16 Processing of Ceramics and Cermets

Chapter Contents

Ceramic materials divide into three categories: (1) traditional ceramics, (2) new ceramics, and (3) glasses. The processing of glass involves solidification primarily and is covered in Chapter 12. The present chapter considers the particulate processing methods used for traditional and new ceramics. Also included is the processing of metal matrix composites and ceramic matrix composites.

Traditional ceramics are made from minerals occurring in nature. They include pottery, porcelain, bricks, and cement. New ceramics are made from synthetically produced raw materials and cover a wide spectrum of products such as cutting tools, artificial bones, nuclear fuels, and substrates for electronic circuits. The starting material for all of these items is powder. In the case of the traditional ceramics, the powders are usually mixed with water to temporarily bind the particles together and achieve the proper consistency for shaping. For new ceramics, other substances are used as binders during shaping. After shaping, the green parts are sintered. This is often called ***firing*** in ceramics, but the function is the same as in powder metallurgy: to effect a solid-state reaction that bonds the material into a hard solid mass.

The processing methods discussed in this chapter are commercially and technologically important because virtually all ceramic products are formed by these methods (except, of course, glass products). The manufacturing sequence is similar for traditional and new ceramics because the form of the starting material is the same: powder. However, the processing methods for the two categories are sufficiently different that they are discussed separately.

16.1 Processing of Traditional Ceramics

This section describes the production technology used to make traditional ceramic products such as pottery, stoneware and other dinnerware, bricks, tile, and ceramic refractories. Bonded grinding wheels are also produced by the same basic methods. What these products have in common is that their raw materials consist primarily of silicate ceramics—clays. The processing sequence for most of the traditional ceramics consists of the steps depicted in Figure 16.1.

16.1.1 PREPARATION OF THE RAW MATERIAL

The shaping processes for traditional ceramics require that the starting material be in the form of a plastic paste. This paste is made of fine ceramic powders mixed with water, and its consistency determines the ease of forming the material and the quality of the final product. The raw ceramic material usually occurs in nature as rocky lumps, and reduction to powder is the purpose of the preparation step in ceramics processing.

Techniques for reducing particle size in ceramics processing involve mechanical energy in various forms, such as impact, compression, and attrition. The term ***comminution*** is used for these techniques, which are most effective on brittle materials, including cement, metallic ores, and brittle metals. Two general categories of comminution operations are distinguished: crushing and grinding.

Crushing refers to the reduction of large lumps from the mine to smaller sizes for subsequent further reduction. Several stages may be required (e.g., primary crushing, secondary crushing), the reduction ratio in each stage being in the range 3 to 6. Crushing of minerals is accomplished by compression against rigid surfaces or by impact against surfaces in a rigid constrained motion [1]. Figure 16.2 shows several types of equipment used to perform crushing: (a) jaw crushers, in which a large jaw toggles back and forth to crush lumps against a hard, rigid surface; (b) gyratory crushers, which use a gyrating cone to compress lumps against a rigid surface; (c) roll crushers, in which

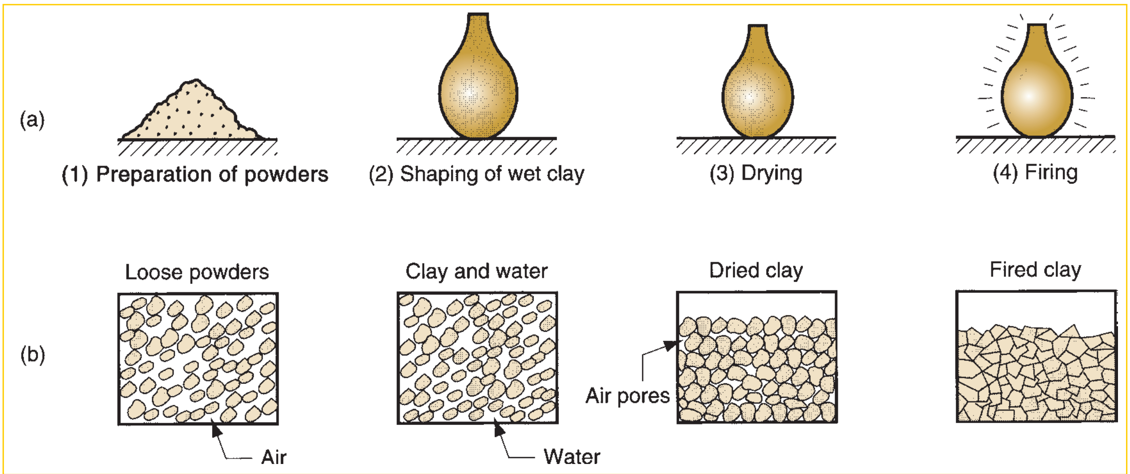

FIGURE 16.1 Usual steps in traditional ceramics processing: (1) preparation of raw materials, (2) shaping, (3) drying, and (4) firing. Part (a) shows the work part during the sequence, whereas (b) shows the condition of the powders.

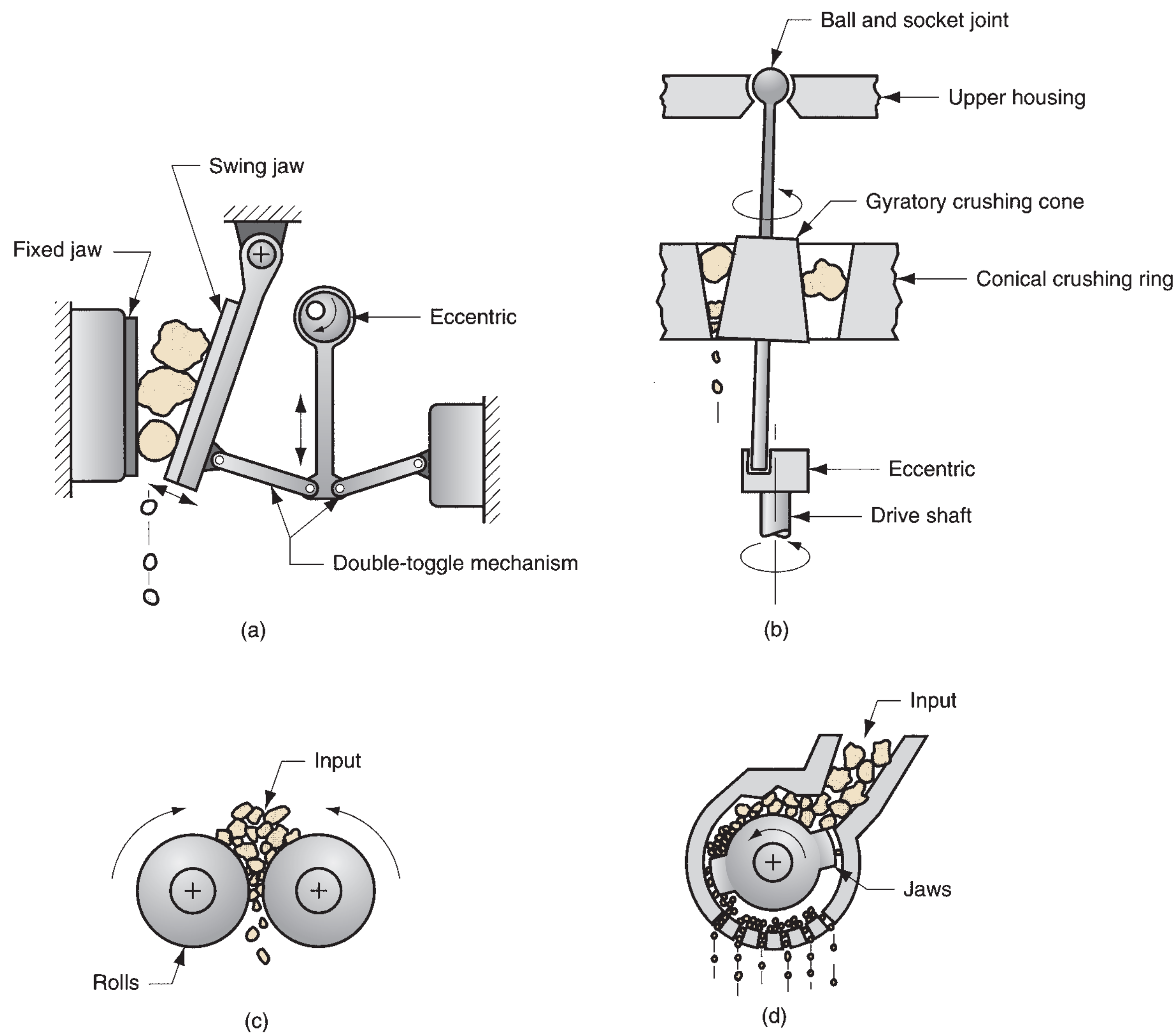

FIGURE 16.2 Crushing operations: (a) jaw crusher, (b) gyratory crusher, (c) roll crusher, and (d) hammer mill.

the ceramic lumps are squeezed between rotating rolls; and (d) hammer mills, which use rotating hammers impacting the material to break up the lumps.

Grinding, in the context here, refers to the operation of reducing the small pieces produced by crushing into a fine powder. Grinding is accomplished by mechanisms such as abrasion, compaction, and impact of the crushed mineral by hard bodies such as balls, rollers, or surfaces. Examples of grinding include (a) ball mill, (b) roller mill, and (c) impact grinding, illustrated in Figure 16.3.

In a ***ball mill***, hard spheres mixed with the stock to be comminuted are tumbled inside a rotating cylindrical container. The rotation causes the balls and stock to be carried up the container wall, and then pulled back down by gravity to accomplish a grinding action by a combination of impact and attrition. These operations are often carried out with water added to the mixture, so that the ceramic is in the form of a slurry. In a ***roller mill***, stock is compressed against a flat horizontal grinding table by rollers riding over the table surface. Although not clearly shown in the sketch, the

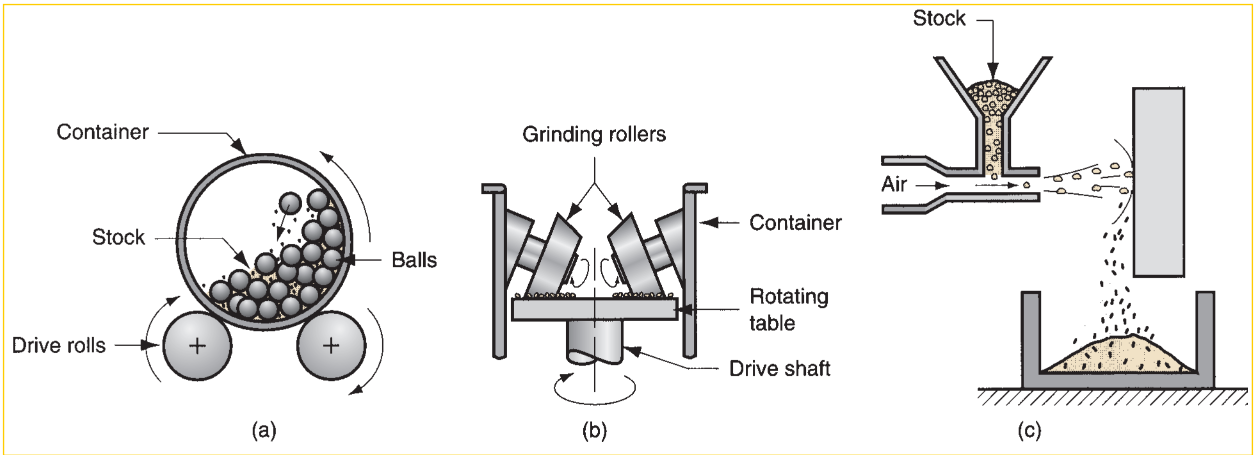

FIGURE 16.3 Mechanical methods of producing ceramic powders: (a) ball mill, (b) roller mill, and (c) impact grinding.

pressure of the grinding rollers against the table is regulated by mechanical springs or hydraulic-pneumatic means. In ***impact grinding***, which seems to be less frequently used, particles of stock are thrown against a hard flat surface, either in a high velocity air stream or a high-speed slurry. The impact fractures the pieces into smaller particles.

The plastic paste required for shaping consists of ceramic powders and water. Clay is usually the main ingredient in the paste because it has ideal forming characteristics. The more water there is in the mixture, the more plastic and easily formed is the clay paste. However, when the formed part is later dried and fired, shrinkage occurs that can lead to cracking in the product. To address this problem, other ceramic raw materials that do not shrink on drying and firing are usually added to the paste, often in significant amounts. Also, other components can be included to serve special functions. Thus, the ingredients of the ceramic paste can be divided into the following three categories [3]: (1) clay, which provides the consistency and plasticity required for shaping; (2) nonplastic raw materials, such as alumina and silica, which do not shrink in drying and firing but unfortunately reduce plasticity in the mixture during forming; and (3) other ingredients, such as fluxes that melt (vitrify) during firing and promote sintering of the ceramic material, and wetting agents that improve mixing of ingredients.

These ingredients must be thoroughly mixed, either wet or dry. The ball mill often serves this purpose in addition to its grinding function. Also, the proper amounts of powder and water in the paste must be attained, so water must be added or removed, depending on the prior condition of the paste and its desired final consistency.

16.1.2 SHAPING PROCESSES

The optimum proportions of powder and water depend on the shaping process used. Some shaping processes require high fluidity; others act on a composition that contains very low water content. At about 50% water by volume, the mixture is a slurry that flows like a liquid. As the water content is reduced, increased pressure is required on the paste to produce a similar flow. Thus, the shaping processes can be divided according to the consistency of the mixture: (1) slip casting, in which the mixture is a slurry with 25% to 40% water; (2) plastic-forming methods that shape the clay in a plastic condition at 15% to 25% water; (3) semi-dry pressing, in which

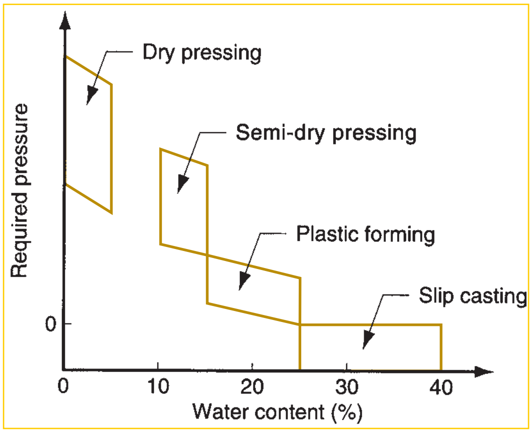

FIGURE 16.4 Four categories of shaping processes used for traditional ceramics, compared with water content and pressure required to form the clay.

the clay is moist (10%–15% water) but has low plasticity; and (4) dry pressing, in which the clay is basically dry, containing less than 5% water. Dry clay has no plasticity. The four categories are represented in the chart of Figure 16.4, which compares the categories with the condition of the clay used as starting material. Each category includes several different shaping processes.

Slip Casting In slip casting, a suspension of ceramic powders in water, called a ***slip***, is poured into a porous plaster of paris ($CaSO_4$–$2H_2O$) mold so that water from the mix is gradually absorbed into the plaster to form a firm layer of clay at the mold surface. The composition of the slip is typically 25% to 40% water, the remainder being clay often mixed with other ingredients. It must be sufficiently fluid to flow into the crevices of the mold cavity, yet lower water content is desirable for faster production rates. Slip casting has two principal variations: drain casting and solid casting. In ***drain casting***, which is the traditional process, the mold is inverted to drain excess slip after the semi-solid layer has been formed, thus leaving a hollow part in the mold; the mold is then opened and the part removed. The sequence, which is very similar to slush casting of metals, is illustrated in Figure 16.5. It is used to make tea pots, vases, art objects, and other hollow-ware products. In ***solid casting***, used to produce solid products, adequate time is allowed for the entire body

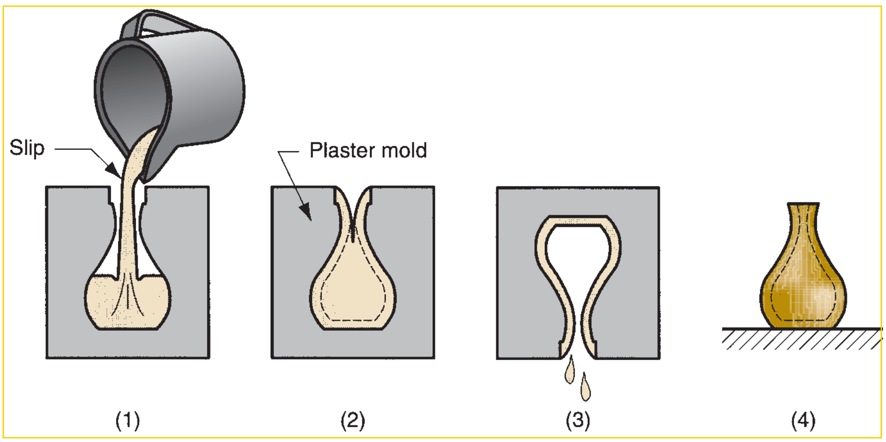

FIGURE 16.5 Sequence of steps in drain casting, a form of slip casting: (1) slip is poured into mold cavity; (2) water is absorbed into plaster mold to form a firm layer; (3) excess slip is poured out; and (4) part is removed from mold and trimmed.

to become firm. Additional slip must be periodically added to account for shrinkage as water is absorbed into the mold.

Plastic Forming This category includes a variety of methods, both manual and mechanized. They all require the starting mixture to have a plastic consistency, which is generally achieved with 15% to 25% water. Manual methods generally make use of clay at the upper end of the range because it provides a material that is more easily formed; however, this is accompanied by greater shrinkage in drying. Mechanized methods generally employ a mixture with lower water content so that the starting clay is stiffer.

Although manual forming methods date back thousands of years, they are still used today by skilled artisans, either in production or for artworks. ***Hand modeling*** involves the creation of the ceramic product by manipulating the mass of plastic clay into the desired geometry. In addition to art pieces, patterns for plaster molds in slip casting are often made this way. ***Hand molding*** is a similar method, only a mold or form is used to define portions of the geometry. ***Hand throwing*** on a potter's wheel is another refinement of the handicraft methods. The ***potter's wheel*** is a round table that rotates on a vertical spindle, powered either by motor or foot-operated treadle. Ceramic products of circular cross section can be formed on the rotating table by throwing and shaping the clay, sometimes using a mold to provide the internal shape.

Strictly speaking, use of a motor-driven potter's wheel is a mechanized method. However, most mechanized clay-forming methods are characterized by much less manual participation than the hand-throwing method described above. These more mechanized methods include jiggering, plastic pressing, and extrusion. ***Jiggering*** is an extension of the potter's wheel methods, in which hand throwing is replaced by mechanized techniques. It is used to produce large numbers of identical items such as houseware plates and bowls. Although there are variations in the tools and methods used, reflecting different levels of automation and refinements to the basic process, a typical sequence is as follows, depicted in Figure 16.6: (1) a wet clay slug is placed on a convex mold; (2) a forming tool is pressed into the slug to provide the initial rough shape—the operation is called ***batting*** and the workpiece thus created is called a ***bat***; and (3) a heated jigger tool is used to impart the final contoured shape to the product by pressing the profile into the surface during rotation of the work part. The reason for heating the tool is to produce steam from the wet clay that prevents sticking. Closely related to jiggering is ***jolleying***, in which the basic mold shape is concave, rather than convex [8]. In both of these processes, a rolling tool is sometimes used in place of the nonrotating jigger (or jolley) tool; this rolls the clay into shape, avoiding the need to first bat the slug.

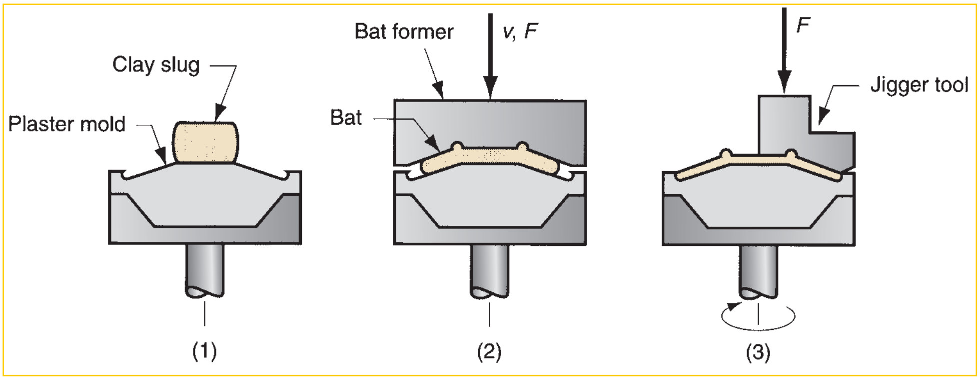

FIGURE 16.6 Sequence in jiggering: (1) wet clay slug is placed on a convex mold; (2) batting; and (3) a jigger tool imparts the final product shape. Symbols v and F indicate motion (v = velocity) and applied force, respectively.

Plastic pressing is a forming process in which a plastic clay slug is pressed between upper and lower molds, contained in metal rings. The molds are made of a porous material such as gypsum, so that when a vacuum is drawn on the backs of the mold halves, moisture is removed from the clay. The mold sections are then opened, using positive air pressure to prevent sticking of the part in the mold. Plastic pressing achieves a higher production rate than jiggering and is not limited to radially symmetric parts.

Extrusion is used in ceramics processing to produce long sections of uniform cross section, which are then cut to required piece length. The extrusion equipment utilizes a screw-type action to assist in mixing the clay and pushing the plastic material through the die opening. This production sequence is widely used to make hollow bricks, shaped tiles, drain pipes, tubes, and insulators. It is also used to make the starting clay slugs for other ceramics processing methods such as jiggering and plastic pressing.

Semi-dry Pressing In semi-dry pressing, the proportion of water in the starting clay is typically 10% to 15%. This results in low plasticity, precluding the use of plastic forming methods that require a very plastic clay. Semi-dry pressing uses high pressure to overcome the material's low plasticity and force it to flow into a die cavity, as depicted in Figure 16.7. Flash is often formed from excess clay being squeezed between the die sections.

Dry Pressing The main distinction between semi-dry and dry pressing is the moisture content of the starting mix. The moisture content of the starting clay in dry pressing is typically below 5%. Binders are usually added to the dry powder mix to provide sufficient strength in the pressed part for subsequent handling. Lubricants are also added to prevent die sticking during pressing and ejection. Because dry clay has no plasticity and is very abrasive, there are differences in die design and operating procedures, compared with semi-dry pressing. The dies must be made of hardened tool steel or cemented tungsten carbide to reduce wear. Because dry clay will

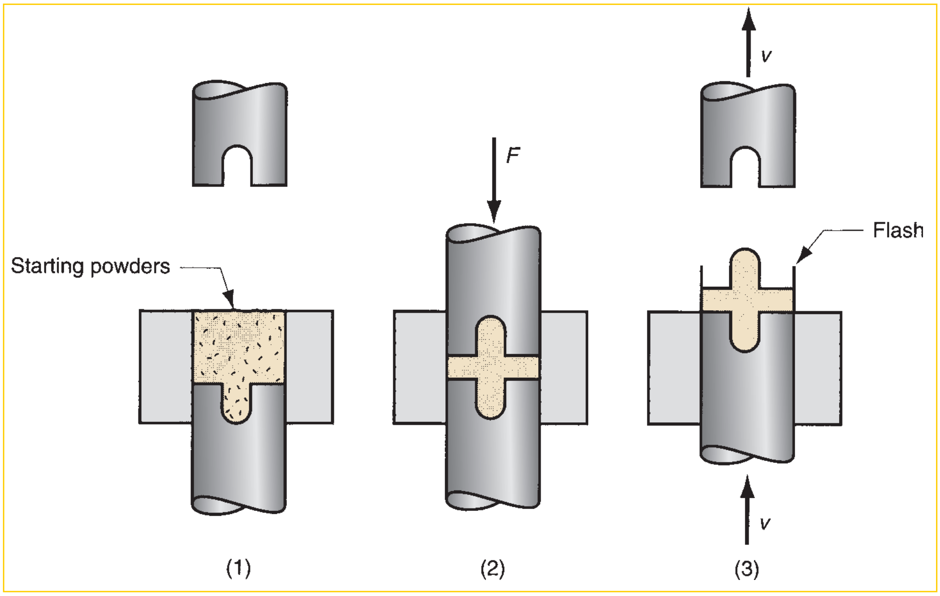

FIGURE 16.7 Semi-dry pressing: (1) depositing moist powder into die cavity, (2) pressing, and (3) opening the die sections and ejection. Symbols v and F indicate motion (v = velocity) and applied force, respectively.

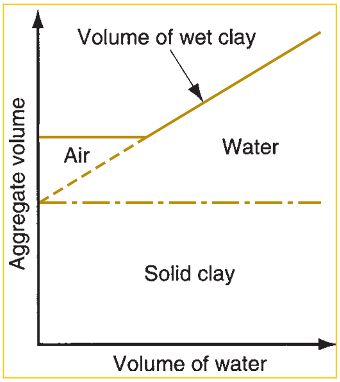

FIGURE 16.8 Volume of clay as a function of water content. Relationship shown here is typical; it varies for different clay compositions.

not flow during pressing, the geometry of the part must be relatively simple, and the amount and distribution of starting powder in the die cavity must be right. No flash is formed in dry pressing, and no drying shrinkage occurs, so drying time is eliminated and good accuracy can be achieved in the dimensions of the final product. The process sequence in dry pressing is similar to semi-dry pressing. Typical products include bathroom tile, electrical insulators, and refractory brick.

16.1.3 DRYING

Water plays an important role in most of the traditional ceramics shaping processes. Thereafter, it serves no purpose and must be removed from the body of the clay piece before firing. Shrinkage is a problem during this step in the processing sequence because water contributes volume to the piece, and when it is removed, the volume is reduced. The effect can be seen in Figure 16.8. As water is initially added to dry clay, it simply replaces the air in the pores between ceramic grains, and there is no volumetric change. Increasing the water content above a certain point causes the grains to become separated and the volume to grow, resulting in a wet clay that has plasticity and formability. As more water is added, the mixture eventually becomes a liquid suspension of clay particles in water.

The reverse of this process occurs in drying. As water is removed from the wet clay, the volume of the piece shrinks. The drying process occurs in two stages, as depicted in Figure 16.9. In the first stage, the rate of drying is rapid and constant,

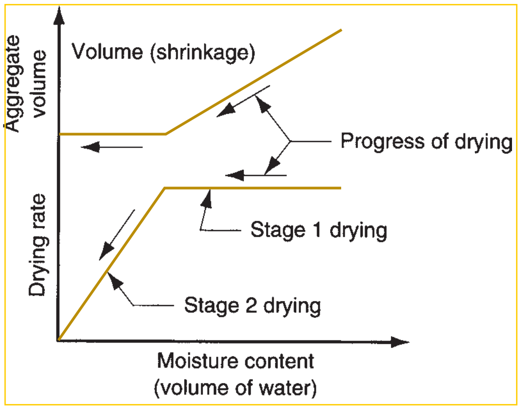

FIGURE 16.9 Typical drying rate curve and associated volume reduction (drying shrinkage) for a ceramic body in drying. Drying rate in the second stage of drying is depicted here as a straight line (constant rate decrease as a function of water content); the function is variously shown as concave or convex in the literature [3], [8].

as water is evaporated from the surface of the clay into the surrounding air, and water from the interior migrates by capillary action toward the surface to replace it. It is during this stage that shrinkage occurs, with the associated risk of warping and cracking because of variations in drying in different sections of the piece. In the second stage of drying, the moisture content has been reduced to where the ceramic grains are in contact, and little or no further shrinkage occurs. The drying process slows, and this is seen in the decreasing rate in the plot.

In production, drying is usually accomplished in drying chambers in which temperature and humidity are controlled to achieve the proper drying schedule. Care must be taken so that water is not removed too rapidly, lest large moisture gradients be set up in the piece, making it more prone to crack. Heating is usually by a combination of convection and radiation, using infrared sources. Typical drying times range between a quarter of an hour for thin sections to several days for very thick sections.

16.1.4 FIRING (SINTERING)

After shaping but before firing, the ceramic piece is said to be ***green*** (same term as in powder metallurgy), meaning not fully processed or treated. The green piece lacks hardness and strength; it must be fired to fix the part shape and achieve hardness and strength in the finished ware. ***Firing*** is the heat treatment process that sinters the ceramic material; it is performed in a furnace called a ***kiln***. In ***sintering***, bonds are developed between the ceramic grains, and this is accompanied by densification and reduction of porosity. Therefore, shrinkage occurs in the polycrystalline material in addition to the shrinkage that has already occurred in drying. Sintering in ceramics is basically the same mechanism as in powder metallurgy. In the firing of traditional ceramics, certain chemical reactions between the components in the mixture may also take place, and a glassy phase also forms among the crystals that acts as a binder. Both of these phenomena depend on the chemical composition of the ceramic material and the firing temperatures used.

Unglazed ceramic ware is fired only once; glazed products are fired twice. ***Glazing*** refers to the application of a ceramic surface coating to make the piece more impervious to water and enhance its appearance (Section 7.2.2). The usual processing sequence with glazed ware is (1) fire the ware once before glazing to harden the body of the piece, (2) apply the glaze, and (3) fire the piece a second time to harden the glaze.

2 Processing of New Ceramics

Most of the traditional ceramics are based on clay, which possesses a unique capacity to be plastic when mixed with water but hard when dried and fired. Clay consists of various formulations of hydrous aluminum silicate, usually mixed with other ceramic materials, to form a rather complex chemistry. New ceramics (Section 7.3) are based on simpler chemical compounds, such as oxides, carbides, and nitrides. These materials do not possess the plasticity and formability of traditional clay when mixed with water. Accordingly, other ingredients must be combined with the ceramic powders to achieve plasticity and other desirable properties during forming, so that conventional shaping methods can be used. The new ceramics are generally designed for applications that require higher strength, hardness, and other properties not found in the traditional ceramic materials. These requirements have motivated the introduction of several new processing techniques not previously used for traditional ceramics.

The manufacturing sequence for the new ceramics can be summarized in the following steps: (1) preparation of starting materials, (2) shaping, (3) sintering, and (4) finishing. Although the sequence is nearly the same as for traditional ceramics, the details are often quite different.

16.2.1 PREPARATION OF STARTING MATERIALS

Because the strength specified for these materials is usually much greater than for traditional ceramics, the starting powders must be more homogeneous in size and composition, and particle size must be smaller (strength of the resulting ceramic product is inversely related to grain size). All of this means that greater control of the starting powders is required. Powder preparation includes mechanical and chemical methods. The mechanical methods consist of the same ball mill grinding operations used for traditional ceramics. The trouble with these methods is that the ceramic particles become contaminated from the materials used in the balls and walls of the mill. This compromises the purity of the ceramic powders and results in microscopic flaws that reduce the strength of the final product.

Two chemical methods are used to achieve greater homogeneity in the powders of new ceramics: freeze drying and precipitation from solution. In ***freeze drying***, salts of the appropriate starting chemistry are dissolved in water and the solution is sprayed to form small droplets, which are rapidly frozen. The water is then removed from the droplets in a vacuum chamber, and the resulting freeze-dried salt is decomposed by heating to form the ceramic powders. Freeze drying is not applicable to all ceramics, because in some cases a suitable water-soluble salt cannot be identified as the starting material.

Precipitation from solution is another preparation method used for new ceramics. In the typical process, the desired ceramic compound is dissolved from the starting mineral, thus permitting impurities to be filtered out. An intermediate compound is then precipitated from solution, which is converted into the desired compound by heating. An example of the precipitation method is the ***Bayer process*** for producing high purity alumina (also used in the production of aluminum). In this process, aluminum oxide is dissolved from the mineral bauxite so that iron compounds and other impurities can be removed. Then, aluminum hydroxide ($Al(OH)_3$) is precipitated from solution and reduced to Al_2O_3 by heating.

Further preparation of the powders includes classification by size and mixing before shaping. Very fine powders are required for new ceramics applications, and so the grains must be separated and classified according to size. Thorough mixing of the particles, especially when different ceramic powders are combined, is required to avoid segregation.

Various additives are often combined with the starting powders, usually in small amounts. The additives include (1) ***plasticizers*** to improve plasticity and workability; (2) ***binders*** to bond the ceramic particles into a solid mass in the final product, (3) ***wetting agents*** for better mixing; (4) ***deflocculants***, which help to prevent clumping and premature bonding of the powders; and (5) ***lubricants***, to reduce friction between ceramic grains during forming and to reduce sticking during mold release.

16.2.2 SHAPING

Many of the shaping processes for new ceramics are borrowed from powder metallurgy (PM) and traditional ceramics. The PM press and sinter methods discussed in Section 15.3 have been adapted to the new ceramic materials. And some of the traditional ceramics forming techniques (Section 16.1.2) are used to shape the new ceramics, including slip casting, extrusion, and dry pressing. The following processes are not normally associated with the forming of traditional ceramics, although several are associated with PM.

Hot Pressing Hot pressing is similar to dry pressing (Section 16.1.2), except that the process is carried out at elevated temperatures, so that sintering of the product is accomplished simultaneously with pressing. This eliminates the need for a separate firing step in the sequence. Higher densities and finer grain size are obtained, but die life is reduced by the hot abrasive particles against the die surfaces.

Isostatic Pressing Isostatic pressing of ceramics is the same process used in powder metallurgy (Section 15.4.1). It uses hydrostatic pressure to compact the ceramic powders from all directions, thus avoiding the problem of nonuniform density in the final product that is often observed in the traditional uniaxial pressing method.

Doctor-blade Process This process is used for making thin sheets of ceramic. One common application of the sheets is in the electronics industry as a substrate material for integrated circuits. The process is diagrammed in Figure 16.10. A ceramic slurry is introduced onto a moving carrier film such as cellophane. Thickness of the ceramic on the carrier is determined by a wiper, called a ***doctor-blade***. As the slurry moves down the line, it is dried into a flexible green ceramic tape. At the end of the line, a take-up spool reels in the tape for later processing. In its green condition, the tape can be cut or otherwise shaped before firing.

Powder Injection Molding Powder injection molding (PIM) is the same as the powder metallurgy process (Section 15.4.2), except that the powders are ceramic rather than metallic. Ceramic particles are mixed with a thermoplastic polymer that acts as a carrier and provides the proper flow characteristics at molding temperatures. The mix is then heated and injected into a mold cavity. Upon cooling, which hardens the polymer, the mold is opened and the part is removed. Because the temperatures needed to plasticize the carrier are much lower than those required for sintering the ceramic, the piece is green after molding. Before sintering, the plastic

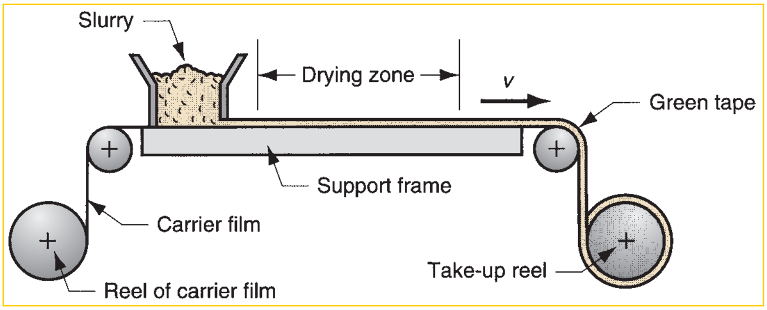

FIGURE 16.10 The doctor-blade process, used to fabricate thin ceramic sheets. Symbol v indicates motion (v = velocity).

binder must be removed. This is called ***debinding***, which is usually accomplished by a combination of thermal and solvent treatments.

Applications of ceramic PIM are currently inhibited by difficulties in debinding and sintering. Burning off the polymer is relatively slow, and its removal significantly weakens the green strength of the molded part. Warping and cracking often occur during sintering. Further, ceramic products made by powder injection molding are especially vulnerable to microstructural flaws that limit their strength.

16.2.3 SINTERING

Because the plasticity needed to shape the new ceramics is not normally based on a water mixture, the drying step so commonly required to remove water from the traditional green ceramics can be omitted in the processing of most new ceramic products. The sintering step, however, is still very much required to obtain maximum possible strength and hardness. The functions of sintering are the same as before, to (1) bond individual grains into a solid mass, (2) increase density, and (3) reduce or eliminate porosity.

Temperatures around 80% to 90% of the melting temperature of the material are commonly used in sintering ceramics. Sintering mechanisms differ somewhat between the new ceramics, which are based predominantly on a single chemical compound (e.g., Al_2O_3), and the clay-based ceramics, which usually consist of several compounds having different melting points. In the case of the new ceramics, the sintering mechanism is mass diffusion across the contacting particle surfaces, probably accompanied by some plastic flow. This mechanism causes the centers of the particles to move closer together, resulting in densification of the final material. In the sintering of traditional ceramics, this mechanism is complicated by the melting of some constituents and the formation of a glassy phase that acts as a binder between the grains.

16.2.4 FINISHING

Parts made of new ceramics sometimes require finishing. In general, these operations have one or more of the following purposes, to (1) increase dimensional accuracy, (2) improve surface finish, and (3) make minor changes in part geometry. Finishing operations usually involve grinding and other abrasive processes (Chapter 24). Diamond abrasives must be used to cut the hardened ceramic materials.

3 Processing of Cermets

Many metal matrix composites (MMCs) and ceramic matrix composites (CMCs) are processed by particulate processing methods. The most prominent examples are cemented carbides and other cermets.

16.3.1 CEMENTED CARBIDES

The cemented carbides are a family of composite materials consisting of carbide ceramic particles embedded in a metallic binder. They are classified as metal matrix composites because the metallic binder is the matrix that holds the bulk material together; however, the carbide particles constitute the largest proportion of the composite material, normally ranging between 80% and 96% by volume. Cemented carbides are technically classified as cermets, although they are often distinguished from the other materials in this class.

The most important cemented carbide is tungsten carbide in a cobalt binder (WC–Co). Generally included within this category are certain mixtures of WC, TiC, and TaC in a Co matrix, in which tungsten carbide is the major component. Other cemented carbides include titanium carbide in nickel (TiC–Ni) and chromium carbide in nickel (Cr_3C_2–Ni). These composites are discussed in Section 9.2.1, and the carbide ingredients are described in Section 7.3.2. The present discussion is directed at the particulate processing of cemented carbide.

To provide a strong and pore-free part, the carbide powders must be sintered with a metal binder. Cobalt works best with WC, whereas nickel is better with TiC and Cr_3C_2. The usual proportion of binder metal is from around 4% up to 20%. Powders of carbide and binder metal are thoroughly mixed wet in a ball mill (or other suitable mixing machine) to form a homogeneous sludge. Milling also serves to refine particle size. The sludge is then dried in a vacuum or controlled atmosphere to prevent oxidation in preparation for compaction.

Compaction Various methods are used to shape the powder mix into a green compact of the desired geometry. The most common process is cold pressing, described earlier and used for high production of cemented carbide parts such as cutting tool inserts. The dies used in cold pressing must be made oversized to account for shrinkage during sintering. Linear shrinkage can be 20% or more. For high production, the dies themselves are made with WC–Co liners to reduce wear, because of the abrasive nature of carbide particles. For smaller quantities, large flat sections are sometimes pressed and then cut into smaller pieces of the specified size.

Other compaction methods used for cemented carbide products include ***isostatic pressing*** and ***hot pressing*** for large pieces, such as draw dies and ball mill balls; and ***extrusion***, for long sections of circular, rectangular, or other cross section. Each of these processes has been described previously, either in this or the preceding chapter.

Sintering Although it is possible to sinter WC and TiC without a binder metal, the resulting material is somewhat less than 100% of true density. Use of a binder yields a structure that is virtually free of porosity.

Sintering of WC–Co involves liquid phase sintering (Section 15.4.5). The process can be explained with reference to the binary phase diagram for these constituents in Figure 16.11. The typical composition range for commercial cemented carbide products is identified in the diagram. The usual sintering temperatures for WC–Co are in the range 1370 to 1425°C (2500–2600°F), which is below cobalt's melting point of 1495°C (2716°F). Thus, the pure binder metal does not melt at the sintering temperature. However, as the phase diagram shows, WC dissolves in Co in the solid state. During the heat treatment, WC is gradually dissolved into the gamma phase, and its melting point is reduced so that melting finally occurs. As the liquid phase forms, it flows and wets the WC particles, further dissolving the solid. The presence of the molten metal also serves to remove gases from the internal regions of the compact. These mechanisms combine to effect a rearrangement of the remaining WC particles into a closer packing, which results in significant densification and shrinkage of the WC–Co

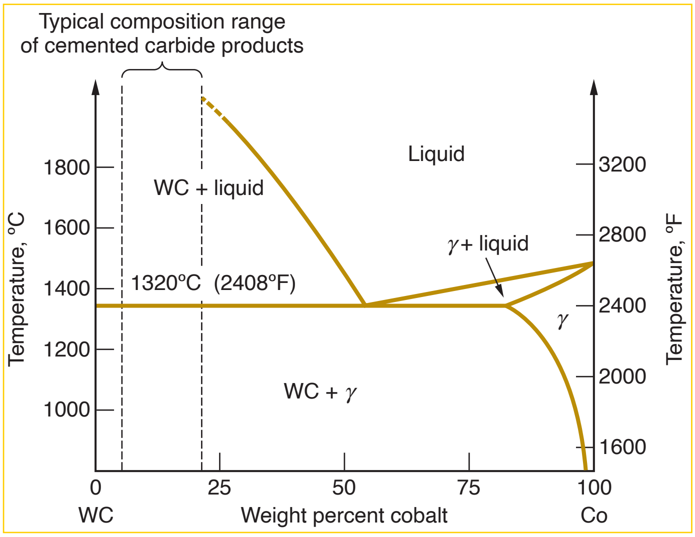

FIGURE 16.11
WC–Co phase diagram.
(Source: [7]).

mass. Later, during cooling in the sintering cycle, the dissolved carbide is precipitated and deposited onto the existing crystals to form a coherent WC skeleton, throughout which the Co binder is embedded.

Secondary Operations Subsequent processing is usually required after sintering to achieve adequate dimensional control of cemented carbide parts. Grinding with a diamond abrasive wheel is the most common secondary operation performed for this purpose. Other processes used to shape the hard cemented carbides include electric discharge machining and ultrasonic machining, two nontraditional material removal processes discussed in Chapter 25.

16.3.2 OTHER CERMETS AND CERAMIC MATRIX COMPOSITES

In addition to cemented carbides, other cermets are based on oxide ceramics such as Al_2O_3 and MgO. Chromium is a common metal binder used in these composite materials. The ceramic-to-metal proportions cover a wider range than those of the cemented carbides; in some cases, the metal is the major ingredient. These cermets are formed into useful products by the same basic shaping methods used for cemented carbides.

The current technology of ceramic matrix composites (Section 9.3) includes ceramic materials (e.g., Al_2O_3, BN, Si_3N_4, and glass) reinforced by fibers of carbon, SiC, or Al_2O_3. If the fibers are whiskers (fibers consisting of single crystals), these CMCs can be processed by particulate methods used for new ceramics (Section 16.2).

16.4 Product Design Considerations

Ceramic materials have special properties that make them attractive to designers if the application is right. The following design recommendations, compiled from Bralla [2] and other sources, apply to both new and traditional ceramic materials, although designers are more likely to find opportunities for new ceramics in engineered products. In general, the same guidelines apply to cemented carbides.

- ➢ Ceramic materials are several times stronger in compression than in tension; accordingly, ceramic components should be designed to be subjected to compressive stresses, not tensile stresses.
- ➢ Ceramics are brittle and possess almost no ductility. Ceramic parts should not be used in applications that involve impact loading or high stresses that might cause fracture.
- ➢ Although many of the ceramic shaping processes allow complex geometries to be formed, it is desirable to keep shapes simple for both economic and technical reasons. Deep holes, channels, and undercuts should be avoided, as should large cantilevered projections.
- ➢ Outside edges and corners should have radii or chamfers; likewise, inside corners should have radii. This guideline is, of course, violated in cutting tool applications, in which the cutting edge must be sharp to function. The cutting edge is often fabricated with a very small radius or chamfer to protect it from microscopic chipping, which could lead to failure.
- ➢ Part shrinkage in drying and firing (for traditional ceramics) and sintering (for new ceramics) may be significant and must be taken into account by the designer in dimensioning and tolerancing. This is mostly a problem for manufacturing engineers, who must determine appropriate size allowances so that the final dimensions will be within the tolerances specified.
- ➢ Screw threads in ceramic parts should be avoided. They are difficult to fabricate and do not have adequate strength in service after fabrication.

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