The Science of Glass

Summary

Glass is an inorganic solid material that has the atomic structure of a liquid. It is formed by cooling a molten liquid so that the atoms are prevented from arraying into a crystalline formation. In cooling a glass-forming liquid, there is a continuous stiffening of the fluid until the atoms are fixed in a random arrangement, similar to what they had when in a fluid state. Glass is hard and brittle, and is usually transparent or translucent. Silica sand is a common ingredient.

Distinct types of glass differ in their chemical composition and physical qualities, though most have qualities in common. All man-made glass passes through a viscous stage when it cools from a fluid state. Colors develop when glass mixtures are infused with certain metallic oxides.

When it is cold, glass is a poor conductor of electricity and of heat. Most types of glass are easily fractured when hit or shocked. Though generally resistant to ordinary solvents, most glass reacts when put in contact with hydrofluoric acid.

Encompassing tableware, containers, tubes, rods, flat glass, and fiberglass, traditional glass products are all made of glass created by the melting process.

Characteristics

Color

Metallic oxides are commonly used to color glass. An oxide can produce different colors in different glass mixtures, and different oxides of the same metal can produce different colors. Constant colors include the purple-blue of cobalt, the chrome green or yellow of chromium, the dichroic canary color of uranium, and the violet of manganese.

Ferrous oxide will yield an olive green or a pale blue based on the glass into which it is mixed. Ferric oxide produces a yellow color but needs an oxidizing agent to avoid reduction to a ferrous state. Lead imparts a pale yellow color; silver oxide creates a permanent yellow stain; vegetable charcoal added to soda-lime glass produces a yellow color. Selenites and selenates yield a pale pink or pinkish yellow; tellurium a pale pink tint. Nickel produces a violet in potash-lead glass, and a brown in a soda-lime glass. Copper generates a peacock blue which becomes green if the amount of copper oxide is increased.

Ductility

The hardness of glass is measured by a diamond microindenter. Application of this instrument to a glassy surface leaves evidence of a plastic deformation (a permanent change in dimension). Otherwise, plastic deformation of glass (or ductility) is not observed. Instead, glass failure is brittle; the glass object fractures suddenly and completely. This behavior can be explained by the atomic structure of the glassy solid.

Since the atoms in molten glass are essentially frozen in their amorphous order upon cooling, they do not orient themselves into the sheets or planes that are typical of crystalline grains. The absence of such a pattern means that there are no grain boundaries between planes of different orientation. Therefore, there are no barriers that might prevent defects such as cracks from extending quickly through the material.

Durability
Chemical durability in glass is primarily determined by an ion exchange reaction in which alkali ions in the glass are exchanged with hydrogen atoms or hydronium ions in atmospheric humidity or water.

The alkali ions that have leached out of the glass react with carbon dioxide and water in the atmosphere, producing alkali carbonates and bicarbonates. Seen as white deposits on a glassy surface from dishwashing or after extended humidity exposure, it is called weathering. In general, glasses that are low in alkali offer increased resistance to weathering. Vitreous silica is the most resistant; borosilicates and aluminosilicates also offer weathering resistance.

To improve the chemical durability of glass, the standard technique is to make the surface as silica-rich as possible. There are two ways to do this: by fire polishing, a procedure that removes alkali ions by volatilization; or by surface treatment with a mixture of sulfur dioxide and steam, which extracts alkali by leaching and converting to washable alkali sulfate. Another method of improving the chemical durability of glass involves limiting its surface exposure to water or humidity.

Electrical Conductivity
Most glass contains charged metallic ions capable of carrying an electric current. However, the high viscosity of the glass hinders the movement of the ions and hence, its electrical activity.

Because univalent alkali ions have the greatest mobility through a glassy structure, they are the primary charge carriers of a glass and therefore determine its electrical conductivity. In general, the higher the concentration of alkalis, the higher the electrical conductivity.

A noted exception from the additivity relationship is the mixed-alkali effect, in which glass containing two or more different types of alkali ions have a lower electrical conductivity than additivity would suggest. Mixed-alkali glasses are useful in applications where low electrical conductivity is desired, such as high-wattage lamps.

Fracturing
Glass is stronger than most metals. When tested in a flawless state, glass can withstand a relatively reversible compression yet not fracture. Its theoretical strength in tension is estimated to be 2 to 5 million pounds per square inch. However, the strength of most commercial glass products ranges from only 2,000 to 25,000 pounds per square inch, owing to the presence of scratches and microscopic flaws. Flaws are stress-concentrating, with the effective stress at the tip of a flaw 100 to 1,000 times greater than the stress applied.

Tensile stress in excess of a low limit, called the fatigue limit, will cause a flaw to experience a subcritical crack growth. Depending on the applied stress, the shape of the flaw, and the temperature and corrosiveness of the environment, the growth velocity of the crack approaches its terminal limit and failure is imminent. Therefore, all glass will eventually experience static fatigue and will fail under negative conditions.

A glass fracture can be examined with a stereo microscope. Fractography of glass is important in its manufacture and service, and is equivalent to a postmortem examination. An experienced fractographer will be able to pinpoint the precise cause of glass failure.

Photosensitivity
In some glass containing small amounts of cerium oxide and ions of copper, silver, or gold, ultraviolet radiation exposure causes the cerium oxidation and reduction of the other elements to their metallic states. With subsequent heat, the metal nuclei grow (or “strike”), developing strong colors (red for copper and gold, yellow for silver) in the ultraviolet-exposed regions of the glass. This technique has been used to produce three-dimensional photographs, with more recent use in micro-photolithography for the production of complex electronic circuits.

Photochromic eyeglasses are generally alkali boroaluminosilicates with 0.01 to 0.1 percent of silver halide and a small amount of copper. On absorbing light, the silver ion reduces to metallic silver, nucleating into colloids about 120 angstroms in size. These colloids are small enough to keep the glass transparent, but dense enough to make the glass look gray or brown. In these eyeglasses, darkening is reversed by the removal of light (optical bleaching) or the raising of temperature (thermal bleaching).

Strength
Most properties of glass are sensitive to its chemical composition, a reflection of its atomic structure. Because glass generally acts as if it were a solution, many of its properties can be estimated by applying what are known as additivity relationships over a narrow range of compositions. In additivity relationships, it is assumed that each ingredient in a glass contributes to the properties of the glass by an amount equal to the concentration of that ingredient multiplied by a specific additivity factor. Many properties of soda-lime-silica glasses follow such relationships closely.

Thermal Expansion
Glass normally expands when heated and shrinks when cooled. If a hot specimen of glass is suddenly cooled, great tension will develop in its outside layers due to their shrinking relative to its inner layers. This tension can lead to cracking. Resistance to this thermal shock is known as the thermal endurance of a glass. It is inversely related to the thermal-expansion coefficient and the thickness of the glass.

Soda-lime-silicates and alkali-lead-silicates have high expansion coefficients and are more susceptible to shocking. Improved thermal shock resistance is found in pyrex™ -type sodium borosilicates or vitreous silicas.

Space-based telescopes often require materials with expansion coefficients close to zero. A silica glass containing 7.5 percent titanium oxide has a near-zero thermal expansion coefficient and is preferred for this application.

Transparency, Opacity, Color
Due to the confinement of electrons in glass molecules to particular energy levels, they cannot absorb and reemit photons (the basic units of light energy) by skipping from one energy band to another. Therefore, light energy travels through glass instead of being absorbed and reflected, making glass transparent. However, most oxide glasses are good absorbers of (and therefore opaque to) ultraviolet radiation of small wavelengths and can be made more transparent to ultraviolet radiation by increasing the silica content.

Glass to which certain metallic oxides have been added will absorb wavelengths corresponding to certain colors and let others pass, thus appearing tinted to the eye. For instance, cobalt gives an intense blue tint to glass, chromium generally gives green, and manganese imparts purple.

Viscosity
Applying heat to solid glass results in a gradual softening until it is transformed into a fluid state. This changing property is known as viscosity, and is what allows glass products to be produced in a continuous fashion; with raw materials melted to a liquid, delivered as a viscous mass to a forming machine, then cooled to a hard and rigid condition.

Viscosity is the key property in glass forming. After melting and conditioning, glass is delivered to a forming machine at a viscosity of approximately 104 poise. At this viscosity, the glass can be worked on to form the desired object and then released in a near-solid condition. Throughout the process, heat is extracted in a controlled manner in order to allow the viscosity to increase from the levels of a liquid to those of a solid.

Creating

Glass From a Gaseous State
Glass also may be created directly from a gas. In one process, known as non-reactive vapor-phase glassmaking, elements such as silicon, germanium, and selenium or their alloys are vacuum-evaporated or sputtered, and then condensed onto a cool substrate.

Another process of creating glass directly from a gas is known as reactive vapor-phase glassmaking. Here, the desired glass is formed by a chemical reaction. Chemical vapor deposition (cvd) belongs to this latter category, with a good example being the making of silica glass by hydroxylation. In the hydroxylation technique, vapors of silicon tetrachloride (sicl4) are reacted at high temperatures with steam (h2o), causing a soot of silica (sio2) to deposit on a cooler substrate. The soot is subsequently sintered to a dense glass.

Glass From a Liquid State

Silica glass can also be produced from a liquid solution. In this technique, known as the sol-gel route, kalcoholic solutions of organometallic precursors, generally alkoxides such as tetraethyl orthosilicate (teos), are hydrolyzed with water at low temperatures while being vigorously stirred. Hydrolysis promotes chelation (the formation of network-type atomic connections) until the mass gels. The gel is then carefully dried to remove excess alcohol and water, and is then sintered to form a dense glass.

Because the sol-gel route avoids high-temperature reactions with containers, it produces glass of higher purity than the melting process. However, it is slow, expensive, and not conducive to obtaining large specimens because of fractures that form during drying. However, the method works well in depositing thin films, such as anti-reflection coatings.

Glass From a Solid State

A solid can become glass through high rates of shearing, possibly caused by a shock wave during an impact. These are called diaplectic glasses. Some glass fragments gathered from the moon may be examples of diaplectic glass formed by meteoroid impacts.

A solid may also be converted to glass by irradiation with high-energy subatomic particles. These are known as metamict solids. Examples are minerals that contain natural high-energy particle radioactivity.

Manufacturing

In the Laboratory

In laboratory melting, a batch is prepared from reagent-grade chemicals. Floated silica, sodium carbonate, calcium carbonate, alumina, and borax are all assumed to convert to equivalent amounts of oxides after decomposition.

The mixed batch is placed in a covered crucible and heated inside an electric resistance furnace. The crucible is made of suitable refractory materials including fireclay (inexpensive but contaminating), fused silica (for good thermal shock resistance), and high-density alumina. To avoid contamination of the molten glass by refractory materials, crucibles may be made of platinum; either pure metal or alloyed with 2 to 20 percent rhodium or 5 percent gold. In view of the expense of these metals, the laboratory glassmaker must be vigilant not to mix a batch that might undergo chemical reaction with the crucible materials upon melting.

Electric-resistance furnaces with programming capability allow for accurate temperature-control. Their heating elements can be made of molybdenum disilicide with low thermal mass insulation, allowing the glass to be poured in graphite or steel molds; or rolled into thin flakes while being poured onto a steel or aluminum chill plate. If fritting, or breaking into small particles, is desired, the molten glass stream can be dropped into water.

Blocks of glass can be cut or drilled with diamond-impregnated saws and drills. Glass can also be ground using diamond-impregnated rotating wheels, silicon carbide paper, or silicon carbide slurry. It also can be polished using cloths loaded with finer-grained abrasives such as diamond, iron oxide, or ceria.

Raw Materials

For glass manufacture on an industrial scale, these chemical compounds must be obtained from properly sized, cleaned, and treated minerals that have been preanalyzed for impurities. Silica is obtained from clean sand; soda from soda ash (sodium carbonate) and sodium hydroxide; lime from limestone (calcium carbonate) or from dolomite (calcium magnesium carbonate) when magnesium oxide is also needed.

In the past it was customary to add about 0.25 percent arsenic oxide and 0.5 percent sodium nitrate to aid in glass fining (removal of bubbles). These chemicals are no longer recommended and are considered hazardous to individuals and the environment. Less noxious compounds such as sodium chloride, sodium sulfate, or sodium nitrate are now used.

In addition to its mineral ingredients, a glass batch traditionally consists of 25 to 60 percent cullet. Cullet is crushed rejected glass, generally of the same composition as the mineral mixture. It is included because it accelerates reactions by bringing the mineral particles together, due to its previous melting in the furnace.

Step 1. The Furnace

Electric melting is by far the most energy-efficient and clean method: it introduces heat where needed and it eliminates the problem of batch materials being carried away with the flue gases. With electric heating, thermal efficiencies as high as 70 to 80 percent can readily be achieved, while getting 40 percent efficiency from fossil-fuel firing is a struggle. Among specialty furnaces incorporating electric melting are "cold-top" furnaces, into which the batch is poured or sprinkled from the top. In these furnaces the melt zone is vertically organized; the batch at the top is solid, while molten glass flows out the bottom. The cold-batch method ensures a very low emission of decomposition, vaporization, and carry-over products. In addition, batches containing fluorides can be melted with little or no escape of toxic fluorine.

In addition, the glass is homogenized by diffusive mixing. In order to ensure that the composition of the melt is uniform throughout, mechanical mixers (or nitrogen or air bubblers) can be installed in the bottom of the melting chamber. Challenges to homogenization can be posed by unmelted material from the batch like sand grains, as well as devitrification products, material from the refractory lining of the melting tank, foreign matter, or vaporization of the various glass constituents, particularly boric oxide and alkali. Glass homogenization is, in fact,the rate-limiting step in the entire glass-melting process.

Another sort of furnace is the recuperative furnace, in which the flue gases continuously exchange heat with the incoming combustible mixture through metal or ceramic partitions. A means of improving combustion efficiency is the use of oxygen-rich air or pure oxygen. The use of oxygen is a particularly important approach since it greatly reduces undesirable nitrogen oxides in the flue gas.

Step 2. The Furnace Melting Chamber

After a glass batch is mixed, it is moved to a hopper at the back of the melting chamber of the furnace (the doghouse). The batch is often slightly moistened to discourage separation of the ingredients by vibrations from the conveyor system, or pressed into pellets or briquettes to improve contact between the particles. The batch is placed in the melting chamber via mechanized shovels, screw conveyors, or blanket feeders. Continuous glass-melting chambers are 20 to 40 feet wide by 100 feet long. They can up to 1,000 tons of glass and produce from 50 to 500 tons per day. These large melting chamber tanks are made of high-density, highly corrosion-resistant refractory materials, such as electrocast alumina-zirconia-silica.

Step 3. The Conditioning Chamber

In the melting chamber, temperatures reach a peak of 2,685 degrees farenheit for soda-lime-silicate glass. At these temperatures, large amounts of gas are produced by the decomposition of raw materials in the batch. Together with trapped air, these gases form bubbles in the glass melt. Larger bubbles will rise to the surface, but small bubbles are trapped in the melt in such numbers that they threaten the quality of the final glass.

The bubbles are removed in a process called fining, which takes place mostly in the conditioning chamber. From the melting chamber, the molten glass is allowed to pass through a throat in a divider wall to the conditioning chamber, where temperatures are held at about 2,375 degrees farenheit. Here, the finer bubbles are eliminated by being dissolved back into the glass.

Step 4. The Forehearth

After the conditioning chamber, the glass is moved via the forehearth (a set of narrow channels) to the forming machines. The amount of time the glass has spent in the tank varies from a half-day to 10 days, based on the rate at which glass is fed to the forming machines (the pull rate), as well as on the flow patterns set up in the tank.

Two problems can manifest at the end stage of glass production: devitrification and reboil. Devitrification, or loss of the glassy state, is the development of crystals caused when the molten glass is subjected to certain temperatures. Glass reboil is the rapid exsolution of dissolved gases as temperatures rise, causing them to nucleate and form bubbles in the glass.

Step 5. Annealing
During the forming process, glass can develop permanent stresses due to regions of it passing through the transition range at varying cooling rates and times. To ensure dimensional stability and avoid the development of excessive tension in critical regions, these stresses must be reduced. This is done through the process of annealing.

The atomic structure of a glassy solid goes through a process of relaxation as it cools through the transition range. The time required for this relaxation to be sufficient to reduce internal stresses can range from a few minutes to a few hours.

Practical annealing is achieved by holding the product at approximately 9 degrees farenheit above its annealing point for 5 to 15 minutes; followed by slowly cooling it through the transition range, the strain point, and finally to room temperature. (often, the glass transition temperature and the annealing point are used synonymously, and the strain point marks the low-temperature end of the range.) Dead-annealing refers to glass that is so well annealed that the internal tension is almost undetectable.

Processes

Finishing
Etching of most silicate glasses can be carried out using a solution of 6 to 30 percent hydrofluoric acid with a small amount of sulfuric acid (not recommended for safety reasons).

Overlay glazing is carried out by firing a thin layer of another glass with lower thermal expansion properties than the substrate onto the glass product.

Laminating
With the lamination process, mechanical energy due to applied stress is absorbed by successive layers of glass and laminate, leaving less energy for cracks to develop. Many glass products are laminated by bonding sheets of tough polymers (ie, polyvinyl butyral, polyurethane, ethylene terpolymer, or polytetrafluoroethane: teflon™) to the glass surface by heat-shrinking.

In automotive applications, not only does an inter-layer help to absorb the energy of an impacting object, but the adhesion of glass to the polymer minimizes the risk of flying shards upon fracture. In aircraft, windshields may have several laminates, with at least one of the inner glass layers strengthened by ion exchange in order to withstand the impact of flying objects such as birds. Bullet proof glass is often laminated, with a single ply of dead-annealed glass as thick as 20 to 25 millimeters used in some applications.

Sealing
Sealing glass to itself, or to other materials, is dependent on the relationships between the thermal-expansion characteristics of the components to be sealed, the wetting and adhesion characteristics of molten glass at the sealing temperatures, and the chemical durability of the glass.

Hermeticity, or air-tightness, is often the desired result of glass sealing. An example of hermetic seals are lightbulbs, where metal conducting wires are sealed through glass in order to maintain an inert atmosphere inside the lamp envelope. Many modern microelectronics also depend on glass sealing, although hermeticity is not required for them.

A critical factor of a successful seal is the thermal contraction of the glass. If there is a thermal-contraction mismatch causing a difference in the contraction rates of the sealed components as they cool, stresses will develop in each component. When the mismatch exceeds 500 parts per million, tensile stresses in the glass can cause it to fracture. There are various techniques to avoid these fractures. In a glass-to-metal seal, it is best to have the glass component under mild compression. Or, to employ a glass-metal system in which the glass component and the metal alloy are known to have closely matched contraction characteristics.

When a contraction mismatch is large, the seal can be accomplished by using a thin metal wire or thin glass coating, by employing a compression seal (where a glass of lower expansion properties is softened inside a higher-expansion metal shell), or by sealing the metal in the form of a thin foil with feathered edges (aka a housekeeper seal).

A common way of applying sealing glass is as frit. Glass is crushed or ball-milled in order to obtain a fine powder and then mixed with a small amount of slurry-making organic vehicles and binders. Metal powders can be mixed in to make conducting pastes; nonmetallic powders can be added to make resistive and dielectric pastes or glass-matrix composites. The slurry is screen-printed onto the object, which is then fired.

Dry frits can be mixed with a small amount of binder and pressed into a shape called a preform. The preform is softened when put in contact with the other components, then is sealed upon being heated.

Strengthening
Glass can be strengthened through several processes. Reducing the severity of flaws can be accomplished via fire polishing or etching (chemical polishing), the introduction of surface compression by overlay glazing, thermal tempering or ion exchange, and toughening by lamination.

Ion-exchange strengthening only applies to alkali-containing glasses. It is carried out by immersing glass in a bath of molten alkali salt at temperatures below the transition range. The salt must have ions greater in size than the host alkali ions in the glass. Through diffusion, the larger ions from the alkali bath exchange sites with the smaller alkali ions in the surface regions of the glass, thus producing, as in thermal tempering, compression in the surface and tension in the interior. Because the invading ions penetrate only 40 to 300 micrometers into the host glass, the magnitude of the internal tension is generally small. Though thin glass specimens may be strengthened using ion-exchange, it is a slow process, generally requiring 2 to 24 hours of immersion in the salt bath.

Thermal Tempering
Thermal tempering uses symmetrically placed air jets to quench (rapidly cool) the glass from a temperature well above the transition range. The outer layers of the glass cool faster than the inside, passing through the glass transition range sooner, shrinking at a higher rate and being compressed while the interior is stretched. Thus, the glass is strengthened.

Many commercial glass products are strengthened by thermal tempering. However, thick glass may fracture spontaneously due to an interior flaw stemming from the high tension that tempering creates in that region. Such glass can break, or dice, violently into a large number of pieces. However, diced glass is unlikely to cause serious injury, making tempered glass products legally required for certain applications, such as shower doors.

Products

Blown Glass Tableware
Tumblers are made by blowing glass at the end of a blowing pipe into a split paste-mold. The paste-mold is made of cast iron and lined with a wetted cork-type or pasted-sawdust material, creating a steam cushion to create a smooth finish on the glass. The piece is rotated in the mold during the blowing step, and the formed vessel is gently knocked off the pipe at a scoreline. The rim is then beaded using a flame.

Containers
Commercially produced narrow-mouth containers like bottles are formed by an individual section (is) machine. In this machine, a stream of molten glass is pushed out of an orifice at the end of the forehearth by a rotating bowl and is then cut into gobs of glass. The gobs travel down chutes to a mold, where the glass is blown by compressed air into a parison shape. A mechanical arm then grips the parisons and moves them to the finishing mold, where a second blowing operation takes them to finished form. The entire production takes approximately 11 seconds. The hot containers are then set on a conveyor belt, cooled, and transported to the annealing lehr. At the entrance to the lehr, sprays of tin chloride solution are applied in order to impart a hard, abrasion-resistant tin oxide coating to the glass surfaces; at the lehr exit sprays of water-based polyethylene emulsions make the surfaces smoother.

Wide-mouth containers are often formed by using a pressing operation. With lightweight containers, forming the parison by pressing allows for a more uniform distribution of glass than is possible by blowing, allowing for better control of their thinner container walls.

Molds used in commercial container manufacture are generally made of cast iron, with alloying elements of carbon, titanium, chromium, vanadium, and molybdenum added to increase the resistance to oxidations. Lubricants are used to keep the hot glass from sticking to the molds.

Fiberglass
Glass-fiber wool is generally produced by the channeling of a molten glass stream into a spinning cup that has numerous holes in its side. Under centrifugal force, the glass fibers are extruded through the holes, then are blasted by high-velocity air that breaks them into short lengths. Descending to a belt below, the fibers are bonded with adhesive spray. The binder is cured, and the wool is packed into chopped batts or rolls for insulation.

Flat Glass
The float process is the modern system for producing flat glass, used for products like windows and mirrors. In this method, molten glass moves over the lip of a broad spout, passes between rollers, and floats over a bath of molten tin in a steel container. Glass enters the container at a viscosity of approximately 103.5 poise, a temperature greater than 1,800 degrees farenheit for soda-lime-silica glass. It is cooled over the length of the tin bath, which has a melting point of 450° degrees farenheit, then exits in a near-solidified sheet form with a viscosity of about 1,013 poise. Under these conditions, gravity spreads the glass to a thickness of 7 millimeters (0.28 inch). If the glass is compressed with graphite paddles or stretched with knurled rollers, it may be output in thicknesses of 2 to 25 millimeters and in widths up to 4 meters.

Finally, the flat sheets are cut by scribing a score line with a diamond tip and applying gentle pressure to advance the crack. Flat glass produced by the float method has excellent thickness control and strength.

Lightbulbs
Lightbulb shells are produced commercially on a ribbon machine. The machine consists of two large upper and lower turrets containing a number of blow heads and molds. As a thin stream of glass exits from the forehearth, it is passed between a pair of water-cooled rollers, forming a series of patties in the stream. The patties are picked up by the blow heads and ultimately are blown into finished shells within the rotating paste-molds on the lower turret, while traveling at high speeds along the length of the turret. The ribbon machine has a normal shell-making speed of 30 units per second.

Bulbs are finished by sealing a pair of metal leads into the lamp shell. A common incandescent lightbulb, made of a soda-lime-silica shell, has leads which are first sealed into a soft glass “flare” and then are fusion-sealed around the skirt to the shell housing.

Optical Fibers
Optical waveguides (owgs), transmit information signals in the form of pulses of light. They consist of a core glass-fiber clad in glass of a lower refractive index.

There are two types of owg, fabricated by different processes. Stepped-index owgs are made by fusing a glass rod of core composition inside a glass tube of clad composition and then drawing them together. They also are made in the double-crucible technique, where two concentric compartments of a platinum crucible are fed glass rods, and a composite stream exits the bottom orifice. In both cases, the glass-fiber is brought to its proper dimension by a high-speed mechanical winder. Between the orifice and the winder, the fiber passes through a laser-monitored diameter-control feedback mechanism and is coated with a polymer to provide protection from surface abrasion.

Optical Glass
The prerequisite for producing optical glass is rigid control of the glass refractive index. It is necessary to use highly controlled materials with impurity levels below the parts-per-million range. This glass melting is carried out in electrically heated furnaces with platinum-lined tanks or platinum crucibles. The molten glass is then cast

into flats, delivered directly into mold blanks, or extruded into rods. In traditional optical-glass manufacturing, the glass is cooled in pots, with good pieces selected and remelted in order to obtain more acceptable homogeneity.

Textiles
Continuous fibers for textiles are made by dropping molten glass or marbles into an electrically heated platinum-rhodium bushing that has been punctured with hundreds or thousands of tiny orifices. The fibers are then joined into a single strand. By pulling the glass with a mechanical winder at linear speeds up to 125 miles per hour, fibers as fine as three micrometers in diameter can be drawn.

Tubes and Rods
Tubes and rods are made in three processes: the danner process, the downdraw process, and the vello process.

In the danner process, a continuous stream of glass flows over a hollow, rotating mandrel mounted on an incline inside a surrounding muffle. With the rotation of the needle, the glass flows downward, gradually forming a hollow tubular envelope that is drawn ultimately into a tube. The tube shape is maintained by a stream of air blown through the mandrel. In producing rods, a slight suction is maintained in order to collapse the walls of the glass envelope as it leaves the mandrel. For both tubes and rods, the forms are gradually pulled by belt tractors into a horizontal position, where sections are cut by scoring, then advancing the crack with pinpoint flames.

In the downdraw process, molten glass flows vertically downward through a defined orifice and is pulled by traction from below. The orifice determines the thickness of the tube wall and the shape of the bore. This process allows for the formation of complex cross sections. Additionally, strips of a second glass can be fused to the primary glass, as in a thermometer, by drawing a stream from an auxiliary melting pot.

The vello process is a hybrid of the downdraw and the danner processes. Here, glass flows downward through a defined orifice and is gently turned horizontally.

Varieties

Chalcogenide Glass
Another of the non-oxide, non-crystalline substances is the chalcogenides. They are formed by melting the chalcogen elements (from the column of elements on the periodic table beginning with oxygen) of sulfur, selenium, or tellurium with elements from group v (arsenic, antimony) and group iv (germanium) of the periodic table. Thanks to their semiconducting properties, the chalcogenides have found use in threshold and memory switching devices and in xerography.

Related to this group are the elemental amorphous semiconductor solids, such as amorphous silicon (a-si) and amorphous germanium (a-ge). These are the basis of most photovoltaic applications such as solar cells in calculators.

Commercial Glass
There are two categories of commercial glass: soda-lime-silica glass (the most common) and special glass. Soda-lime-silica glasses are made from three main materials: sand (silicon dioxide: sio2), limestone (calcium carbonate: caco3), and sodium carbonate (na2co3).

Fused Silica Glass
Standard glass, due to stresses generated during production, is liable to fracture when exposed to a sudden change in temperature. By reducing the coefficient of thermal expansion, glass can be made less susceptible to thermal shock. The glass with the lowest expansion coefficient is fused silica. (another is borosilicate glass, used for making cookware and laboratory vessels.) In fused silica glass, much of the sodium oxide that has been added as flux has been replaced by boric oxide (b2o3), and some of the lime has been replaced by alumina.

Though an excellent glass, fused silica is expensive due to the high cost of attaining the required temperature of above 3,092 degrees farenheit to melt sand (crystalline silica). The uses for fused silica glass are limited to those where its properties (chemical inertness and the ability to withstand sudden temperature changes) justify its cost. Still, fused silica glass production is a large industry.

Glass Ceramics
Glassy materials that are produced with a degree of crystallization throughout their atomic structure are called glass ceramics. These products possess strengths far beyond those of the parent glass or corresponding ceramic. Examples include corningware™ cookware and dicor™ dental implants.

Glass Composites
Useful glass products can also be made by mixing ceramic, metal, and polymer powders. Products made from such blends result in combinations of the properties of their various ingredients. Examples of composite products include glass-fiber reinforced plastics and thick-film conductor, resistor, and dielectric pastes used in the packaging of microcircuits.

Glassy Metals
Glassy metals form another non-oxide group. They are produced by the high-speed quenching of fluid metals. One glassy metal that is a compound of iron, nickel, phosphorus, and boron is commercially available as metglas™ ; it is used in flexible magnetic shielding and power transformers.

Industrial Glass
The properties of industrial glass—luster, transparency, and durability—are what make it the material of choice for household objects like windowpanes, bottles, and lightbulbs.

Metallic Glass
Some metallic glass has magnetic properties and is useful in the magnetic cores of electrical power transformers.

Natural Glasses
Several inorganic glasses are found in nature. These include obsidians (volcanic glasses), fulgurites (formed by lightning strikes), tektites (found on land in australasia and associated microtektites from the bottom of the indian ocean), moldavites (found in central europe), and libyan desert glass (from western egypt). Microtektite compositions are particularly attractive for hazardous waste immobilization or conversion due to their high chemical durability from under the sea.

Non-oxide Glass
Non-oxide glass (aka hmfg or heavy-metal fluoride glass) is used for telecommunication fibers due to its relatively low optical losses. However, hmfg has poor chemical durability and is difficult to form.

Non-silica Glass
Oxide glass is not based on silica and is of little commercial importance. Generally made of phosphates and borates, they have some use in bioresorbable products like surgical mesh and time-release capsules.

Sheet Glass
Sheet glass usually consists of 6 percent lime (calcium oxide: cao) and 4 percent magnesium oxide (mgo). Bottle glass adds about 2 percent aluminum oxide (al2o3) to the mix. Additional materials can be added to assist in refining the glass to remove bubbles or improve its color.

Silica-based Glass
Most commercial glass is formed from silica (silicon dioxide: sio2). This mineral is abundant in nature, particularly in quartz and beach sands. Glass made exclusively of silica is known as silica glass or vitreous silica. It is called fused quartz if it is the result of melting quartz crystals. Silica glass is used where high temperature, high thermal shock resistance, high chemical durability, low electrical conductivity, and good ultraviolet transparency are desired.

Soda-lime-silica Glass
Low cost and high durability are key requirements for common glass products like containers, windows, and lightbulbs. The glass that best meets these needs is of the soda-lime-silica variety.

In addition to silica, soda-lime glasses are made up of soda (sodium oxide: na2o) and lime (calcium oxide: cao). The na2o usually comes from sodium carbonate or soda ash; the cao is commonly derived from roasted limestone.

Other ingredients may be added to obtain different properties. Opal glass is created by adding sodium fluoride or calcium fluoride.

Another silica-based variation is borosilicate glass, used where high thermal shock resistance and chemical durability are desired (ie, cookware, laboratory glassware, and automobile headlamps).

Leaded crystal tableware is made of glass containing high amounts of lead oxide (pbo), which provided a high refractive index (the brilliance), a high elastic modulus (the sonority or “ring”), and a long working temperature range.

Aluminosilicate is another silica-based glass. This is the intermediate between vitreous silica and the more common soda-lime-silica glass in thermal properties as well as cost.