diameter (lower size limit is around 0.0025 mm or 0.0001 in) are produced by drawing strands of molten glass through small orifices in

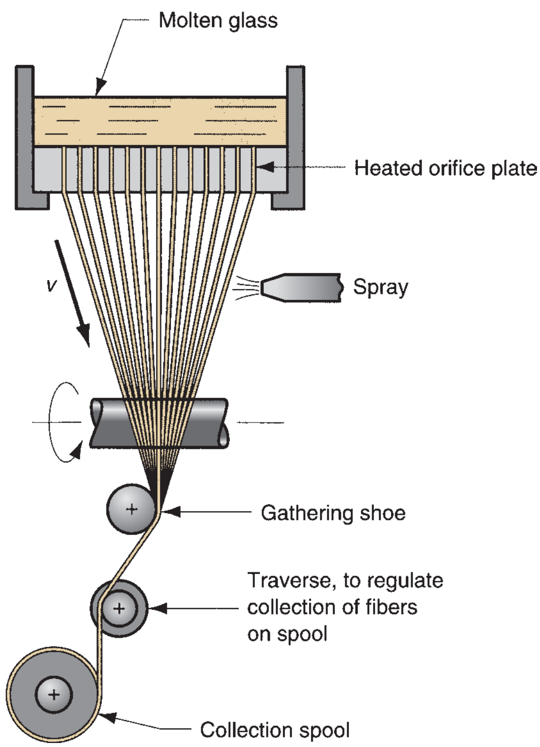

FIGURE 12.9 Drawing of continuous glass fibers.

a heated plate made of a platinum alloy. The plate may have several hundred holes, each making one fiber. The individual fibers are collected into a strand by reeling them onto a spool. Before spooling, the fibers are coated with various chemicals to lubricate and protect them. Drawing speeds of around 50 m/s (10,000 ft/min) or more are not unusual.

2.3 Heat Treatment and Finishing

Heat treatment of the glass product is the third step in the glassworking sequence. For some products, additional finishing operations are performed.

12.3.1 HEAT TREATMENT

Glass-ceramics were discussed in Section 7.4.3. This unique material is made by a special heat treatment that transforms most of the vitreous state into a polycrystalline ceramic. Other heat treatments performed on glass cause changes that are less dramatic technologically but perhaps more important commercially; examples include annealing and tempering.

Annealing Glass products usually have undesirable internal stresses after forming, which reduce their strength. Annealing is done to relieve these stresses; the treatment therefore has the same function in glassworking as it does in metalworking. ***Annealing*** involves heating the glass to an elevated temperature and holding it for a certain period to eliminate stresses and temperature gradients, then slowly cooling the glass to suppress stress formation, followed by more rapid cooling to room temperature. Common annealing temperatures are around 500°C (900°F). The length of time the product is held at the temperature, as well as the heating and cooling rates during the cycle, depend on thickness of the glass, the usual rule being that the required annealing time varies with the square of thickness.

Annealing in modern glass factories is performed in tunnel-like furnaces, called ***lehrs***, in which the products flow slowly through the hot chamber on conveyors. Burners are located only at the front end of the chamber, so that the glass experiences the required heating and cooling cycle.

Tempered Glass and Related Products A beneficial internal stress pattern can be developed in glass products by a heat treatment known as ***tempering***, and the resulting material is called ***tempered glass***. As in the treatment of hardened steel, tempering increases the toughness of glass. The process involves heating the glass to a temperature somewhat above its annealing temperature and into the plastic range, followed by quenching of the surfaces, usually with air jets. When the surfaces cool, they contract and harden while the interior is still plastic and compliant. As the internal glass slowly cools, it contracts, thus putting the hard surfaces in compression. Like other ceramics, glass is much stronger when subjected to compressive stresses than tensile stresses. Accordingly, tempered glass is much more resistant to scratching and breaking because of the compressive stresses on its surfaces. Applications include windows for tall buildings, all-glass doors, safety glasses, and other products requiring toughened glass.

When tempered glass fails, it does so by shattering into numerous small fragments that are less likely to cut someone than conventional (annealed) window glass. Interestingly, automobile windshields are not made of tempered glass, because of the danger posed to the driver by this fragmentation. Instead, conventional glass is used; however, it is fabricated by sandwiching two pieces of glass on either side of a tough polymer sheet. Should this ***laminated glass*** fracture, the glass splinters are retained by the polymer sheet and the windshield remains relatively transparent.

12.3.2 FINISHING

Finishing operations are sometimes required for glassware products. These secondary operations include grinding, polishing, and cutting. When glass sheets are produced by drawing and rolling, the opposite sides are not necessarily parallel, and the surfaces contain defects and scratch marks caused by the use of hard tooling on soft glass. The glass sheets must be ground and polished for most commercial applications. In pressing and blowing operations when split dies are used, polishing is often required to remove the seam marks from the container product.

In continuous glassworking processes, such as plate and tube production, the continuous sections must be cut into smaller pieces. This is accomplished by first scoring the glass with a glass-cutting wheel or cutting diamond and then breaking the section along the score line. Cutting is generally done as the glass exits the annealing lehr.

Decorative and surface processes are performed on certain glassware products. These processes include mechanical cutting and polishing operations; sandblasting; chemical etching (with hydrofluoric acid, often in combination with other chemicals); and coating (for example, coating of plate glass with aluminum or silver to produce mirrors).

12.4 Product Design Considerations

Glass possesses special properties that make it desirable in certain applications. The following design recommendations are compiled from Bralla [1] and other sources.

- Glass is transparent and has certain optical properties that are unusual if not unique among engineering materials. For applications requiring transparency, light transmittance, magnification, and similar optical properties, glass is likely to be the material of choice. Certain polymers are transparent and may be competitive, depending on design requirements.
- Glass is several times stronger in compression than in tension; components should be designed so that they are subjected to compressive stresses, not tensile stresses.
- Ceramics, including glass, are brittle. Glass parts should not be used in applications that involve impact loading or high stresses which might cause fracture.
- Certain glass compositions have very low thermal expansion coefficients and are therefore tolerant of thermal shock. These glasses can be selected for applications in which this characteristic is important (e.g., cookware).
- Outside edges and corners on glass parts should have large radii or chamfers; likewise, inside corners should have large radii. Both outside and inside corners are potential points of stress concentration.
- Unlike parts made of traditional and new ceramics, threads may be included in the design of glass parts; they are technically feasible with the press-and-blow shaping processes. However, the threads should be coarse.