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Glass Science

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3.1 Introduction

The glass has been used as an engineering material since ancient times. But because of the rapid progress made in the glass industry in recent times, the glass has come out as the most versatile engineering material of the modern times. The first glass objects made by man were of natural glass such as obsidian and rock crystal.

Glass refers to an amorphous, or noncrystalline, structure of a solid material. The glassy state occurs in a material when insufficient time is allowed during cooling from the molten condition for the crystalline structure to form. It turns out that all three categories of engineering materials (metals, ceramics, and polymers) can assume the glassy state, although the circumstances for metals to do so are quite rare.

Glass is an inorganic, nonmetallic compound (or mixture of compounds) that cools to a rigid condition without crystallizing; it is a ceramic that is in the glassy state as a solid material.

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. 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.

3.2 Glass Compositions and Properties

The principal ingredient in virtually all glasses is silica (SiO_2), most commonly found as the mineral quartz in sandstone and silica sand. Quartz occurs naturally as a crystalline substance; but when melted and then cooled, it forms vitreous silica. Silica glass has a very low thermal expansion coefficient and is therefore quite resistant to thermal shock. These properties are ideal for elevated temperature applications; accordingly, Pyrex and chemical glassware designed for heating are made with high proportions of silica glass.

In order to reduce the melting point of glass for easier processing, and to control properties, the composition of most commercial glasses includes other oxides as well as silica. Silica remains as the main component in these glass products, usually comprising 50% to 75% of total chemistry.

The reason SiO_2 is used so widely in these compositions is because it is the best glass former. It naturally transforms into a glassy state upon cooling from the liquid, whereas most ceramics crystallize upon solidification.

Table 3.1 lists typical chemistries for some common glasses. The additional ingredients are contained in a solid solution with SiO_2 , and each has a function:

- (1) acting as flux (promoting fusion) during heating;
- (2) increasing fluidity in the molten glass for processing;
- (3) retarding devitrification—the tendency to crystallize from the glassy state;
- (4) reducing thermal expansion in the final product;
- (5) improving the chemical resistance against attack by acids, basic substances, or water;
- (6) adding color to the glass; and
- (7) altering the index of refraction for optical applications (e.g., lenses).

Table 3.1 - Typical compositions of selected glass products.

Product	Chemical Composition (by weight to nearest %)								
	SiO ₂	Na ₂ O	CaO	Al ₂ O ₃	MgO	K ₂ O	PbO	Bi ₂ O ₃	Other
Soda-lime glass	71	14	13	2					
Window glass	72	15	8	1	4				
Container glass	72	13	10	2	2	1			
Light bulb glass	73	17	5	1	4				
Laboratory glass:									
Vycor	96			1				3	
Pyrex	81	4		2				13	
E-glass (fibers)	54	1	17	15	4			9	
S-glass (fibers)	64			26	10				
Optical glasses:									
Crown glass	67	8				12		12	ZnO
Flint glass	46	3				6	45		

3.3 Raw Materials, Preparation and Melting of Glass

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. The various other components, such as soda ash (source of Na₂O), limestone (source of CaO), aluminum oxide, potash (source of K₂O), 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.

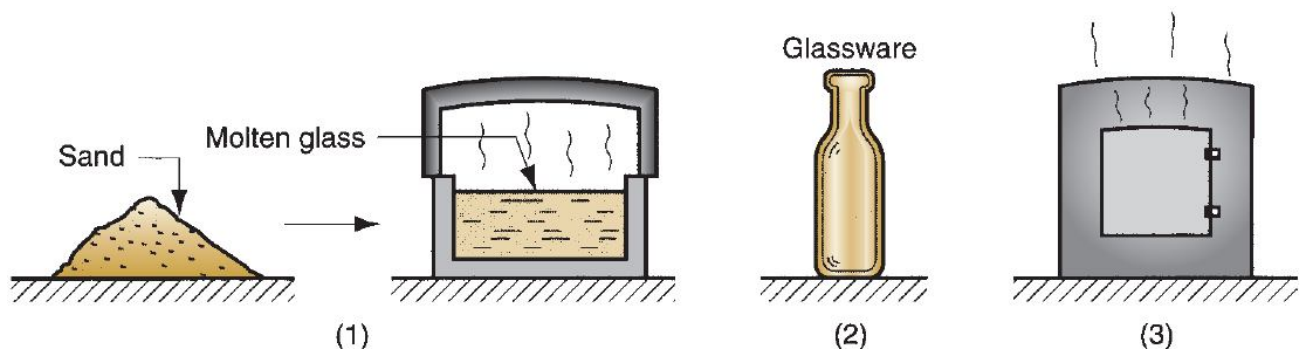


Fig.3.1 - The typical process sequence in glassworking
 (1) preparation of raw materials and melting, (2) shaping, and (3) heat treatment.

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. Glassmelting furnaces can be divided into the following types:

- (1) **Pot furnaces**—ceramic pots of limited capacity in which melting occurs by heating the walls of the pot;
- (2) **Tank furnaces**—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. 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.

3.4 Properties of Glass

The main characteristics of glass are transparency, heat resistance, pressure and breakage resistance and chemical resistance. Properties of glass are given below:

- ▶ **Mechanical Properties**
 - Density
 - Hardness
 - Compression resistance
 - Modulus of elasticity
 - Bending strength
- ▶ **Thermal Properties**
 - Transformation range
 - Temp&Softening temperature
 - Specific Heat
 - Thermal conductivity
 - Thermal expansion
- ▶ **Optical Properties**
 - Refractive index
- ▶ **Technical Properties**
 - Chemical resistance against water, acid and alkaline
 - Wear resistance

3.5 Shaping Processes of Glass

The shaping processes to fabricate the glass 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.

3.5.1 Shaping of Piece Ware

Most of the processes 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 *Fig.3.2*. 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.

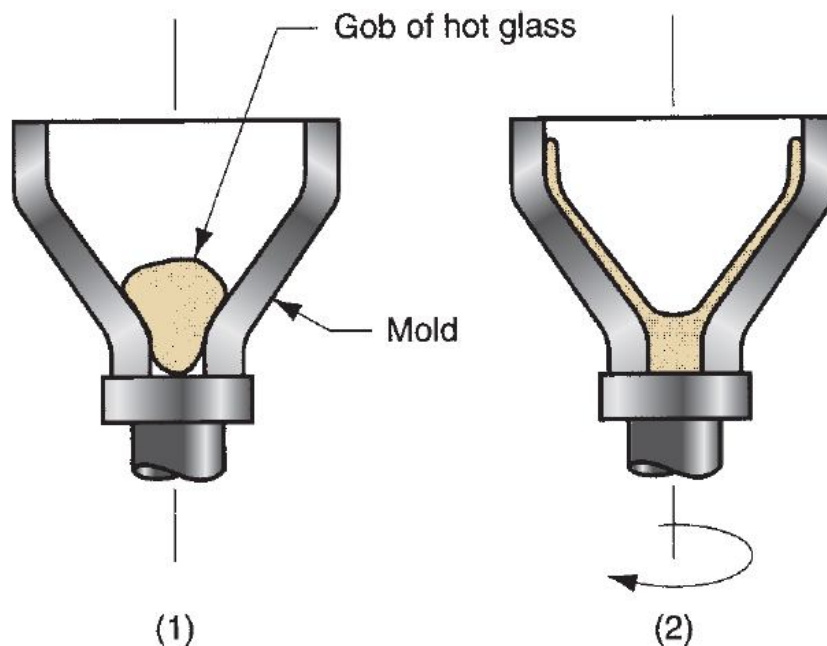


Fig.3.2 – Spinning of funnel-shaped glass parts

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 *Fig.3.3*.

- (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.

The large quantities of most pressed products justify a high level of automation in this production sequence.

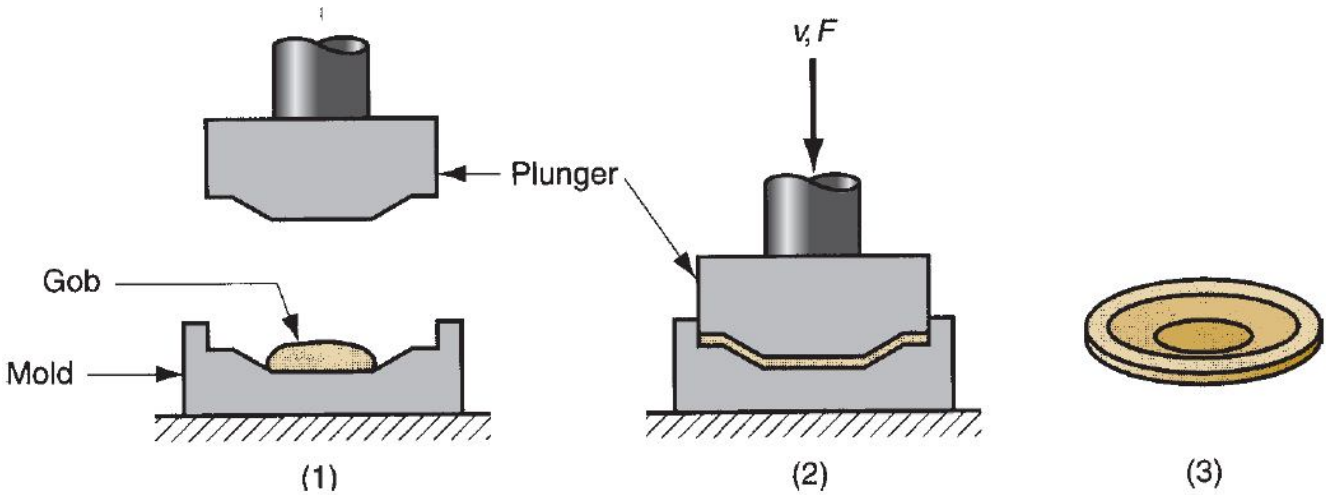


Fig.3.3 – Pressing of a flat glass piece

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 Fig.3.4

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

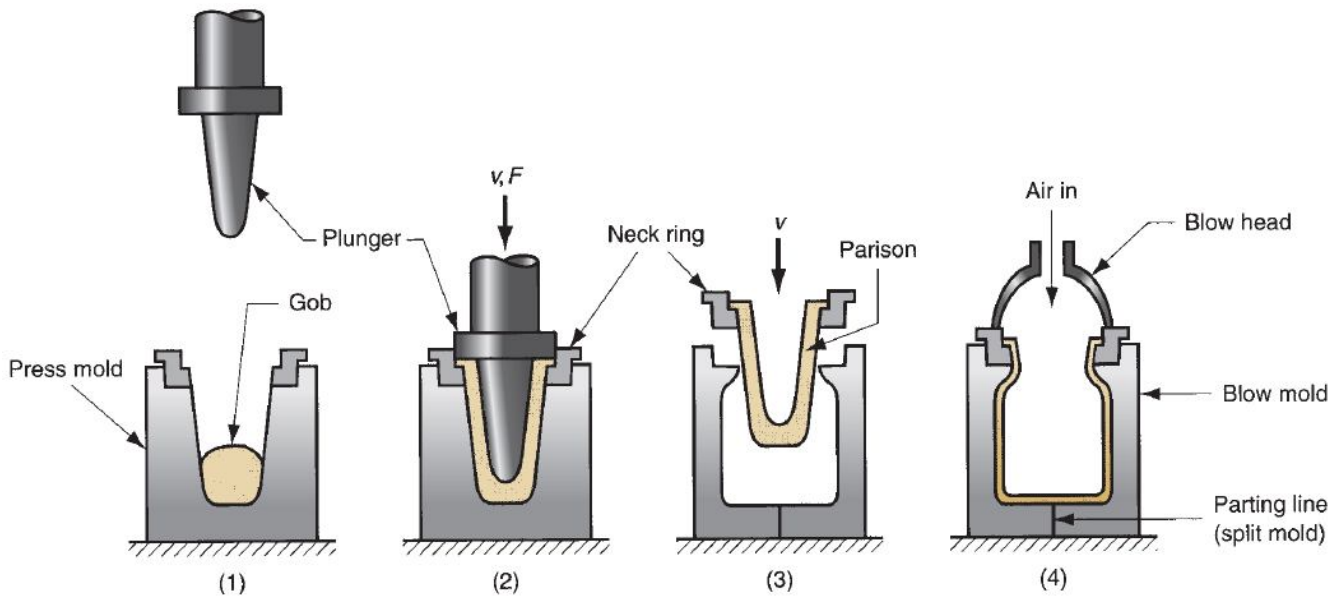


Fig.3.4 – Press-and-blow forming process

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 Fig.3.5.

- (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.

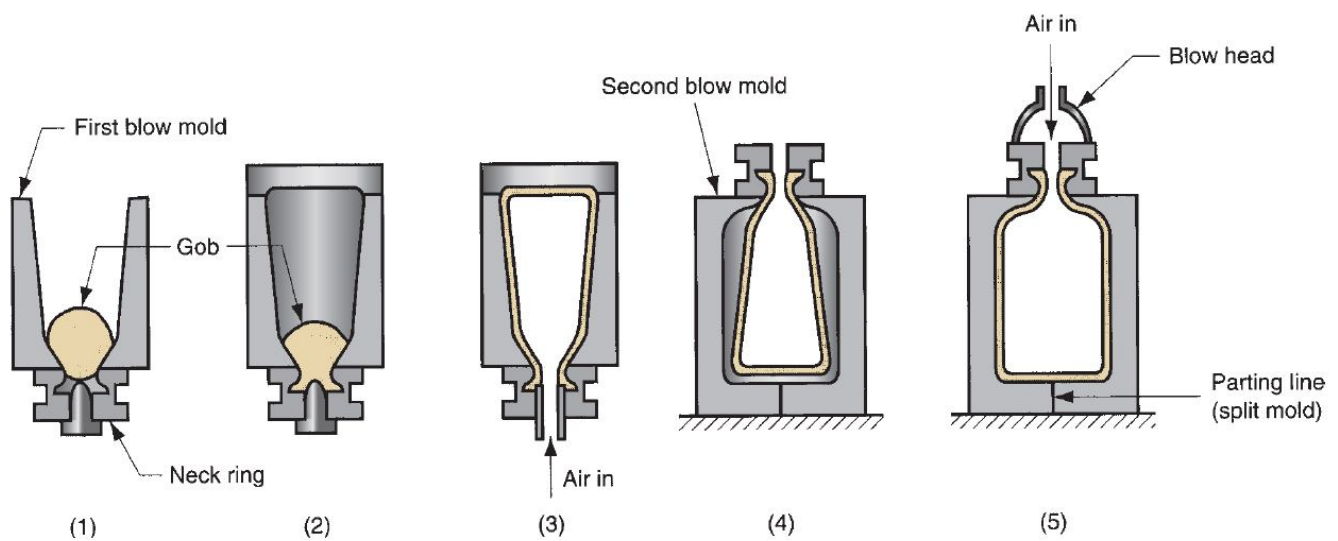


Fig.3.5 – Blow-and-blow forming process

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.

3.5.2 Shaping of Flat and Tubular Glass

In modern technologies, two methods for making plate glass and one method for producing tube stock are used. 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.

Rolling of Flat Plate: Flat plate glass can be produced by rolling, as illustrated in Fig.3.6. 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.

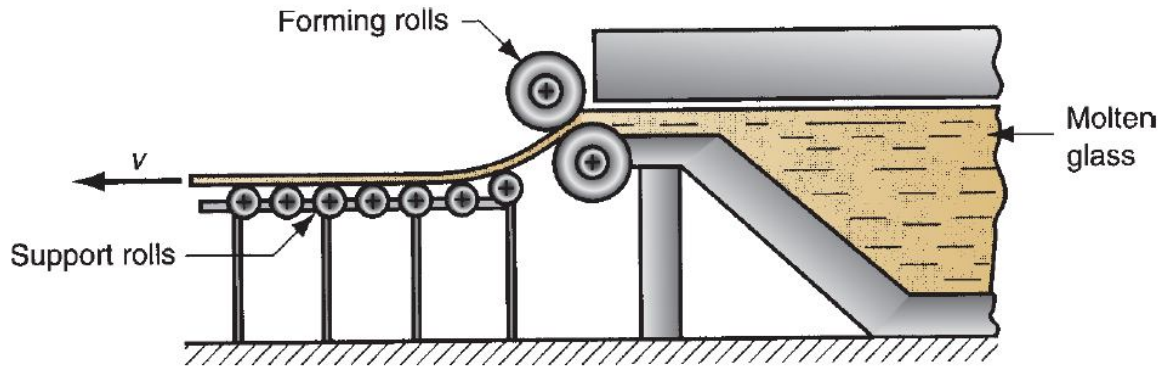


Fig.3.6 – Rolling of flat glass

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 Fig.3.7, 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.

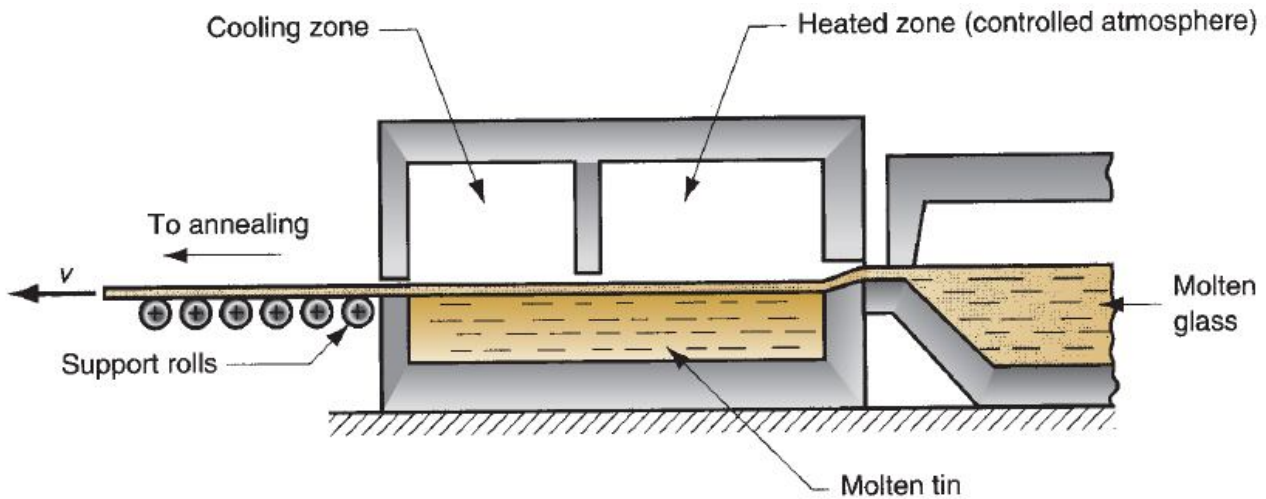


Fig.3.7 – The float process for producing sheet glass

Drawing of Glass Tubes:

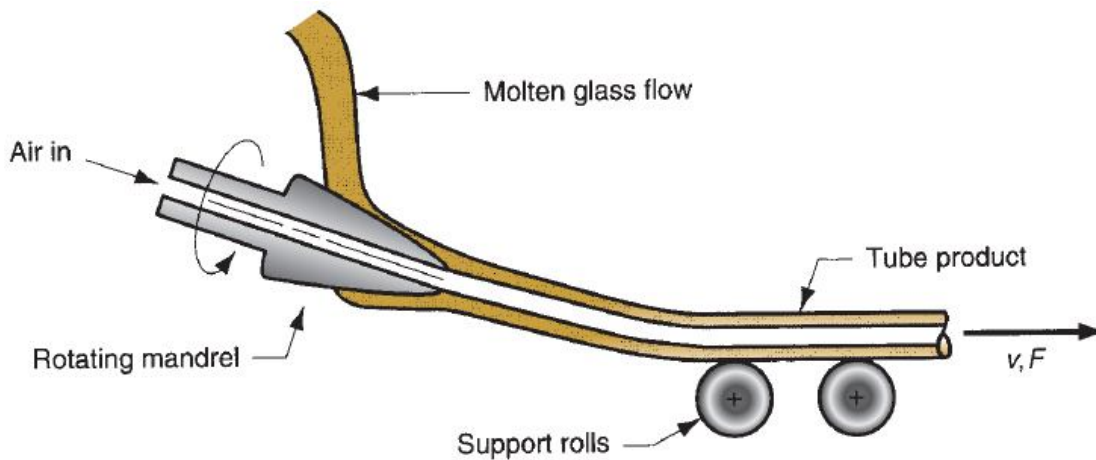


Fig.3.8 – Drawing of glass tubes by the Danner process

Glass tubing is manufactured by a drawing process known as the Danner process, illustrated in Fig.3.8. 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, 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 beyond the mandrel. The continuous tubing is then cut into standard lengths. Tubular glass products include laboratory glassware, fluorescent light tubes, and thermometers.

3.5.3 Forming of Glass Fibers

Glass fibers are used in applications ranging from insulation wool to fiber optics communications lines. Glass fiber products can be divided into two categories:

- (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.

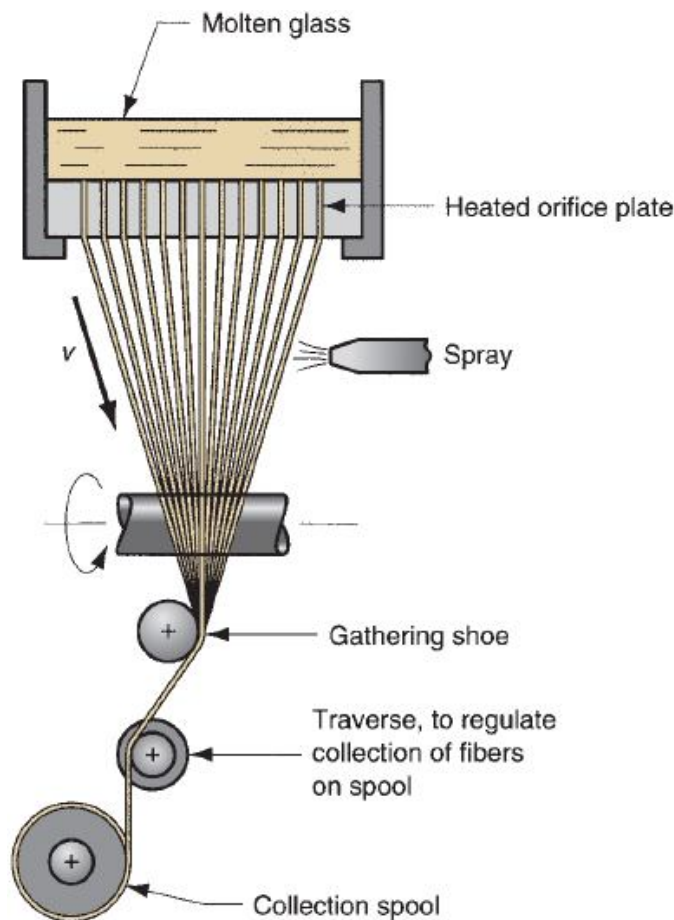


Fig.3.9 – Drawing of continuous glass fibers

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 Fig.3.9, continuous glass fibers of small diameter (lower size limit is around 0.0025 mm) are produced by drawing strands of molten glass through small orifices in 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 or more are not unusual.

3.6 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.

3.6.1 Heat Treatment

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. 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.

3.6.2 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).

3.7 Application of Glass

Glass is an unlimited and innovative material that has plenty of applications. It is an essential component of numerous products that we use every day, most often without noticing it.

It is clear that modern life would not be possible without glass!

Glass is used in the following non-exhaustive list of products:

- ▶ Packaging (jars for food, bottles for drinks, flacon for cosmetics and pharmaceuticals)
- ▶ Tableware (drinking glasses, plate, cups, bowls)
- ▶ Housing and buildings (windows, facades, conservatory, insulation, reinforcement structures)
- ▶ Interior design and furnitures (mirrors, partitions, balustrades, tables, shelves, lighting)
- ▶ Appliances and Electronics (oven doors, cook top, TV, computer screens, smart-phones)
- ▶ Automotive and transport (windscreens, backlights, light weight but reinforced structural components of cars, aircrafts, ships, etc.)
- ▶ Medical technology, biotechnology, life science engineering, optical glass
- ▶ Radiation protection from X-Rays (radiology) and gamma-rays (nuclear)
- ▶ Fibre optic cables (phones, TV, computer: to carry information)
- ▶ Renewable energy (solar-energy glass, windturbines)

3.8 References

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