8 Glass Packaging Materials

8.1 INTRODUCTION

Glass has been defined by the ASTM (2010) as “an amorphous, inorganic product of fusion that has been cooled to a rigid condition without crystallizing.” Although glass is often regarded as a synthetic material, it was formed naturally from common elements in the earth’s crust long before the world was inhabited. Natural materials such as obsidian (from magma or molten igneous rock) and tektites (from meteors) have compositions and properties similar to those of synthetic glass; pumice is a naturally occurring foam glass.

Although the origin of the first synthetic glasses is lost in antiquity and legend, the first glass vessels were probably sculpted from solid blocks about 3000 BCE. In about 1000 BCE, the techniques of pouring molten glass or winding glass threads over a sand mold were developed, resulting in the formation of crude but useful glass objects. However, the real revolution in glassmaking came around 200 BCE with the introduction of the blowing iron, a tube to which red-hot, highly malleable glass adheres. Blowing through one end of the iron causes the viscous liquid to balloon at the other end, leading to the production of hollow glass objects.

By 200 CE, articles of glass were in fairly common use in Roman households. During the following 1000 years, glassmaking techniques spread over Europe. However, glass remained expensive until improved techniques in the eighteenth and nineteenth centuries brought down the price of bottles and jars to a relatively affordable level.

Mechanization of glass container manufacture was introduced on a large scale in 1892, and several important developments occurred over the next few decades. These included the first fully automated machine for making bottles, which was designed and built in 1903 by Michael J. Owens at the Toledo, Ohio, plant of Edward D. Libbey.

Added impetus was given to automatic production processes in 1923 with the development of the gob (mass or lump of molten glass) feeder, which ensured the rapid supply of more consistently sized gobs in bottle production. Soon afterward, in 1925, the Hartford Empire Company developed its IS (now generally taken to mean “individual section,” but actually named after its inventors Ingersall and Smith) blow and blow (B&B) machine (Hanlon et al., 1998). Used in conjunction with the gob feeders, IS (individual section) machines allowed the simultaneous production of a number of bottles from one piece of equipment. The gob feeder–IS machine combination remains the basis of most automatic glass container production today.

Further developments have occurred, resulting in the production of a wide range of glass containers for packaging. The two main types of glass container used in food packaging are bottles (which have narrow necks) and jars (which have wide openings). About 75% of all glass food containers in the United States are bottles and approximately 85% of container glass is clear, the remainder being mainly amber. Generally, today’s glass containers are lighter but stronger than their predecessors, with the weight of many bottles and jars having been reduced by 25%–50% over the last 50 years. Through developments such as this, the glass container has remained competitive and continues to play a significant but declining role in the packaging of foods.

8.2 COMPOSITION AND STRUCTURE

The basic raw materials for glassmaking come from mines or quarries and must be smelted or chemically reduced to their oxides at temperatures exceeding 1500°C. The principal ingredient of glass is silica derived from sand, flint or quartz. Silica can be melted at very high temperatures

(1723°C) to form fused silica glass which, because it has a very high melting point, is used for specialized applications including some laboratory glass.

For most glass, silica is combined with other raw materials in various proportions. Alkali fluxes (commonly sodium and potassium carbonates) lower the fusion temperature and viscosity of silica. Calcium and magnesium carbonates (limestone and dolomite) act as stabilizers, preventing the glass from dissolving in water. Other ingredients are added to give glass certain physical properties. For example, lead gives clarity and brilliance although at the expense of softness of the glass; alumina increases hardness and durability. The addition of about 6% boron to form a borosilicate glass reduces the leaching of sodium (which is loosely combined with the silicon) from glass.

As a consequence of the sodium in glass being loosely combined in the silica matrix, the glass surface is subject to three forms of "corrosion": etching, leaching and weathering. Etching is characterized by alkaline attack, which slowly destroys the silica network, releasing other glass components. Leaching is characterized by acid attack in which hydrogen ions exchange for alkali or other positively charged mobile ions. The remaining glass (principally silica) usually retains its normal integrity. Although not fully understood, weathering is not a problem in commercial glass packaging applications since it may take centuries to become apparent. However, a mild form of weathering is commonly known as surface bloom and may occur under extended storage conditions.

The most aggressive solution on glass is double-distilled water at neutral pH 7. The effect of dilute acidic solutions is much less, the main action being the extraction of sodium ions which are replaced by hydrogen ions. The result is a surface zone where the glass is depleted of sodium, this dealkalized layer forming a barrier to further ionic diffusion. It is worth remembering that the aqueous phase of almost all foods is acidic.

A typical formula for soda-lime glass is given in Table 8.1. In practice, however, the quantities vary slightly; for example, silica (SiO_2) 68%–73%, calcia (CaO) 10%–13%, soda (Na_2O) 12%–15%, alumina (Al_2O_3) 1.5%–2% and iron oxides (FeO) 0.05%–0.25%, depending on the glassmaker and the raw materials being used. The loss on ignition or fusion loss (generally the oxides of carbon and sulfur) can vary from 7% to 15%, depending on the quantity of cullet (i.e., scrap or recycled glass) used, there being less fusion loss the greater the quantity of cullet. Soda-lime

TABLE 8.1
Typical Formula for a 1 Tonne Batch of Soda-Lime Container Glass

Material	Weight (kg)	Oxides Supplied (kg)					LOI[a] (kg)
		SiO_2	Al_2O_3	CaO	Na_2O	FeO	
Sand SiO_2	300	299.3	0.2			0.3	0.5
Soda ash Na_2CO_3	100				58.3		41.7
Aragonite $CaCO_3$	90			49.0		0.02	40.7
Feldspar ($SiO_2 \cdot Al_2O_3$)	40	26.4	7.6	0.4	1.3	0.03	0.1
Salt cake NaCl	4				2.1		1.9
Cullet	460	333.7	9.2	48.8	67.2	1.03	0.1
Total	994	659.4	17.0	98.2	128.9	1.95	85.0
Yield of glass	909						
Wt% oxides		72.6	1.9	10.8	14.2	0.1	

Source: Adapted from Boyd, D.C. et al., Glass, in: *Kirk-Othmer Encyclopedia of Chemical Technology*, 4th edn., Kroschwitz, J. (Ed.), Vol. 12, John Wiley & Sons, New York, pp. 555–628, 1994.

[a] Loss on ignition (also referred to as fusion loss).

glass accounts for nearly 90% of all glass produced and is used for the manufacture of containers where exceptional chemical durability and heat resistance are not required (Boyd et al., 1994). Replacement of alkali by boric oxide leads to the production of borosilicate glass which is used for glass ovenware.

Glass is neither a solid nor a liquid but exists in a vitreous or glassy state in which molecular units have a disordered arrangement but sufficient cohesion to produce mechanical rigidity. Although glass has many of the properties of a solid, it is really a highly viscous liquid. During cooling, glass undergoes a reversible change in viscosity, the final viscosity being so high as to make the glass rigid for all practical purposes. Although glass at ambient temperatures has the characteristics of a solid, it is a supercooled liquid and will flow even at ambient temperatures over long periods of time, albeit extremely slowly.

Physically, glass has a random atomic structure in that the atoms are capable of arranging themselves in different orders. The basic structural unit is the silicon-oxygen tetrahedron in which a silicon atom is tetrahedrally coordinated to four surrounding oxygen atoms. However, although the silica atoms are always surrounded by four oxygen atoms, large groupings tend to be unordered. This amorphous structure, without slip planes formed by crystal boundaries that might allow deformation, is responsible for the stiffness and brittleness of glass.

8.3 PHYSICAL PROPERTIES

8.3.1 Mechanical Properties

Because of its amorphous structure, glass is brittle and usually breaks because of an applied tensile stress. It is now generally accepted that fracture of glass originates at small imperfections or flaws, the large majority of which are found at the surface. A bruise or contact with any hard body will produce on the glass surface very small cracks or checks that may be invisible to the naked eye. However, because of their extreme narrowness, they cause a concentration of stress that may be many times greater than the nominal stress at the section containing them. Because of their ductility, metals yield at such points and equalize stress before failure occurs. Since glass cannot yield, the applied stress (when it is high enough) causes these flaws to propagate (Girling, 1999). Thus, it is the ultimate tensile strength of a glass surface which determines when a container will break. The fracture formula is

$$\text{Tensile Stress} + \text{Stress Concentrator} = \text{Fracture}$$

In practice, a stress concentrator may be a small crack or check induced in the manufacturing process, or a scratch resulting from careless container handling. Therefore, the major step taken to make glass more break resistant involves the elimination of surface flaws (e.g., microcracks) by careful handling during and after forming and annealing, since the condition of the surface has a great deal to do with its tensile properties.

The mechanical strength of a glass container is a measure of its ability to resist breaking when forces or impacts are applied. Glass deforms elastically until it breaks in direct proportion to the applied stress, the proportionality constant between the applied stress and the resulting strain being Young's modulus E. It is about 70 GPa for typical glass (Boyd et al., 1994).

The principles of fracture analysis or diagnosis of the cause(s) of glass container breakage have been described by Moody (1977) in an excellent book that is regrettably now out of print. The following four aspects are important:

1. *Internal pressure resistance*: This is important for bottles produced for carbonated beverages, and when the glass container is likely to be processed in boiling water or in pressurized hot water. Internal pressure produces bending stresses at various points on the outer surface of the container, as shown in Figure 8.1.

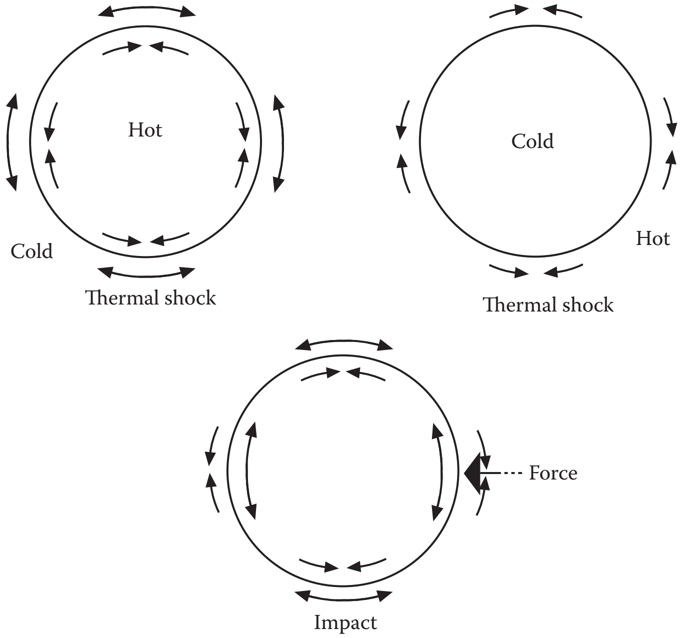

FIGURE 8.1 Cross section of a round glass container illustrating various stresses on the inside and outside surfaces.

2. *Vertical load strength*: While glass can resist severe compression, the design of the shoulder (see Figure 8.5 for details of glass container nomenclature) is important in minimizing breakage during high-speed filling and sealing operations.
3. *Resistance to impact*: Two forms of impact are important—a moving container contacting a stationary object (as when a bottle is dropped) and a moving object contacting a stationary bottle (as in a filling line). In the latter situation, design features are incorporated into the sidewall to strengthen contact points. The development of surface treatments (including energy absorbing coatings) to lessen the fragility of glass when it contacts a stationary object has been very successful. A cross section of a round bottle illustrating the ways in which tensile stresses on the inside and outside surfaces vary at various points around the bottle circumference is shown in Figure 8.1.
4. *Resistance to scratches and abrasions*: The overall strength of glass can be significantly impaired by surface damage such as scratches and abrasions. This is especially important in the case of reduced wall thickness bottles such as "one-trip" bottles. Surface treatments involving tin compounds (in conjunction with other treatments) provide scuff resistance, thereby overcoming susceptibility to early failure during bottle life.

Although the mechanical strength of a bottle or jar can increase with glass weight, this is at the expense of thermal strength which decreases with increasing glass weight. Considerable expertise is required by the glassmaker to determine the most appropriate design to satisfy the mechanical strength requirements and to balance the thermal strength demands of the finished product.

8.3.2 THERMAL PROPERTIES

The thermal strength of a glass container is a measure of its ability to withstand sudden temperature change. In the food industry, the behavior of glass with respect to temperature is of major significance, because relative to other forms of food packaging, glass has the least resistance to temperature changes. The resistance to thermal failure depends on the type of glass employed, the shape of the container and the wall thickness.

When a glass container is suddenly cooled (e.g., on removal from a hot oven), tensile stresses are set up on the outer surfaces, with compensating compressional stresses on the inner surface, as shown in Figure 8.1. Conversely, sudden heating leads to surface compression and internal tension. In both situations, the stresses are temporary and disappear when the equilibrium temperature has been reached. Because glass containers fracture only in tension, the temporary stresses from sudden cooling are much more damaging than those resulting from sudden heating, since the potentially damaged outside surface is in tension. It is found in practice (Moody, 1977) that the amount of tension produced in one surface of a bottle by suddenly chilling it is about twice as great as the tension produced by suddenly heating the other surface, assuming the same temperature change in both cases.

Thermal shock resistance cannot be calculated directly because the strength of glass containers is greater under momentary stress than under prolonged load. Therefore, empirical testing procedures are used. ASTM C149 covers the determination of the relative resistance of commercial glass containers (bottles and jars) to thermal shock, and is intended to apply to all types of glass containers that are required to withstand sudden temperature changes (thermal shock) in service such as in washing, pasteurization or “hot fill” processes, or in being transferred from a warmer to a colder medium or *vice versa*. Resistance to breaking is determined by transferring glass containers which have been totally immersed in a hot water bath (typically at 63°C) for 5 min to a cold water bath (typically at 21°C) and observing the number of breakages.

8.3.3 OPTICAL PROPERTIES

Because glass has no crystalline structure, when it is homogeneous and free from any stresses, it is optically isotropic. The optical properties of glass relate to the degree of penetration of light and the subsequent effect of that transmission, transmission being a function of wavelength. The spectral transmission of glass is determined by reflection at the glass surface and the optical absorption within the glass. In silicate glasses, transmission is limited by the absorption of silica at approximately 150 nm in the UV and at 6000 nm in the IR region. Iron impurities further reduce transmission in the UV and near-IR regions (Boyd et al., 1994).

Transmission may be controlled by the addition of coloring additives such as metallic oxides, sulfides or selenides and the compounds that are frequently used are listed in Table 8.2. Most of the transition metal oxides (e.g., cobalt, nickel, chromium, iron, etc.) will give rise to absorption bands, not only in the visible but also in the UV and IR regions of the spectrum. The presence

TABLE 8.2
Coloring Agents Used in Glass

Effect	Oxide
Colorless, UV absorbing	CeO_2, TiO_2
Blue	Co_3O_4, $Cu_2O + CuO$
Purple	Mn_2O_3, NiO
Green	Cr_2O_3, $Fe_2O_3 + Cr_2O_3 + CuO$, V_2O_3
Brown	MnO, $MnO + Fe_2O_3$, $TiO_2 + Fe_2O_3$, $MnO + CeO_2$
Amber	Na_2S
Yellow	CdS, $CeO_2 + TiO_2$
Orange	CdS + Se
Red	CdS + Se, Au, Cu, Sb_2S_3
Black	Co_3O_4 (+ Mn, Ni, Fe, Cu, Cr oxides)

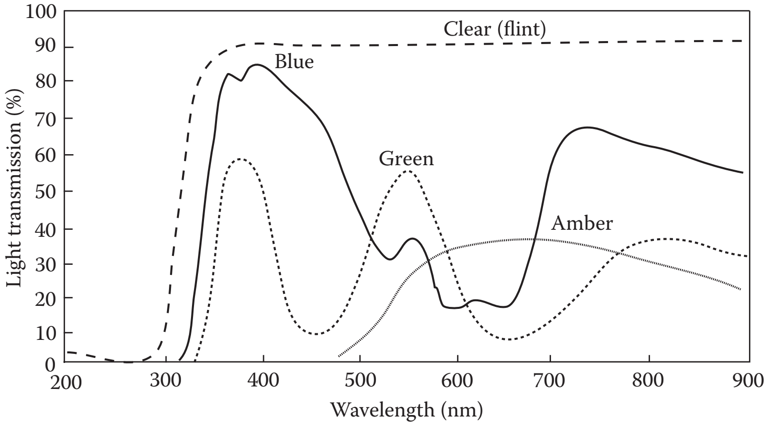

FIGURE 8.2 Typical light transmission of common container glasses.

of iron oxide in glass produces a green color owing to the absorption bands in the UV and IR regions. The three main colors of glass used to produce containers are flint or clear, amber or brown and green.

The U.S. Pharmacopoeia (2004) defines a light-resistant container as one which passes no more than 10% of incident radiation at any wavelength between 290 and 450 nm through the average sidewall thickness. Amber glass provides this degree of light protection quite economically, as shown in Figure 8.2.

Glasses and other transparent materials tend to darken and lose much of their ability to transmit light when bombarded by high energy radiations such as those used in food irradiation. There are two principal causes of this coloration of glass. First, the impact of the radiations may displace electrons, which can become lodged in holes in the structure, forming color centers. Second, changes produced in the valence of bivalent or multivalent metal oxides may result in the increased absorption of light in the visible range. This second effect forms the basis of the process to protect glass from this coloration where a metal oxide (which will change its valence under bombardment more readily than the electrons are displaced) is included in the composition of the glass. Provided that the oxide is free from serious light absorption bands in both valences, protection from discoloration may be obtained. The addition of CeO_2 (it is reduced to Ce_2O_3 by the radiations) in glasses in amounts up to 1.5% has proved an effective means of reducing coloration. Unfortunately, it is a very expensive oxide, so glass containers treated this way are significantly more costly than standard containers.

8.4 MANUFACTURE

8.4.1 Mixing and Melting

The typical composition of a soda-lime glass is given in Table 8.1. The largest constituent (68%–73%) is silica; the second largest constituent (15%–50%) is cullet, originating both as glass scrap from the factory and recycled glass from consumers (so-called *postconsumer* glass). Flint glass is the most color sensitive with a tolerance of 1% green or 5% amber cullet in the batch mix. Amber glass can tolerate 10% green cullet, while up to a 50% mixture of amber and flint cullet can be used in the production of green glass. The use of cullet can cause problems with the production of some types of glass unless there is good separation of colored glass and removal of associated material such as labels. In addition to the problem of color mixing, ceramic and metal contamination (especially aluminum bottle caps) can also limit the use of cullet in glass manufacturing. However, the use of cullet is economically desirable since less energy is required to melt cullet than new raw materials.

Cullet also reduces the amount of dust and other particulate matter that often accompanies a batch made exclusively from new raw materials (Boyd et al., 1994). Although the total primary energy use decreases as the percent of cullet rises, the maximum energy saved is only about 13% (Gaines and Mintz, 1994).

The raw materials are weighed, mixed and charged into a glass-melting furnace, which is maintained at a temperature of approximately 1500°C. Here, they are converted into molten glass that is chemically homogeneous and virtually free of gaseous inclusions (bubbles). The melting process consists of two phases: (1) changing the solids into a liquid and (2) fining or "clearing up" of the liquid. During the refining process, gases (principally CO_2, SO_2 and water vapor) produced by the chemical reaction rise to the surface of the furnace and are removed. When the molten glass becomes free of gas (seed-free), it is then ready for forming into containers. It moves from the furnace into the working end of the furnace (mistakenly called the *refiner*) where thermal homogenization and cooling of the glass to the viscosity required for the particular operation begin. At this point, the temperature of the melt has been lowered from 1250°C to 1350°C to approximately 1100°C.

The preferred energy source for glassmaking is natural gas, although alternate fuels such as oil and propane are used in some plants. With increasingly stringent environmental regulations limiting the emissions of NO_x from glass container furnaces, various systems have been introduced using natural gas and O_2 as the furnace fuel (Cavanagh, 1997). When air (78% N_2) is subjected to very high temperatures, various oxides of nitrogen are formed. By using natural gas and O_2 as the furnace fuel, there is no N_2 to be oxidized. In addition, there are improvements in energy efficiency since only two volumes of O_2 are needed to burn 1 volume of natural gas compared to 10 volumes when air is used. This reduces the total energy requirement by up to one-third (Cavanagh, 1997).

8.4.2 FORMING PROCESSES

The glass is carried from the working end of the furnace to the forming machine in a channel-like structure called a *forehearth*, which is fired by a number of small burners, the aim being to ensure uniform temperature distribution throughout the depth of the glass. At the end of the forehearth is a gob-forming mechanism consisting of a rotating sleeve and vertical plunger. The glass exits in a continuous, viscous stream which is cut by rapidly moving, horizontal steel blades to form what is known as a "gob" (i.e., a mass or lump of molten glass).

Precise control of temperature and shape during the formation of the gob is required for the high-speed production of accurately formed glass containers. Temperatures in the vicinity of 1100°C varying by no more than ±1°C are typical.

The process of converting a cylindrically shaped gob of glass into a bottle or jar is called forming, and it is essentially a controlled cooling process. While various types of forming machines are used throughout the world, the most predominant type is the IS machine. As its name implies, it consists of up to 16 sections, each one an individually functioning, hollow glass machine. It performs two basic functions: it shapes the gob into a hollow container, and simultaneously removes heat from the gob to prevent it from deforming significantly under its own weight.

Two basic types of processes are used to make containers on the IS machine: the blow and blow (B&B) and the press and blow (P&B). A closure size of approximately 35 mm is the dividing line between narrow-neck B&B containers (i.e., bottles) and wide-mouth P&B containers (i.e., jars).

8.4.2.1 Blow and Blow

Bottles are normally produced by a two-step B&B process (Figure 8.3), whereby a gob of glass, accurately sheared in terms of weight and shape, is delivered into an externally air cooled, cast iron mold from above to shape a preform (also known as a parison or body blank). Some of the glass flows

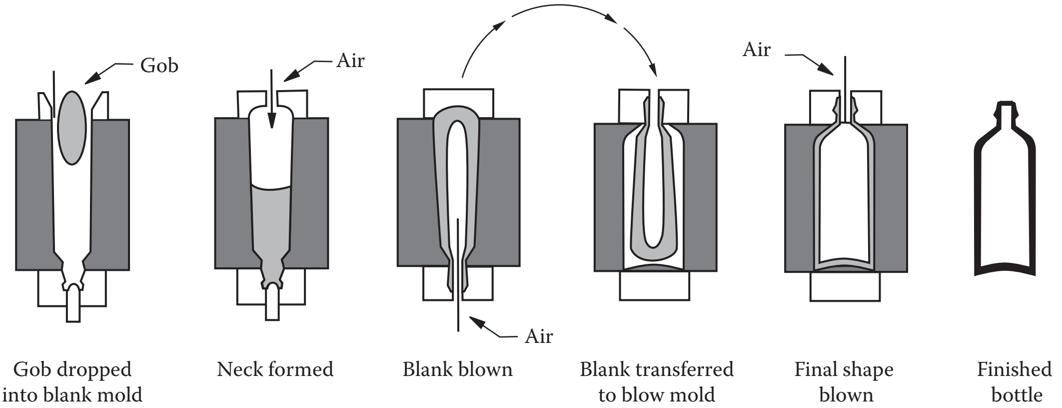

FIGURE 8.3 "Blow and blow" process for glass container manufacture.

over a plunger in the base of the mold, which is used to mold the finish (so-called because in the early days of glass manufacturing, it was the part of the container to be fabricated last) of the container by means of ring molds. Compressed air is applied to force the glass down onto the plunger to form the neck ring. Sometimes, vacuum is applied from the bottom as an alternative or additional procedure.

When the finish molding is complete, the plunger is retracted and air blown in from the bottom of the mold, enlarging the size of the bubble until the glass is pressed out against the blank mold to form a hollow, thick-walled preform or parison. This is then inverted and transferred to the blow mold where it elongates under its own weight until it nearly touches the base of the mold. Air at about 200 kPa is applied so that the glass is pressed against the metal surface of the blow mold, which is air-cooled to ensure rapid removal of heat. The mold is then opened and the fully blown parison (now at approximately 650°C) is removed and briefly held over a deadplate to allow air to flow up through the deadplate and around the container to further cool it. It is then transported to the annealing lehr.

8.4.2.2 Wide Mouth Press and Blow

In the case of jars, a two-step WMP&B process (Figure 8.4) is used. The body blank or parison is formed by pressing the gob of molten glass against the mold walls with a large plunger. When the cavity is filled, glass is then pushed down into the neck ring and the finish is formed. No baffle or

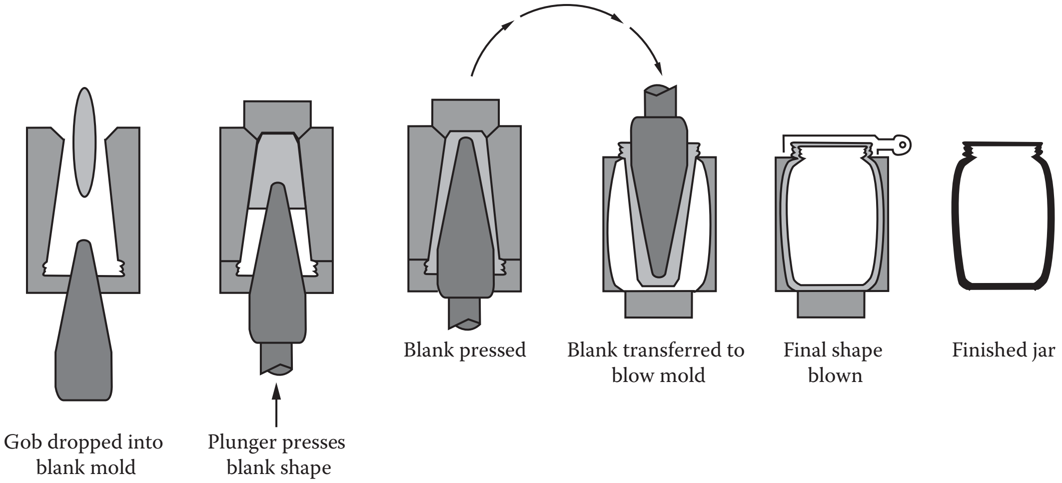

FIGURE 8.4 Wide mouth "press and blow" process for glass container manufacture.

counterblow air is used in the formation of the parison, with the operation relying on the mechanical introduction of the plunger into the glass. The rest of the steps in the WMP&B process are identical to those in the B&B process.

8.4.2.3 Narrow Neck Press and Blow

Narrow neck press and blow (NNP&B) is a more recent process for lightweight bottles, in which the gob is delivered into the blank mold and pressed by a metal plunger. The plunger and gob together have the same volume as the blank mold cavity. This enables the glassmaker to decide exactly how the glass is distributed in the parison and, hence, to be able to more accurately control the uniformity of glass distribution in the finished container. Indeed, weight savings of up to 30% can be made. The second stage is similar to the B&B process. The parison is blown to a finished container having a more uniform wall thickness and, as a result, higher strength.

The mechanical performance of lightweight glass bottles produced by the NNP&B process has been compared with the same glass bottles (regular weight 20% heavier) produced by the conventional B&B process (Jaime et al., 2002). The lightweight glass bottles had a more homogenous thickness distribution in comparison with the regular weight bottles and a better performance (about 33% improvement) in relation to the impact strength, especially in the heel. The vertical load strength of the lightweight glass bottle also indicated a superior performance to the regular weight bottle. Due to the better thickness distribution of lightweight glass bottles, they withstood a maximum temperature difference (progressive thermal shock) of 5°C–10°C higher than the regular weight bottles.

8.4.3 ANNEALING

The term annealing generally refers to the removal of stress, and the annealing temperature or point is defined (ASTM C336) as the temperature at which stresses in the glass are relieved in a few minutes. The containers are transferred from the deadplate to a large oven, known as a lehr, which is equipped with a belt conveyer. The function of the annealing lehr is to produce a stable product by removing any residual stresses resulting from nonuniform cooling rates during forming and handling. This is achieved by raising the temperature of the container to approximately 540°C (almost the softening point of the glass), holding it there for a few minutes and then cooling at a rate which is consistent with the removal of stress from a predetermined wall thickness.

The critical area of temperature is between the upper annealing point (softening point) and the lower annealing point, after which they may be cooled at a rate which enables them to be handled as they emerge from the lehr. During cooling, the inside surface is hotter than the outside; this results in compression on the outer surface but tension at the inner surface. As mentioned earlier, glass fractures only in tension and usually at the surface. Sudden cooling introduces tensile stresses into the outer surfaces and compensating compressional stresses in the interior. Poorly annealed containers may be subject to breakage if the tension is high or the inner surface is bruised (Boyd et al., 1994).

8.4.4 SURFACE TREATMENTS

The strength of a newly made glass container can be rapidly reduced by moisture or abrasion, and some form of surface treatment to increase the strength is essential, since glass is nonlubricious. Two general types of surface treatment are applied to glass containers to modify mechanical properties.

8.4.4.1 Hot-End Treatment

In hot-end treatment (typically carried out while the glass container is at 550°C), vapor containing tin or titanium (generally in the form of a tetrachloride) is brought into contact with the outside of the container, forming a thin unimolecular film of metal oxide. This treatment prevents surface damage while the container is still hot, strengthens the surface and improves the adhesion of the subsequent cold-end coating.

8.4.4.2 Cold-End Treatment

Cold-end treatment (typically carried out while the glass container is at less than 100°C) is designed to protect the container surface and assist its flow through the filling line. Typically, it involves spraying an organic material in an aqueous base containing either waxes, stearates, silicones, oleic acid or polyethylene onto the outside of the container to increase its lubricity by providing a surface with a low coefficient of friction (Cavanagh, 1997). It is important to check the compatibility of the cold-end treatment with any adhesives used to attach labels. Sometimes, only the cold-end treatment is applied.

8.4.4.3 Shrink Sleeves

Although not strictly related to surface treatment of glass containers, shrink sleeves will be considered here since they can have an important influence on the formation of imperfections leading to container breakage due to surface contact. Most shrink sleeves are made of oriented plastic films that shrink around a glass container when heat is applied. Two types of protective labels are used on glass bottles in the form of a body sleeve: one constructed from thin, foamed PS; the other is made from uniaxially oriented PVC or PS. The former offers some thermal insulation, while the latter (which can completely wrap the bottle from its neck to underneath the base if desired) contains the glass fragments and prevents shattered glass being scattered in all directions if the bottle is dropped. Shrink sleeves are discussed in more detail in Section 9.5.4.

8.4.5 Defects in Glass Containers

Some 60 defects can occur in finished glass containers, ranging from critical defects such as "birdswings" and "spikes" (long, thin strands inside the container that would probably break off when the container was filled) to minor defects such as "wavy appearance" (an irregular surface on the inside). Defects are classed as "critical" if they are hazardous to the user and make the container completely unusable, "major" if they reduce the usability of the container or its contents and "minor" if they detract from its appearance or acceptability to the consumer (Hanlon et al., 1998).

Accurate classification of defects in glass packaging and their commercial significance are areas of specific expertise and no attempt will be made to describe or catalog them here.

8.5 GLASS CONTAINER DESIGN

One of the major advantages of glass as a packaging material is its capability to be formed into a wide range of shapes related to specific end uses, customer requirements and aesthetic appeal. The commercialization of computer-aided design (CAD) and computer-aided manufacture (CAM) has made the task of designing and manufacturing new glass containers considerably easier and more rapid. This has lead to greater flexibility and resulted in considerable efficiencies through a more thorough analysis of stresses and strength/weight factors and calculation of likely mechanical performance. In particular, the application of finite element analysis (FEA) has resulted in lightweighting of glass containers with improved mechanical performance (Davis, 2009). Numerical modeling and simulations have also been applied in the production of glass containers to optimize performance (Dijkstra and Mattheij, 2008). For example, the forming process has been modeled as a coupled thermodynamic/mechanical problem with corresponding interaction between glass, air and equipment and correctly represented the flow of the glass and the energy exchange during the process. As well, simulations have helped optimize cooling conditions and increased production speeds.

8.5.1 GLASS CONTAINER NOMENCLATURE

The basic nomenclature used for glass containers is shown in Figure 8.5. Usually, the shape of the container is determined by the nature of the product, each product group having a characteristic shape. Thus, liquid products generally have small diameter finishes for easier pouring; solid products require larger finishes for filling and removing the contents. As well as filling and emptying requirements, consideration must also be given to the nature and manner of labeling the container, and its compatibility with packaging and shipping systems.

The container finish is the part of the container that holds the cap or closure (i.e., the glass surrounding the opening in the container). It must be compatible with the cap or closure and can be broadly classified by size (i.e., diameter), sealing method (e.g., twist cap, cork, etc.) and special features (e.g., snap cap, pour-out, etc.).

The finish has several specific areas including the sealing surface, which may be on the top or side of the finish, or a combination of the two; the glass lug, which is one of several horizontal, tapering and protruding ridges of glass around the periphery of the finish on which the closure can be secured by twisting; the continuous thread, which is a spiral projecting glass ridge on the finish, intended to mesh with the thread of a screw-type closure; a transfer bead, which is a continuous horizontal ridge near the bottom of the finish, used in transferring the container from one part of the manufacturing operation to another; a vertical neck ring seam resulting from the joining of the two parts of the neck ring; and a neck ring parting line, which is a horizontal mark on the glass surface at the bottom of the neck ring or finish ring, resulting from the matching of the neck ring parts with the body mold parts. Not all glass containers have transfer beads or vertical neck ring seams.

Although there are literally hundreds of different finishes used on glass containers, a series of voluntary standards containing specific dimensions, specifications and tolerances has been established for every finish designation by the Glass Packaging Institute (GPI) in the United States and equivalent bodies in other parts of the world. These voluntary standards are intended to provide a basis for achieving compatibility and interchangeability between manufacturers and users of glass containers and closures.

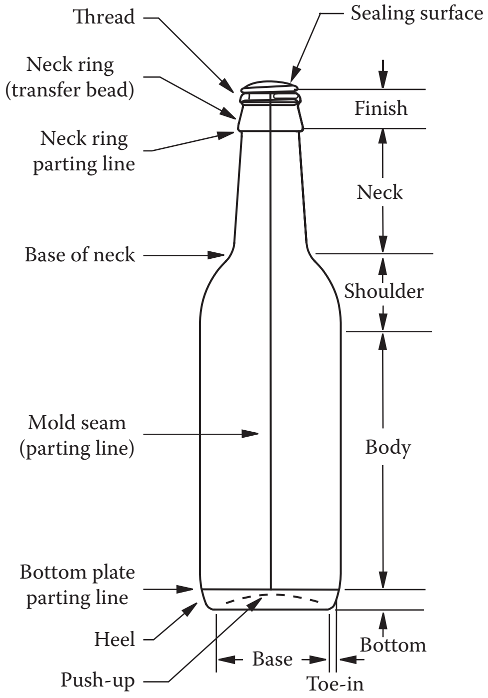

FIGURE 8.5 Glass container nomenclature.

Once a design has been accepted, the molds used in the manufacturing process must be made. They are usually constructed of cast iron and consist of three parts: a bottom plate, a body mold (divided vertically into two halves) and a neck or finish mold, which is also usually split into two parts. Because of the high cost of mold manufacture, changes to container size and shape are usually made only if large quantities of the container are required. Generally, customers select their containers from the standard range provided by glass manufacturers unless they are extremely large users, in which case the extra expense of customized designs is justified.

The GPI has established limits which are generally accepted as reasonable tolerances by most manufacturers. Allowances have been made for increases in container size as a consequence of mold wear, as well as expected process capabilities of the manufacturer. Although closer tolerances can be met, this often incurs a higher cost since molds must be replaced more frequently.

8.5.2 GLASS CONTAINER STRENGTH FACTORS

The shape, surface condition, applied stresses and glass weight all combine to determine the strength of a glass container (Glass container design, 1997). Sharp transitions in container shape (e.g., a rectangular cross section compared to a circular cross section) lead to high stress concentrations. Small surface imperfections formed as a result of surface contact during the manufacturing process and subsequent handling operations can influence container strength. Good design will incorporate specific contact areas (e.g., knurls or small protrusions) that concentrate abrasions where they will have minimal effect on glass strength. Surface treatments (see Section 8.4.4) also assist in reducing surface abrasions.

The forces applied to a glass container during its intended use depend largely on the function of the container. Carbonated beverages and vacuum-packed foods develop internal pressure stresses, predominantly circumferential and longitudinal. In the cylindrical part of a typical glass bottle, the circumferential stress S depends on the bottle diameter d, the glass thickness x and the pressure p as follows (Glass container design, 1997):

$$S = \frac{pd}{2x} \tag{8.1}$$

The longitudinal stress in this part of the bottle is one-half of the circumferential value S; Equation 8.1 does not hold for the noncylindrical parts of a bottle.

Typical pressures inside a carbonated beverage bottle at ambient temperatures are 400 kPa (four volumes of CO_2 gas per volume of beverage), rising to about 700 kPa at 40°C and 1000 kPa at pasteurization temperatures. Bottles for carbonated beverages have target bursting strengths well in excess of the equilibrium pressure of a carbonated beverage. The target bursting strength of a nonrefillable, one-way bottle is between 1240 and 1380 kPa, and for a returnable bottle about 1720 kPa. Willhoft (1986) presented figures which indicated that the mean bursting pressure for a brand new, untouched glass bottle was 4054 kPa, falling to 2331 kPa on delivery to the bottler and to 1524 kPa after long use.

Vertical load stresses are generated by stacking containers on top of each other or by applying a closure; these compressive forces produce tensile stresses in the shoulder and heel region of up to 690 kPa. These stresses can be lowered by decreasing the diameter difference between the neck and the body, by increasing the shoulder radius and by reducing the diameter difference between the body and the bearing surface (Glass container design, 1997).

During hot filling or pasteurizing of glass containers, the rapid temperature changes lead to the development of tension stresses on the cold surface and compression stresses on the hot surface, with additional bending stresses being generated by expansions and contractions of the container (see Section 8.3.2). Thermal stresses can be reduced by minimizing the temperature gradient from the hot to the cold side, decreasing the glass thickness, and avoiding sharp corners, especially in the heel.

Stresses caused by steady-state thermal gradients may or may not cause failure, depending on the degree of constraint imposed by some parts of the container on others, or by the external mounting. Consequently, under minimum constraint and maximum uniformity of gradient through the thickness, very large temperature differences can be tolerated (Boyd et al., 1994).

8.6 CLOSURES FOR GLASS CONTAINERS

The final, critical aspect of glass packaging is the closure which can consist of a cap, lid, cork or plug to seal the jar or bottle. Although glass is an excellent barrier to moisture vapor, gases and odors, an incorrectly designed or applied closure may negate the benefits that glass packaging offers in protecting foods from deterioration. Closures for glass containers are discussed in Chapter 10.

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