Composites and Powder Metallurgy
Ch 13 “Applications and Processing of Ceramics”

Dr. Eng. Yazan Al-Zain
Department of Industrial Engineering
University of Jordan

Introduction

- Due to the significant disparity between the physical characteristics of metals and ceramics.
  - Ceramics are used in completely different kinds of applications and, in this regard, tend to complement each other and also the polymers.
- Most ceramic materials fall into an application–classification scheme that includes the following groups:
  - glasses, structural clay products, whitewares, refractories, abrasives, cements, carbons, and the newly developed advanced ceramics.

Introduction

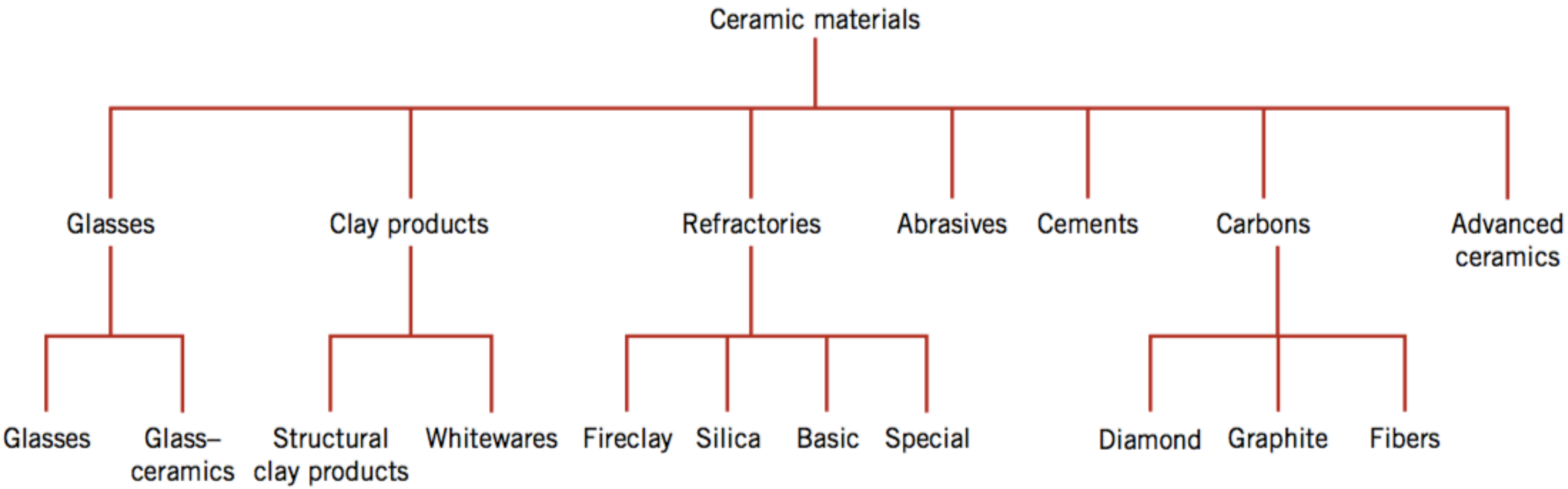


Figure 13.1 Classification of ceramic materials on the basis of application.

Types and Applications of Ceramics / *Glasses*

- The glasses are a familiar group of ceramics; containers, lenses, and fiberglass represent typical applications.
  - They are noncrystalline silicates containing other oxides, notably CaO, Na_2O, K_2O, and Al_2O_3, which influence the glass properties.
  - A typical soda-lime glass consists of approximately 70 wt% SiO_2, the balance being mainly Na_2O (soda) and CaO (lime).
- Possibly the two prime assets of these materials are their optical transparency and the relative ease with which they may be fabricated.

Types and Applications of Ceramics / *Glasses*

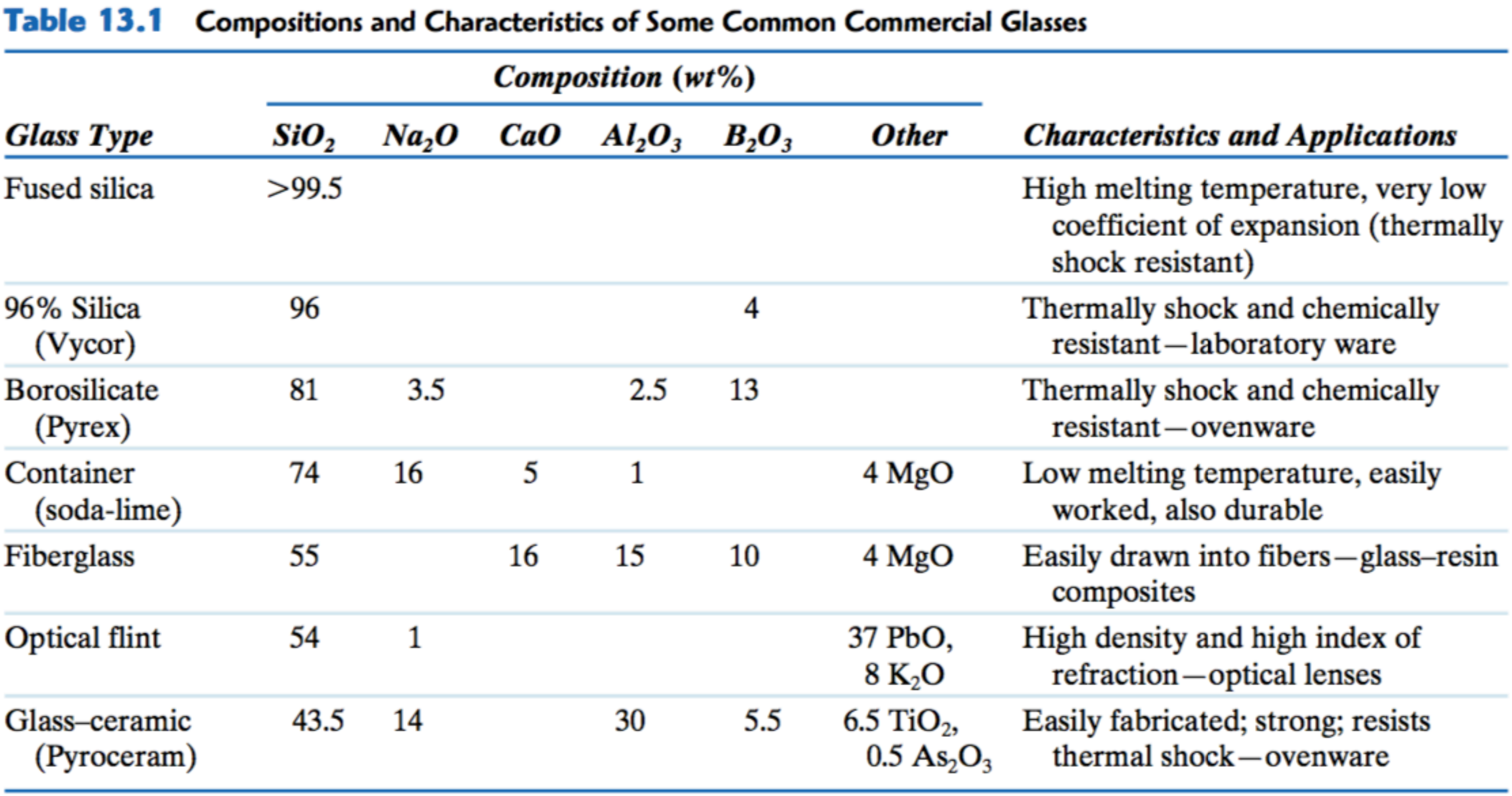


Table 13.1 Compositions and Characteristics of Some Common Commercial Glasses

	Composition (wt%)						
Glass Type	***SiO_2***	***Na_2O***	***CaO***	***Al_2O_3***	***B_2O_3***	***Other***	***Characteristics and Applications***
Fused silica	>99.5						High melting temperature, very low coefficient of expansion (thermally shock resistant)
96% Silica (Vycor)	96				4		Thermally shock and chemically resistant—laboratory ware
Borosilicate (Pyrex)	81	3.5		2.5	13		Thermally shock and chemically resistant—ovenware
Container (soda-lime)	74	16	5	1		4 MgO	Low melting temperature, easily worked, also durable
Fiberglass	55		16	15	10	4 MgO	Easily drawn into fibers—glass–resin composites
Optical flint	54	1				37 PbO, 8 K_2O	High density and high index of refraction—optical lenses
Glass–ceramic (Pyroceram)	43.5	14		30	5.5	6.5 TiO_2, 0.5 As_2O_3	Easily fabricated; strong; resists thermal shock—ovenware

Types and Applications of Ceramics / *Glass-Ceramics*

- A Glass-Ceramic: a fine-grained polycrystalline material.

    - Most inorganic glasses can be made to transform from a noncrystalline state into one that is crystalline by the proper high-temperature heat treatment.

    - A nucleating agent (frequently titanium dioxide) is often added to the glass to promote crystallization. The presence of a nucleating agent shifts the begin and end transformation curves to shorter times.

Types and Applications of Ceramics / *Glass-Ceramics*

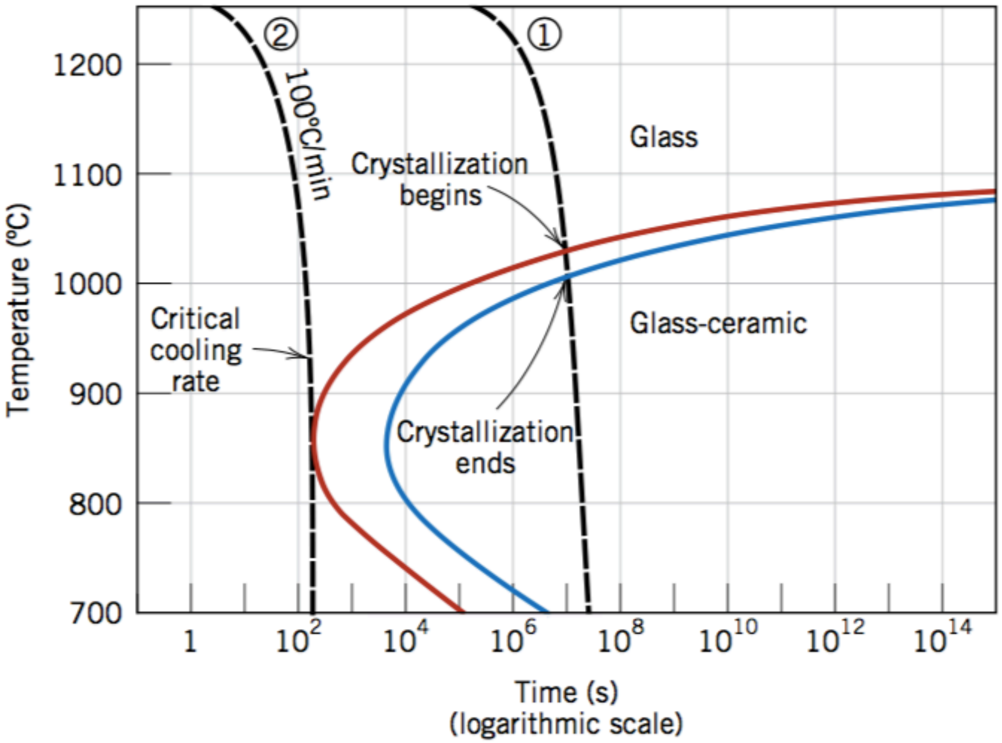


Figure 13.2 Continuous-cooling transformation diagram for the crystallization of a lunar glass (35.5 wt% SiO_2, 14.3 wt% TiO_2, 3.7 wt% Al_2O_3, 23.5 wt% FeO, 11.6 wt% MgO, 11.1 wt% CaO, and 0.2 wt% Na_2O). Superimposed on this plot are two cooling curves, labeled 1 and 2. (Reprinted from *Glass: Science and Technology*, Vol. 1, D. R. Uhlmann and N. J. Kreidl (Editors), "The Formation of Glasses," p. 22, copyright 1983, with permission from Elsevier.)

Curve 1: crystallization begins at its intersection with the upper curve and progresses as time increases and temperature continues to decrease; upon crossing the lower curve, all of the original glass has crystallized.

Curve a: misses the nose of the crystallization start curve. It represents a critical cooling rate (for this glass, 100 °C/min)—that is, the minimum cooling rate for which the final room-temperature product is 100% glass

Types and Applications of Ceramics / *Glass-Ceramics (Properties and Applications)*

- Glass–ceramic materials have been designed to have the following characteristics:

    - Relatively high mechanical strengths; low coefficients of thermal expansion (to avoid thermal shock); good high-temperature capabilities; good dielectric properties (for electronic packaging applications); and good biological compatibility.

    - Some glass–ceramics may be made optically transparent; others are opaque.

- The most common uses for these materials are as ovenware, tableware, oven windows, etc, primarily because of their strength and excellent resistance to thermal shock.

Types and Applications of Ceramics / *Clay Products*

- One of the most widely used ceramic raw materials is clay.
  - This inexpensive ingredient, found naturally in great abundance, often is used as mined without any upgrading of quality.
  - Another reason for its popularity lies in the ease with which clay products may be formed; when mixed in the proper proportions, clay and water form a plastic mass that is very amenable to shaping.
  - The formed piece is dried to remove some of the moisture, after which it is fired at an elevated temperature to improve its mechanical strength.

Types and Applications of Ceramics / *Clay Products*

- Most clay-based products fall within two broad classifications: the structural clay products and whitewares.
    - Structural clay products include building bricks, tiles, and sewer pipes—applications in which structural integrity is important.
    - Whiteware ceramics become white after high-temperature firing. Included in this group are porcelain, pottery, tableware, china, and plumbing fixtures (sanitary ware).

Types and Applications of Ceramics / *Refractories*

- Refractory ceramics: important class of ceramics that are used in large tonnages .
  - The properties: include the capacity to withstand high temperatures without melting or decomposing and the capacity to remain unreactive and inert when exposed to severe environments.
  - In addition, the ability to provide thermal insulation is often an important consideration.
  - Most common form: bricks.
  - Applications: furnace linings for metal refining, glass manufacturing, metallurgical heat treatment, and power generation.

Types and Applications of Ceramics / *Refractories*

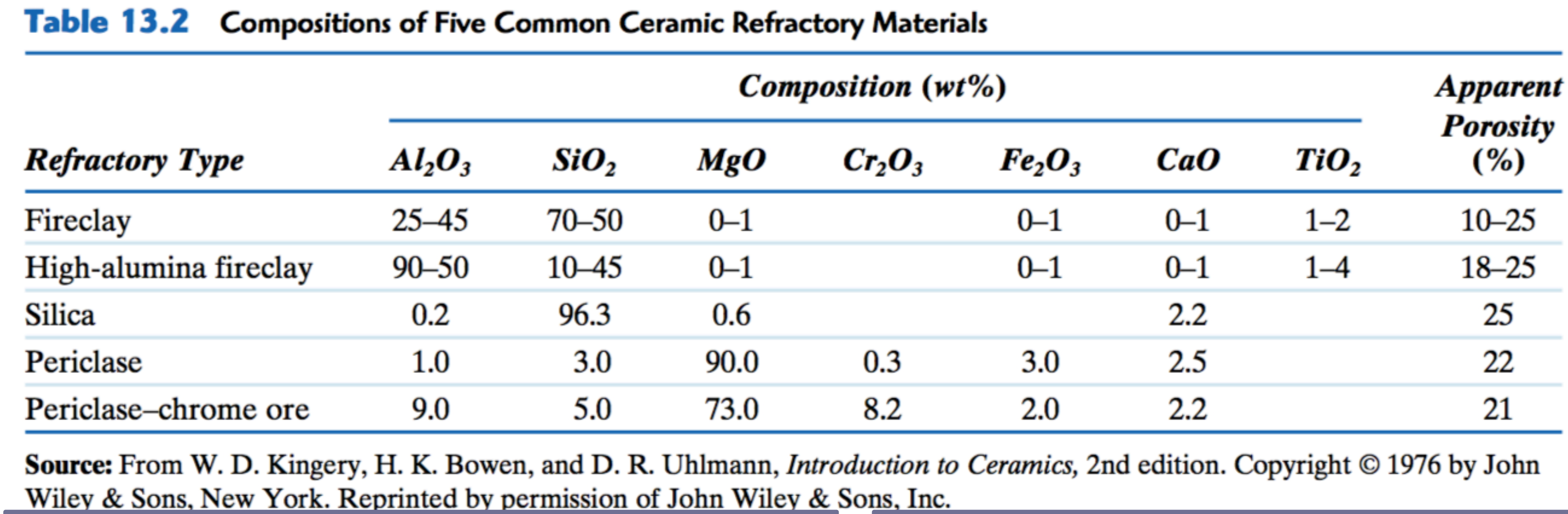


Table 13.2 **Compositions of Five Common Ceramic Refractory Materials**

	Composition (wt%)							
Refractory Type	Al_2O_3	SiO_2	MgO	Cr_2O_3	Fe_2O_3	CaO	TiO_2	***Apparent Porosity (%)***
Fireclay	25–45	70–50	0–1		0–1	0–1	1–2	10–25
High-alumina fireclay	90–50	10–45	0–1		0–1	0–1	1–4	18–25
Silica	0.2	96.3	0.6			2.2		25
Periclase	1.0	3.0	90.0	0.3	3.0	2.5		22
Periclase–chrome ore	9.0	5.0	73.0	8.2	2.0	2.2		21

Source: From W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, *Introduction to Ceramics*, 2nd edition. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

The raw ingredients consist of both large particles and fine particles, which may have different compositions. Upon firing, the fine particles normally are involved in the formation of a bonding phase, which is responsible for the increased strength of the brick. The service temperature is normally below that at which the refractory piece was fired.

Porosity is one microstructural variable that must be controlled to produce a suitable refractory brick. Strength, load-bearing capacity, and resistance to attack by corrosive materials all increase with porosity reduction. At the same time, thermal insulation characteristics and resistance to thermal shock are decreased.

Types and Applications of Ceramics / *Refractories (Fireclay Refractories)*

- The primary ingredients for the fireclay refractories are high-purity fireclays, alumina and silica mixtures usually containing between 25 and 45 wt% alumina.

  - Upgrading the alumina content increases the maximum service temperature.

  - Fireclay bricks are used principally in furnace construction to confine hot atmospheres and to thermally insulate structural members from excessive temperatures.

  - For fireclay brick, strength is not ordinarily an important consideration because support of structural loads is usually not required.

Types and Applications of Ceramics / *Refractories (Silica Refractories)*

- Main ingredient: silica, sometimes called acid refractories.
  - Good for their high-temperature load-bearing capacity.
  - Commonly used in the roofs of steel- and glass-making furnaces; for these applications, temperatures as high as 1650 ºC may be realized.
  - Under these conditions, some small portion of the brick actually exists as a liquid. The presence of even small concentrations of alumina has an adverse influence on the performance of these refractories,
  - According to Figure 12.2: Because the eutectic composition (7.7 wt% Al_2O_3) is very near the silica extremity of the phase diagram, even small additions of Al_2O_3 lower the liquidus temperature significantly, which means that substantial amounts of liquid may be present at temperatures. in excess of 1600 ºC. Thus, the alumina content should be held to a minimum, normally to between 0.2 and 1.0 wt%.

These refractory materials are also resistant to slags that are rich in silica (called *acid slags*). However, they are readily attacked by slags composed of a high proportion of CaO and/or MgO (basic slags), and contact with these oxide materials should be avoided.

Types and Applications of Ceramics / *Refractories (Basic Refractories)*

- The refractories that are rich in periclase, or magnesia (MgO), are termed basic; they may also contain calcium, chromium, and iron compounds.

- The presence of silica is deleterious to their high-temperature performance. Basic refractories are especially resistant to attack by slags containing high concentrations of MgO and CaO

    - They find extensive use in some steel-making open hearth furnaces.

Types and Applications of Ceramics / *Abrasives*

- Abrasive ceramics are used to wear, grind, or cut away other material, which necessarily is softer.
  - Therefore, the prime requisite for this group of materials is hardness or wear resistance.
  - In addition, a high degree of toughness is essential to ensure that the abrasive particles do not easily fracture.
  - Furthermore, high temperatures may be produced from abrasive frictional forces, so some refractoriness is also desirable.
- Diamonds, both natural and synthetic, are used as abrasives; however, they are relatively expensive. The more common ceramic abrasives include silicon carbide, tungsten carbide (WC), aluminum oxide (or corundum), and silica sand.

Types and Applications of Ceramics / *Cements*

- Several familiar ceramic materials are classified as inorganic cements: cement, plaster of Paris, and lime, which, as a group, are produced in extremely large quantities.

    - The characteristic feature of these materials is that when mixed with water, they form a paste that subsequently sets and hardens. This trait is especially useful in that solid and rigid structures having just about any shape may be formed expeditiously.

- Also, some of these materials act as a bonding phase that chemically binds particulate aggregates into a single cohesive structure.

    - One important difference, is that the cementitious bond develops at room temperature.

Types and Applications of Ceramics / *Cements*

- Of this group of materials, Portland cement is consumed in the largest tonnages.
  - It is produced by grinding and intimately mixing clay and lime-bearing minerals in the proper proportions and then heating the mixture to about 1400 ºC in a rotary kiln; this process, sometimes called calcination, produces physical and chemical changes in the raw materials.
- The resulting “clinker” product is then ground into a very fine powder, to which is added a small amount of gypsum ($CaSO_4$–$2H_2O$) to retard the setting process. This product is Portland cement.
  - The properties of Portland cement, including setting time and final strength, to a large degree depend on its composition.

Types and Applications of Ceramics / *Carbons (Diamonds)*

- The physical properties of diamond are extraordinary.

  - Chemically, it is very inert and resistant to attack by a host of corrosive media. Of all known bulk materials, diamond is the hardest.
  - In addition, of all solids, it has the lowest sliding coefficient of friction.
  - Its thermal conductivity is extremely high.
  - Its electrical properties are notable, and, optically, it is transparent in the visible and infrared regions of the electromagnetic spectrum.
  - The high index of refraction and optical brilliance of single crystals makes diamond a most highly valued gemstone.

Types and Applications of Ceramics / *Carbons (Diamonds)*

- High-pressure high-temperature (HPHT) techniques to produce synthetic diamonds were developed beginning in the mid-1950s.

  - These techniques have been refined to the degree that today a large proportion of industrial-quality diamonds are synthetic, as are some of those of gem quality.

- Industrial-grade diamonds are used for a host of applications that exploit diamond’s extreme hardness, wear resistance, and low coefficient of friction.

  - These include diamond- tipped drill bits and saws, dies for wire drawing, and as abrasives used in cutting, grinding, and polishing equipment

Types and Applications of Ceramics / *Carbons (Graphite)*

- Graphite is highly anisotropic—property values depend on crystallographic direction along which they are measured.
  - For example, electrical resistivities parallel and perpendicular to the graphene plane are, respectively, on the order of 10^{-5} and 10^{-2} Ω.m.
  - Delocalized electrons are highly mobile, and their motions in response to the presence of an electric field applied in a direction parallel to the plane are responsible for the relatively low resistivity (i.e., high conductivity) in that direction.
  - Also, as a consequence of the weak interplanar van der Waals bonds, it is relatively easy for planes to slide past one another, which explains the excellent lubricative properties of graphite.

Applications for graphite are many, varied, and include lubricants, pencils, battery electrodes, friction materials (e.g., brake shoes), heating elements for electric furnaces, welding electrodes, metallurgical crucibles, high-temperature refractories and insulations, rocket nozzles, chemical reactor vessels, electrical contacts (e.g., brushes), and air purification devices.

Types and Applications of Ceramics / *Carbons (Graphite)*

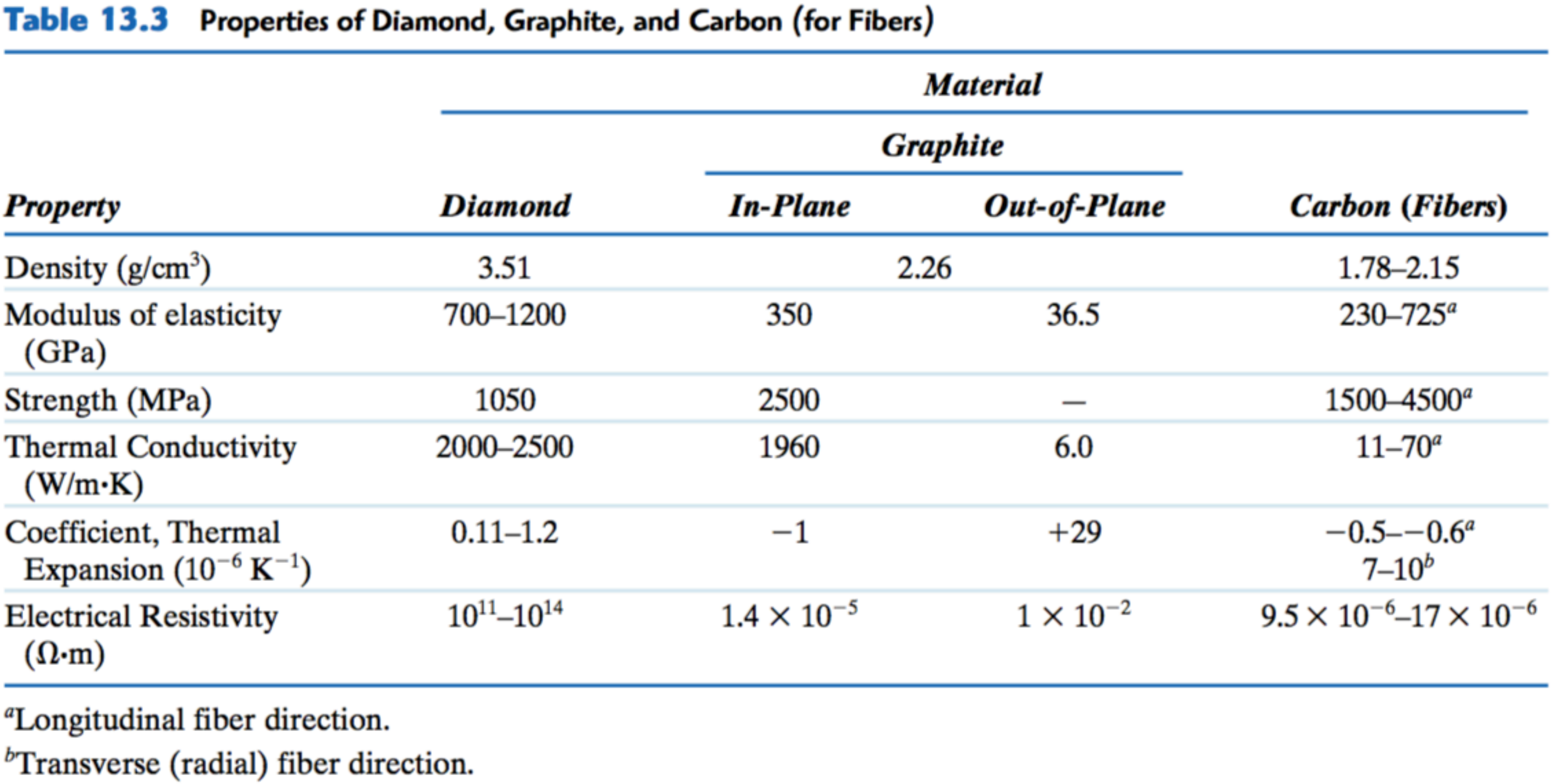


Table 13.3 Properties of Diamond, Graphite, and Carbon (for Fibers)

	Material			
		Graphite		
Property	***Diamond***	***In-Plane***	***Out-of-Plane***	***Carbon (Fibers)***
Density (g/cm^3)	3.51	2.26		1.78–2.15
Modulus of elasticity (GPa)	700–1200	350	36.5	230–725[a]
Strength (MPa)	1050	2500	—	1500–4500[a]
Thermal Conductivity (W/m·K)	2000–2500	1960	6.0	11–70[a]
Coefficient, Thermal Expansion (10^{-6} K^{-1})	0.11–1.2	−1	+29	−0.5–−0.6[a] 7–10[b]
Electrical Resistivity (Ω·m)	10^{11}–10^{14}	1.4×10^{-5}	1×10^{-2}	9.5×10^{-6}–17×10^{-6}

[a] Longitudinal fiber direction.

[b] Transverse (radial) fiber direction.

Types and Applications of Ceramics / *Carbons (Carbon Fibers)*

- Small-diameter, high-strength, and high-modulus fibers composed of carbon are used as reinforcements in polymer-matrix composites

    - For what are termed graphitic carbon fibers, the graphene layers assume the ordered structure of graphite—planes are parallel to one another having relatively weak van der Waals interplanar bonds.
    - Alternatively, a more disordered structure results when, during fabrication, graphene sheets become randomly folded, tilted, and crumpled to form what is termed turbostratic carbon.
    - Hybrid graphitic– turbostratic fibers, composed of regions of both structure types, may also be synthesized.

Types and Applications of Ceramics / *Carbons (Carbon Fibers)*

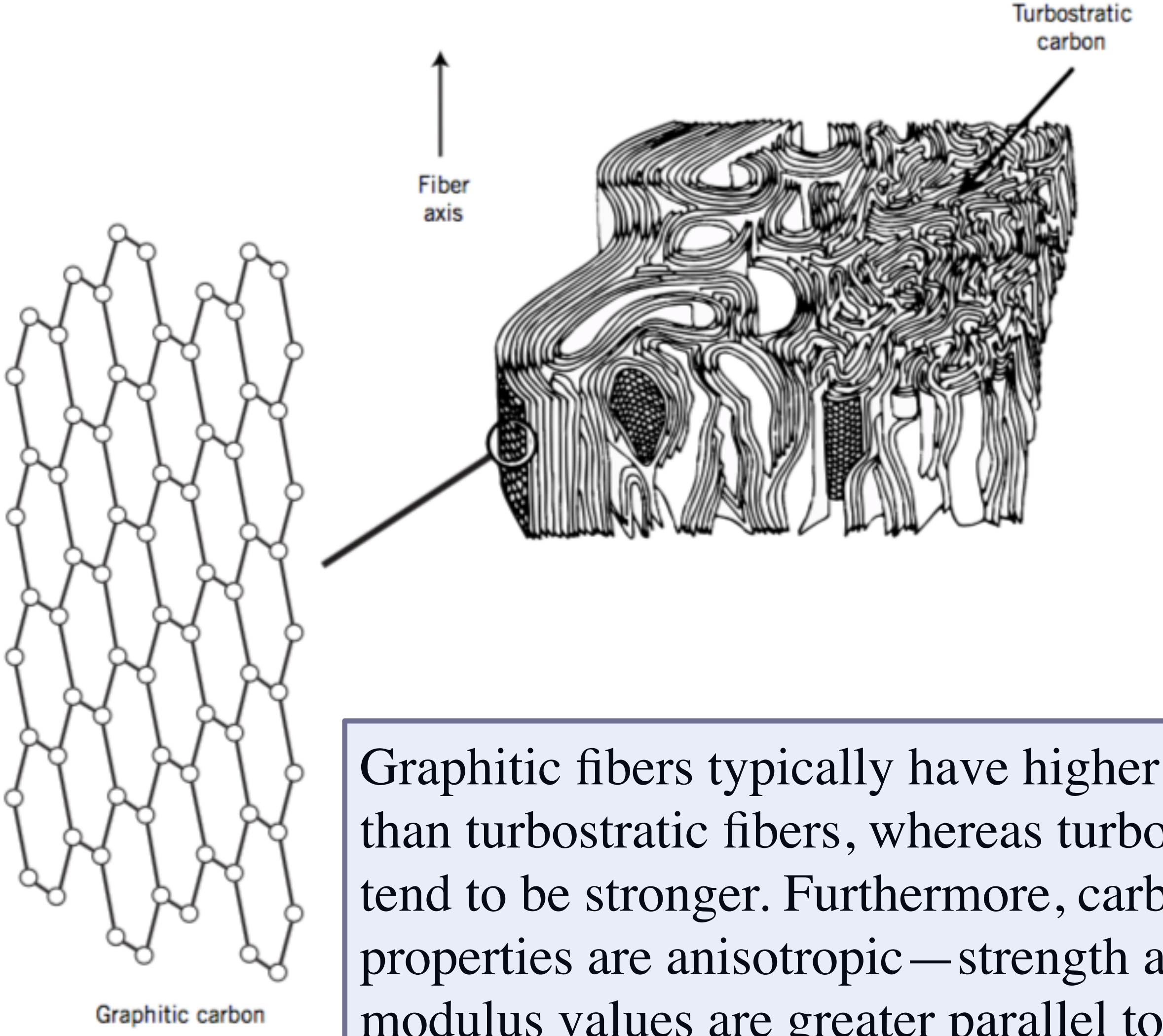


Figure 13.5 Schematic diagram of a carbon fiber that shows both graphitic and turbostratic carbon structures.
(Adapted from S. C. Bennett and D. J. Johnson, *Structural Heterogeneity in Carbon Fibres*, "Proceedings of the Fifth London International Carbon and Graphite Conference," Vol. I, Society of Chemical Industry, London, 1978. Reprinted with permission of S. C. Bennett and D. J. Johnson.)

Graphitic fibers typically have higher elastic moduli than turbostratic fibers, whereas turbostratic fibers tend to be stronger. Furthermore, carbon fiber properties are anisotropic—strength and elastic modulus values are greater parallel to the fiber axis

Types and Applications of Ceramics / *Carbons (Carbon Fibers)*

- Of the three most common reinforcing fiber types used for polymer-reinforced composites (carbon, glass, and aramid), carbon fibers have the highest modulus of elasticity and strength; in addition, they are the most expensive.

    - Furthermore, carbon fiber– reinforced polymer composites have outstanding modulus- and strength-to-weight ratios.

Fabrication and Processing of Ceramics

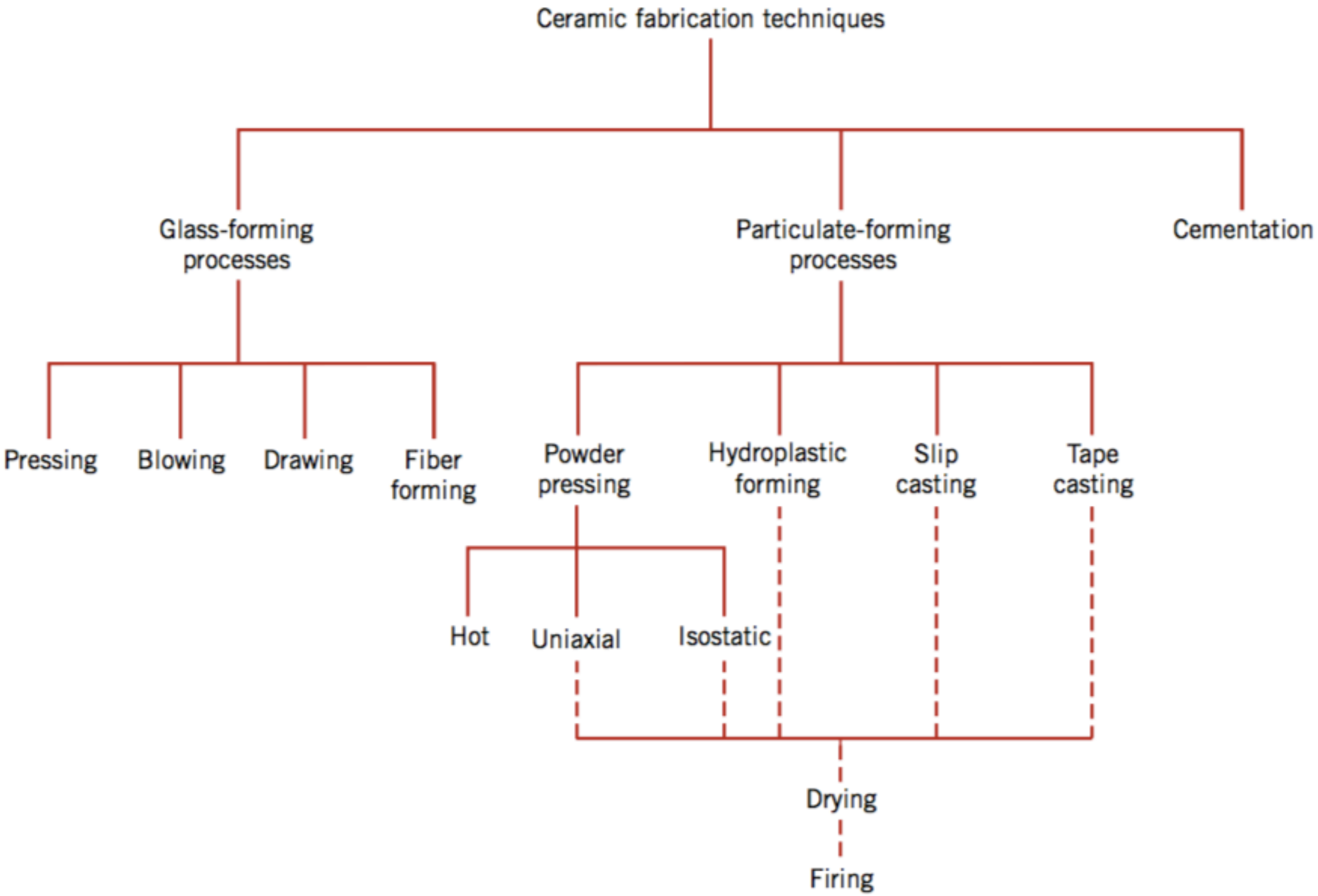
- Because ceramic materials have relatively high melting temperatures, casting them is normally impractical.

- Furthermore, in most instances the brittleness of these materials precludes deformation.

  - Some ceramic pieces are formed from powders (or particulate collections) that must ultimately be dried and fired.
  - Glass shapes are formed at elevated temperatures from a fluid mass that becomes very viscous upon cooling.
  - Cements are shaped by placing into forms a fluid paste that hardens and assumes a permanent set by virtue of chemical reactions.

Fabrication and Processing of Ceramics

Figure 13.10 A classification scheme for the ceramic-forming techniques discussed in this chapter.



FABRICATION AND PROCESSING OF GLASSES AND GLASS–CERAMICS (Glass Properties)

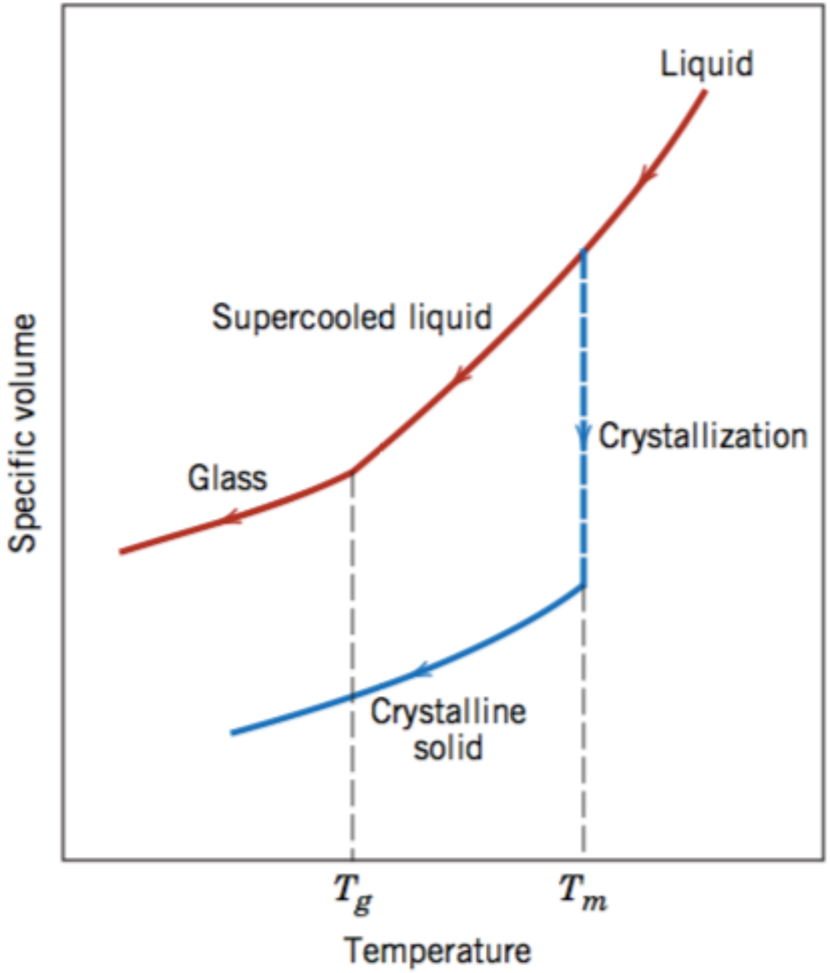


Figure 13.11 Contrast of specific volume–versus–temperature behavior of crystalline and noncrystalline materials. Crystalline materials solidify at the melting temperature T_m. Characteristic of the noncrystalline state is the glass transition temperature T_g.

- Upon cooling, a glass becomes more and more viscous in a continuous manner with decreasing temperature; there is no definite temperature at which the liquid transforms into a solid as with crystalline materials.

FABRICATION AND PROCESSING OF GLASSES AND GLASS–CERAMICS (Glass Properties)

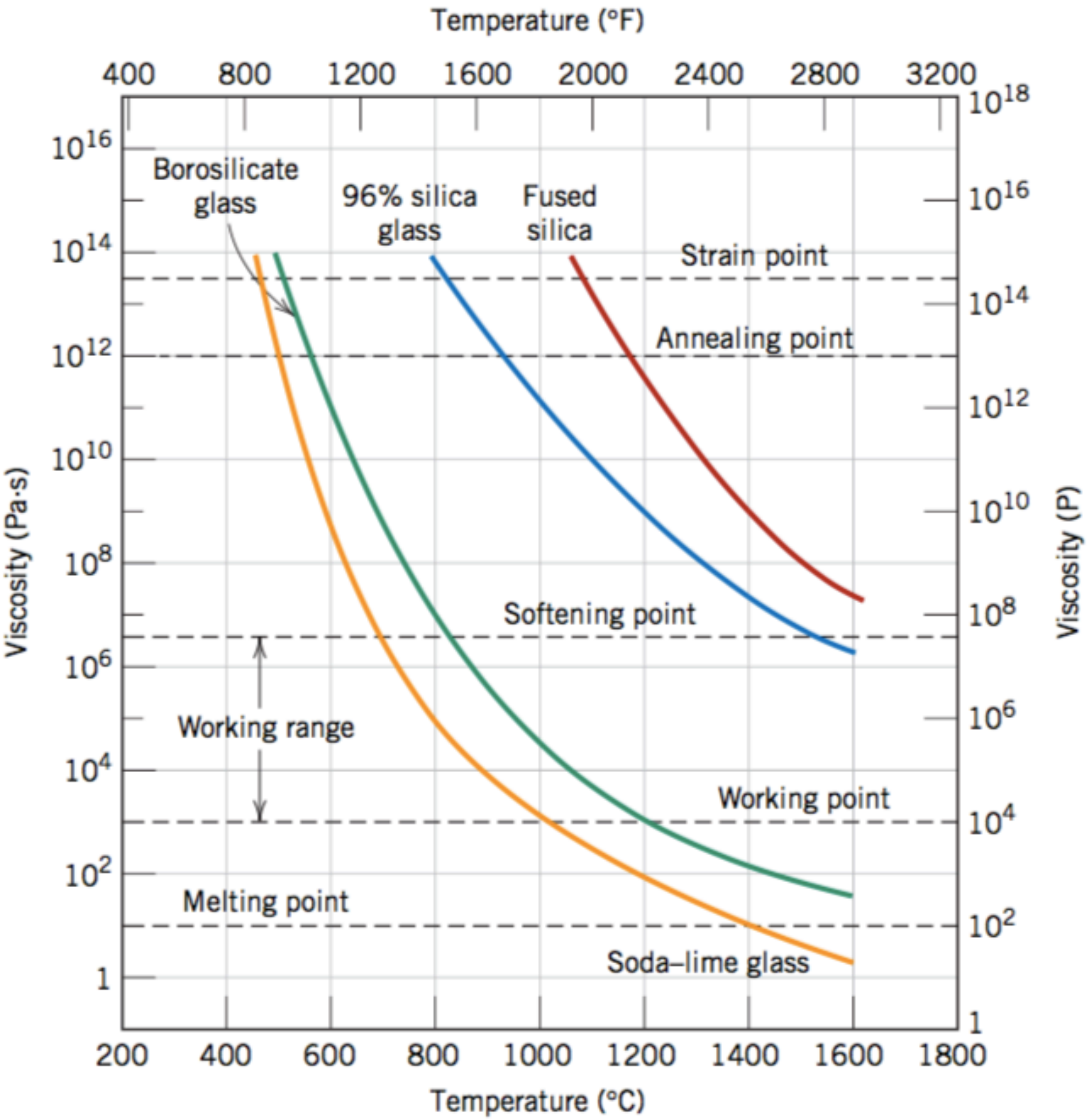


Figure 13.12 Logarithm of viscosity versu temperature for fused silica and three silica glasses.
(From E. B. Shand, *Engineering Glass,* Modern Materials, Vol. 6, Academic Press, New York, 1968, p. 262.)

On the viscosity scale, several specific points that are important in the fabrication and processing of glasses are labeled:

FABRICATION AND PROCESSING OF GLASSES AND GLASS–CERAMICS (Glass Properties)

- The melting point corresponds to the temperature at which the viscosity is 10 Pa.s; the glass is fluid enough to be considered a liquid.

- The working point represents the temperature at which the viscosity is 10^3 Pa.s; the glass is easily deformed at this viscosity.

- The softening point, the temperature at which the viscosity is $4x10^6$ Pa.s, is the maximum temperature at which a glass piece may be handled without causing significant dimensional alterations.

- The annealing point is the temperature at which the viscosity is 10^{12} Pa.s; at this temperature, atomic diffusion is sufficiently rapid that any residual stresses may be removed within about 15 min.

- The strain point corresponds to the temperature at which the viscosity becomes $3x10^{13}$ Pa.s; for temperatures below the strain point, fracture will occur before the onset of plastic deformation. The glass transition temperature will be above the strain point.

- Most glass-forming operations are carried out within the working range—between the working and softening temperatures.

FABRICATION AND PROCESSING OF GLASSES AND GLASS–CERAMICS (Glass Forming)

- Glass is produced by heating the raw materials to an elevated temperature above which melt- ing occurs.

- Most commercial glasses are of the silica-soda-lime variety; the silica is usually supplied as common quartz sand, whereas Na_2O and CaO are added as soda ash (Na_2CO_3) and limestone ($CaCO_3$).

- Five different forming methods are used to fabricate glass products: pressing, blowing, drawing, and sheet and fiber forming.

  - Pressing is used in the fabrication of relatively thick-walled pieces such as plates and dishes. The glass piece is formed by pressure application in a graphite-coated cast iron mold having the desired shape; the mold is typically heated to ensure an even surface.

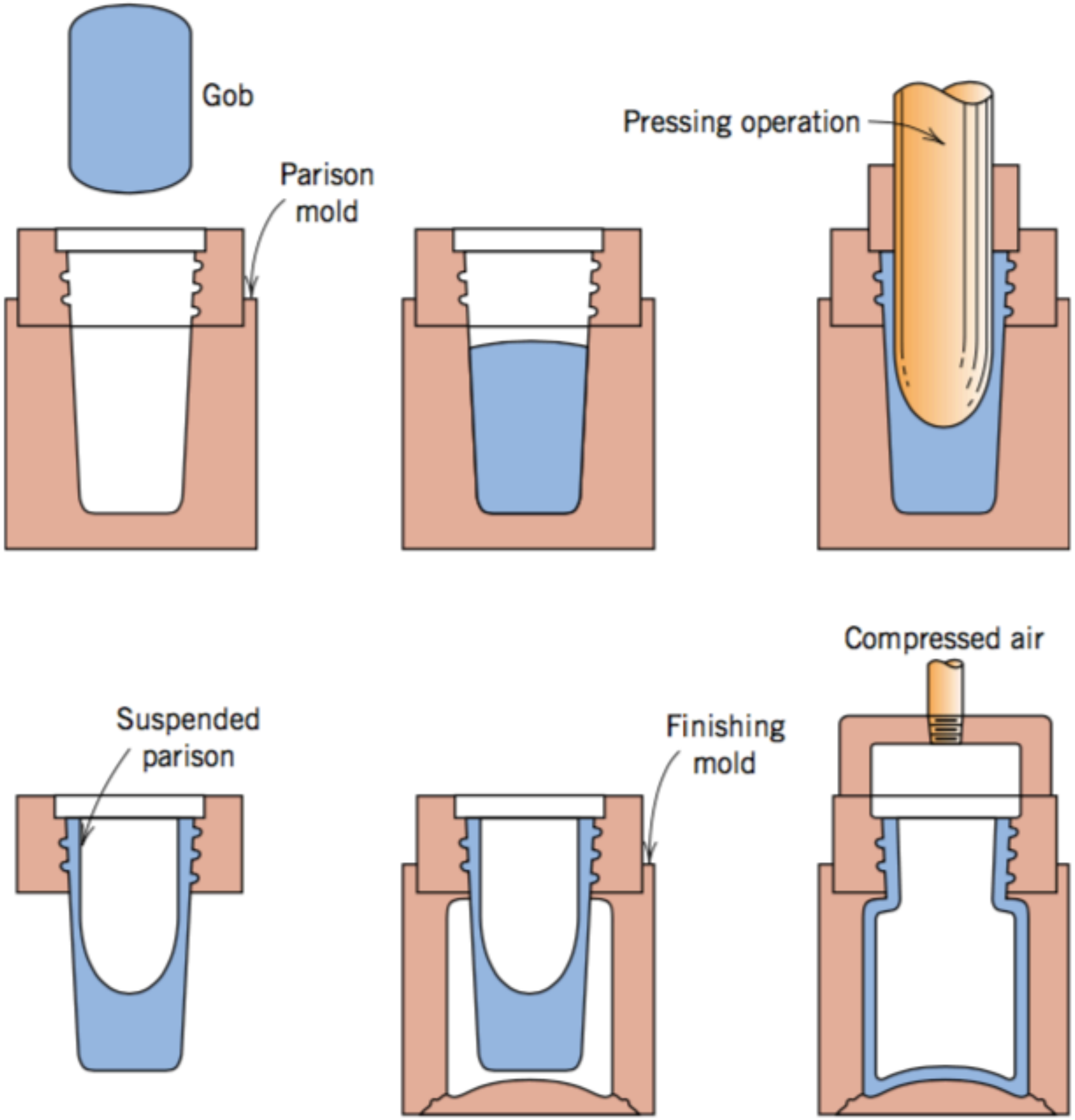
FABRICATION AND PROCESSING OF GLASSES AND GLASS–CERAMICS (Glass Forming)

- Although some glass blowing is done by hand, especially for art objects, the process has been completely automated for the production of glass jars, bottles, and light bulbs.

- From a raw gob of glass, a parison, or temporary shape, is formed by mechanical pressing in a mold. This piece is inserted into a finishing or blow mold and forced to conform to the mold contours by the pressure created from a blast of air (See figure of next slide).

FABRICATION AND PROCESSING OF GLASSES AND GLASS–CERAMICS (Glass Forming)

Figure 13.13 The press-and-blow technique for producing a glass bottle.
(Adapted from C. J. Phillips, *Glass: The Miracle Maker*. Reproduced by permission of Pitman Publishing Ltd., London.)



FABRICATION AND PROCESSING OF GLASSES AND GLASS–CERAMICS (Glass Forming)

- Production of sheet glass (or plate): float process was patented in 1959 in England. With this technique
  - The molten glass passes (on rollers) from one furnace onto a bath of liquid tin located in a second furnace. Thus, as this continuous glass ribbon "floats" on the surface of the molten tin, gravitational and surface tension forces cause the faces to become perfectly flat and parallel and the resulting sheet to be of uniform thickness.
  - Furthermore, sheet faces acquire a bright, "fire-polished" finish in one region of the furnace.
  - The sheet next passes into an annealing furnace (lehr), and is finally cut into sections. The success of this operation requires rigid control of both temperature and chemistry of the gaseous atmosphere.

FABRICATION AND PROCESSING OF GLASSES AND GLASS–CERAMICS (Glass Forming)

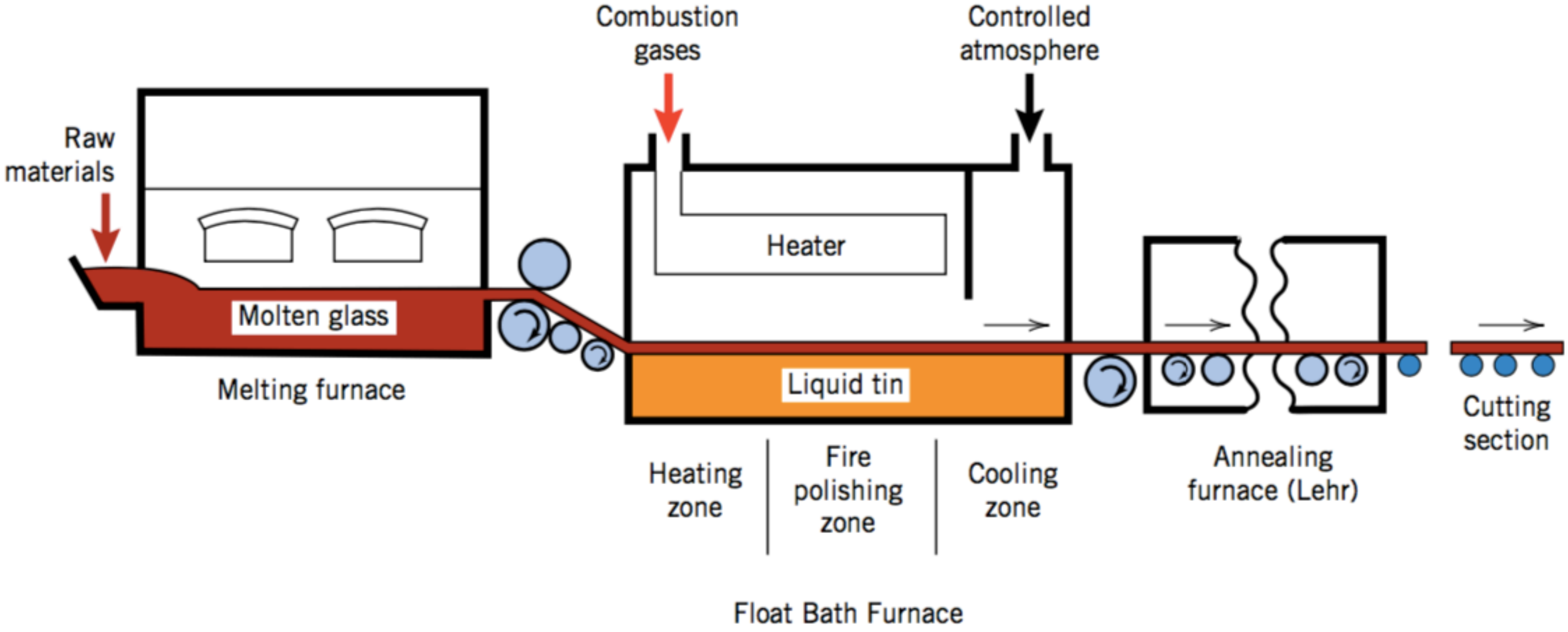


Figure 13.14 Schematic diagram showing the float process for making sheet glass. (Courtesy of Pilkington Group Limited.)

FABRICATION AND PROCESSING OF GLASSES AND GLASS–CERAMICS (Heat-Treating Glasses/Annealing)

- When a ceramic material is cooled from an elevated temperature, internal stresses, called thermal stresses, may be introduced as a result of the difference in cooling rate and thermal contraction between the surface and interior regions.

  - These thermal stresses are important in brittle ceramics, especially glasses, because they may weaken the material or, in extreme cases, lead to fracture, which is termed thermal shock.

  - Elimination, or at least a reduction in their magnitude, is possible by an annealing heat treatment in which the glassware is heated to the annealing point, then slowly cooled to room temperature.

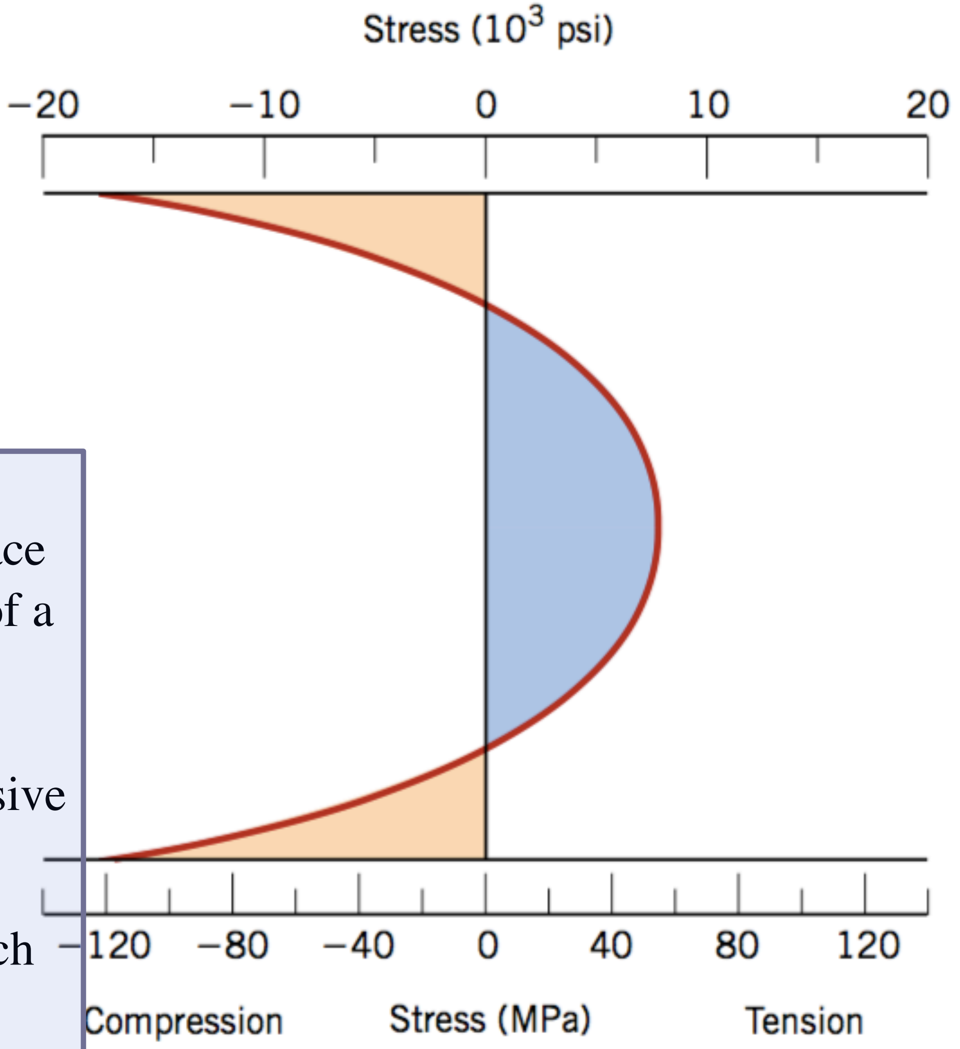
FABRICATION AND PROCESSING OF GLASSES AND GLASS–CERAMICS (Heat-Treating Glasses/Tempering)

- Glass Tempering: a heat treatment procedure done to enhance the strength of a glass piece by intentionally inducing compressive residual surface stresses.

- With this technique, the glassware is heated to a temperature above the glass transition region yet below the softening point. It is then cooled to room temperature in a jet of air. The residual stresses arise from differences in cooling rates for surface and interior regions.
- Initially, the surface cools more rapidly and, once it has dropped to a temperature below the strain point, it becomes rigid. At this time, the interior, having cooled less rapidly, is at a higher temperature (above the strain point) and, therefore, is still plastic.
- With continued cooling, the interior attempts to contract to a greater degree than the now-rigid exterior will allow. Thus, the inside tends to draw in the outside, or to impose inward radial stresses.
- As a consequence, after the glass piece has cooled to room temperature, it sustains compressive stresses on the surface and tensile stresses at interior regions.

FABRICATION AND PROCESSING OF GLASSES AND GLASS–CERAMICS (Heat-Treating Glasses/Tempering)

Figure 13.15 Room-temperature residual stress distribution over the cross section of a tempered glass plate. (From W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, *Introduction to Ceramics*, 2nd edition. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)



The failure of ceramic materials almost always results from a crack that is initiated at the surface by an applied tensile stress. To cause fracture of a tempered glass piece, the magnitude of an externally applied tensile stress must be great enough to first overcome the residual compressive surface stress.

Tempered glass is used for applications in which high strength is important; these include large doors and eyeglass lenses.

FABRICATION AND PROCESSING OF CLAY PRODUCTS

- This class of materials includes the structural clay products and the whitewares.
  - In addition to clay, many of these products also contain other ingredients.
  - After being formed, pieces most often must be subjected to drying and firing operations; each of the ingredients influences the changes that take place during these processes and the characteristics of the finished piece.

FABRICATION AND PROCESSING OF CLAY PRODUCTS
(The Characteristics of Clay)

- The clay (aluminosilicates composed of alumina and silica that contain chemically bound water) minerals play two very important roles in ceramic bodies.
  - First, when water is added, they become very plastic, a condition termed hydroplasticity.
    - This property is very important in forming operations, as discussed shortly.
  - In addition, clay fuses or melts over a range of temperatures; thus, a dense and strong ceramic piece may be produced during firing without complete melting such that the desired shape is maintained.

FABRICATION AND PROCESSING OF CLAY PRODUCTS (The Characteristics of Clay)

- The most common clay minerals that are of interest have what is called the kaolinite structure.
- Kaolinite clay $[Al_2(Si_2O_5)(OH)_4]$.
- When water is added, the water molecules fit between these layered sheets and form a thin film around the clay particles.
- The particles are thus free to move over one another, which accounts for the resulting plasticity of the water–clay mixture.

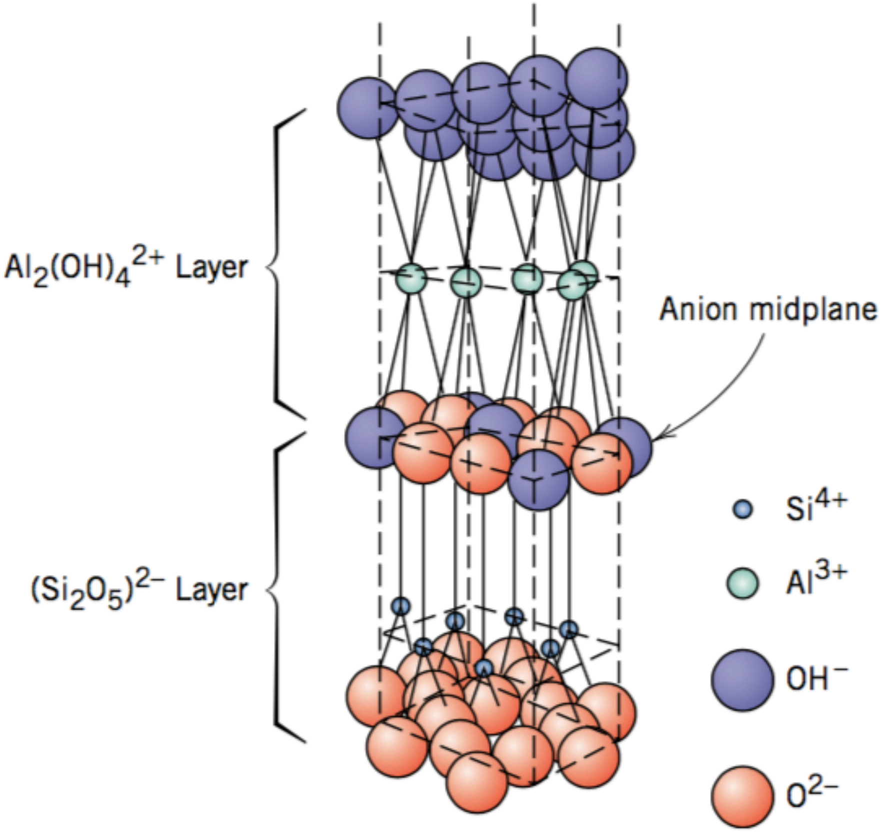


Figure 12.14 The structure of kaolinite clay. (Adapted from W. E. Hauth, "Crystal Chemistry of Ceramics," *American Ceramic Society Bulletin*, Vol. 30, No. 4, 1951, p. 140.)

FABRICATION AND PROCESSING OF CLAY PRODUCTS (Fabrication Techniques)

- The as-mined raw materials usually have to go through a milling or grinding operation in which particle size is reduced; this is followed by screening or sizing to yield a powdered product having a desired range of particle sizes.

- For multicomponent systems, powders must be thoroughly mixed with water and perhaps other ingredients to give flow characteristics that are compatible with the particular forming technique.

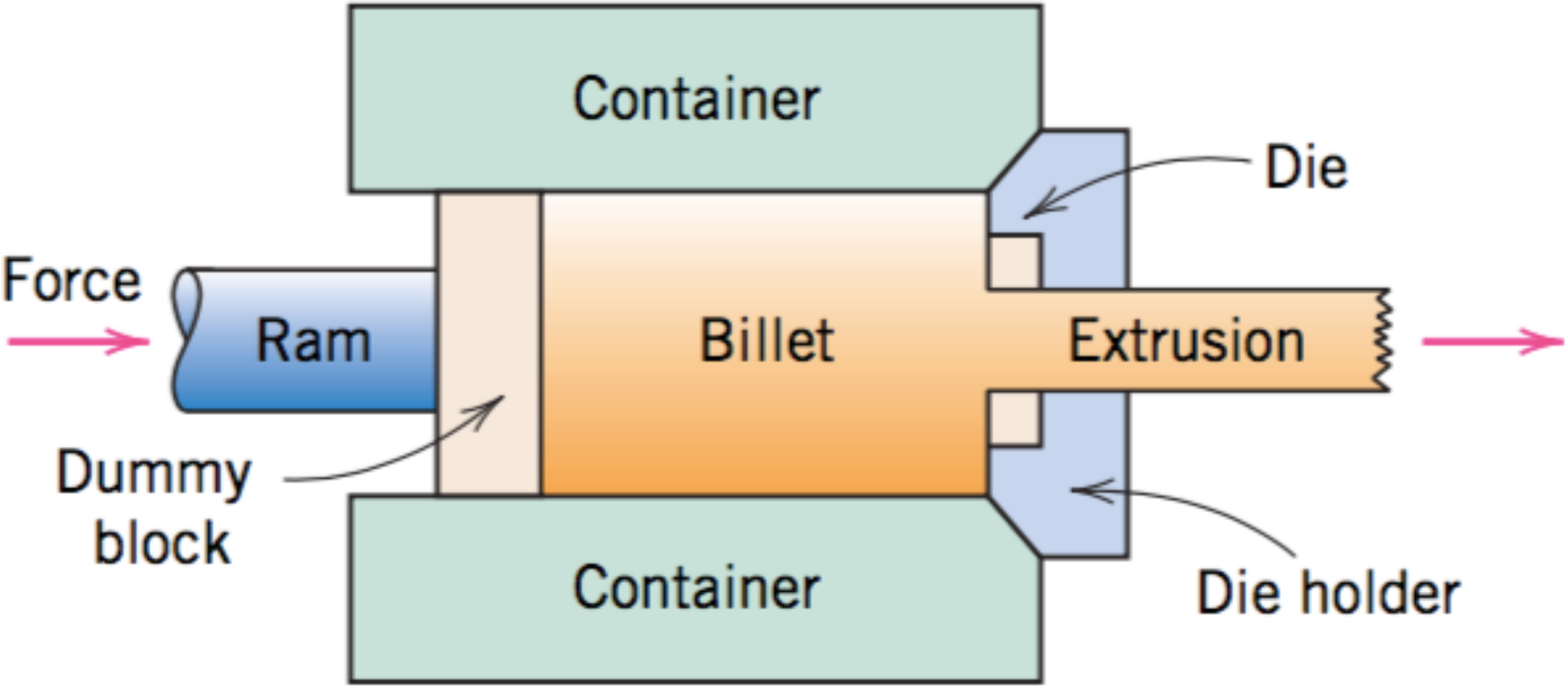
- The formed piece must have sufficient mechanical strength to remain intact during transporting, drying, and firing operations.

  - Two common shaping techniques are used to form clay-based compositions: *hydroplastic forming* and *slip casting*.

FABRICATION AND PROCESSING OF CLAY PRODUCTS
(Fabrication Techniques / *Hydroplastic Forming*)

- Clay minerals, when mixed with water, become highly plastic and may be molded without cracking;
  - However, they have extremely low yield strengths.
  - The consistency (water–clay ratio) of the hydroplastic mass must give a yield strength sufficient to permit a formed ware to maintain its shape during handling and drying.
- The most common hydroplastic forming technique is extrusion, in which a stiff plastic ceramic mass is forced through a die orifice having the desired cross-sectional geometry.
  - Brick, pipe, ceramic blocks, and tiles are all commonly fabricated using hydroplastic forming.

FABRICATION AND PROCESSING OF CLAY PRODUCTS
(Fabrication Techniques / *Hydroplastic Forming*)



FABRICATION AND PROCESSING OF CLAY PRODUCTS (Fabrication Techniques / *Slip Casting*)

- A slip is a suspension of clay and/or other nonplastic materials in water.

- When poured into a porous mold (commonly made of plaster of Paris), water from the slip is absorbed into the mold, leaving behind a solid layer on the mold wall, the thickness of which depends on the time.

- This process may be continued until the entire mold cavity becomes solid (solid casting), as demonstrated in Figure 13.17a.

- Alternatively, it may be terminated when the solid shell wall reaches the desired thickness, by inverting the mold and pouring out the excess slip; this is termed drain casting (Figure 13.17b). As the cast piece dries and shrinks, it pulls away (or releases) from the mold wall; at this time, the mold may be disassembled and the cast piece removed.

FABRICATION AND PROCESSING OF CLAY PRODUCTS (Fabrication Techniques / *Slip Casting*)

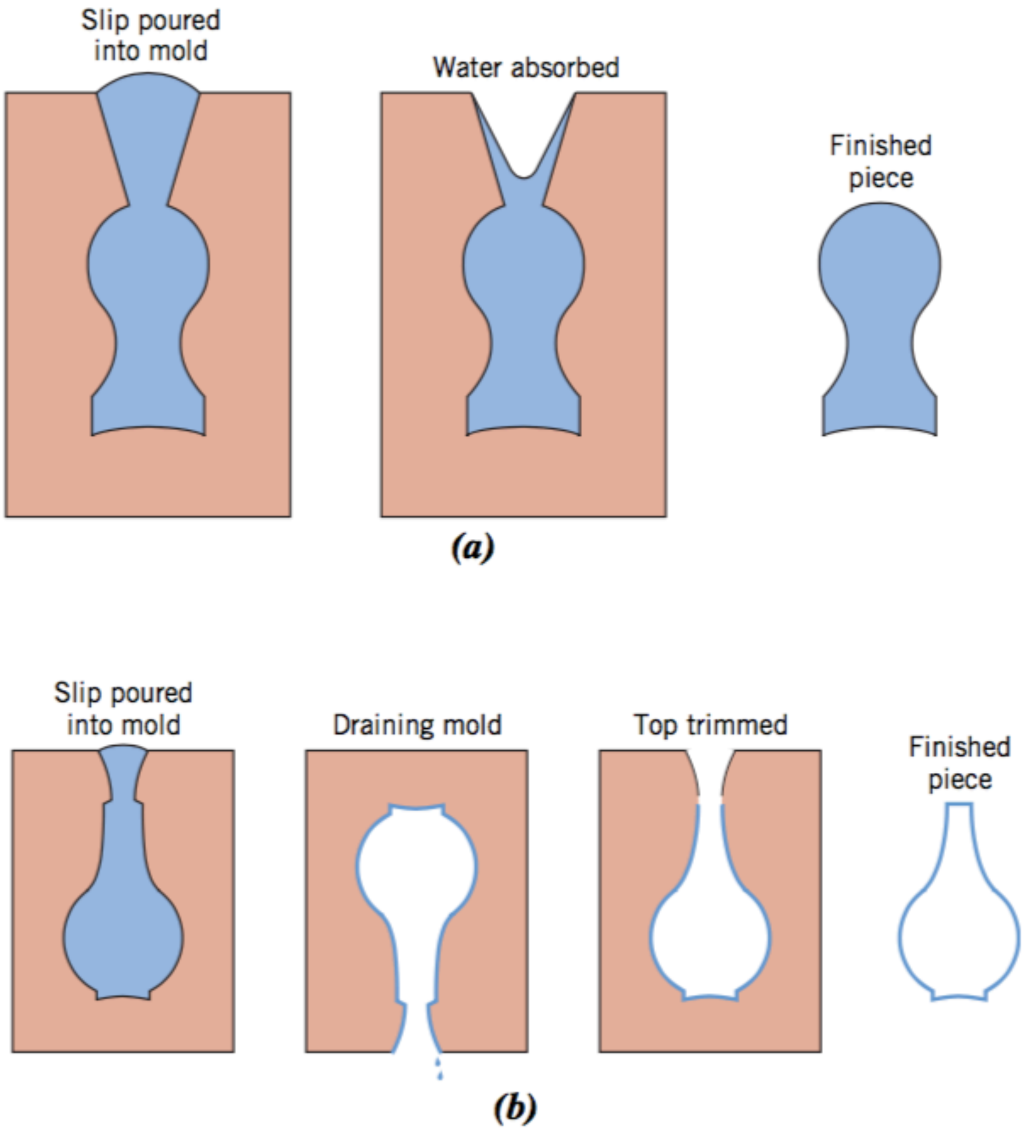


Figure 13.17 The steps in (*a*) solid and (*b*) drain slip casting using a plaster of Paris mold. (From W. D. Kingery, *Introduction to Ceramics.* Copyright © 1960 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

Products: sanitary lavatory ware, art objects, and specialized scientific laboratory ware such as ceramic tubes.

FABRICATION AND PROCESSING OF CLAY PRODUCTS (Drying and Firing)

- A ceramic piece that has been formed hydroplastically or by slip casting retains significant porosity and has insufficient strength for most practical applications.
    - In addition, it may still contain some of the liquid (e.g., water) that was added to assist in the forming operation.
    - This liquid is removed in a drying process; density and strength are enhanced as a result of a high-temperature heat treatment or firing procedure.
- A body that has been formed and dried but not fired is termed green.
    - Drying and firing techniques are critical inasmuch as defects that ordinarily render the ware useless (e.g., warpage, distortion, cracks) may be introduced during the operation. These defects normally result from stresses that are set up from nonuniform shrinkage.

FABRICATION AND PROCESSING OF CLAY PRODUCTS (Drying and Firing / *Drying*)

- As a clay-based ceramic body dries, it also experiences some shrinkage. In the early stages of drying, the clay particles are virtually surrounded by and separated from one another by a thin film of water. As drying progresses and water is removed, the inter- particle separation decreases, which is manifested as shrinkage.

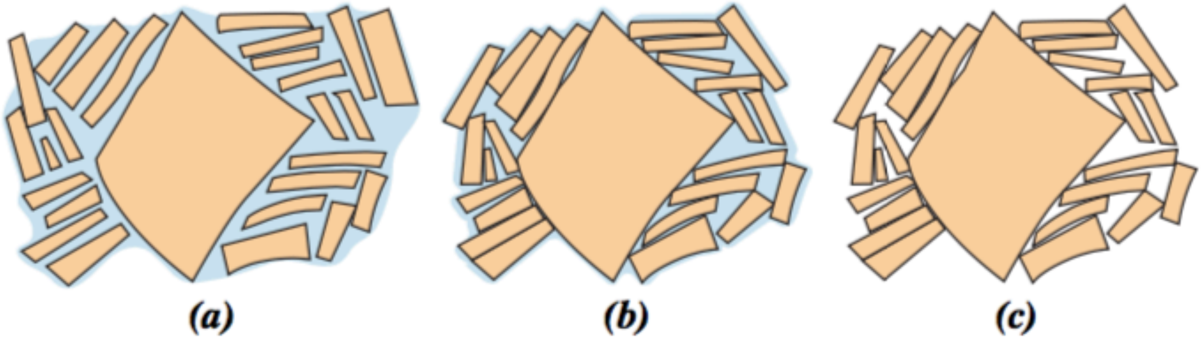


Figure 13.18 Several stages in the removal of water from between clay particles during the drying process. (*a*) Wet body. (*b*) Partially dry body. (*c*) Completely dry body. (From W. D. Kingery, *Introduction to Ceramics*. Copyright © 1960 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

FABRICATION AND PROCESSING OF CLAY PRODUCTS (Drying and Firing / *Firing*)

- After drying, a body is usually fired at a temperature between 900 ºC and 1400 ºC. During the firing operation, the density is further in- creased and the mechanical strength is enhanced.
- When clay-based materials are heated to elevated temperatures, some rather complex and involved reactions occur. One of these is *vitrification*—the gradual formation of a liquid glass that flows into and fills some of the pore volume.
- This fused phase flows around the remaining unmelted particles and fills in the pores as a result of surface tension forces (or capillary action); shrinkage also accompanies this process. Upon cooling, this fused phase forms a glassy matrix that results in a dense, strong body. Thus, the final microstructure consists of the vitrified phase, any unreacted quartz particles, and some porosity.

FABRICATION AND PROCESSING OF CLAY PRODUCTS (Drying and Firing / *Firing*)

Complete vitrification is avoided during firing because a body becomes too soft and will collapse.

Bricks: fired at 900 ºC.

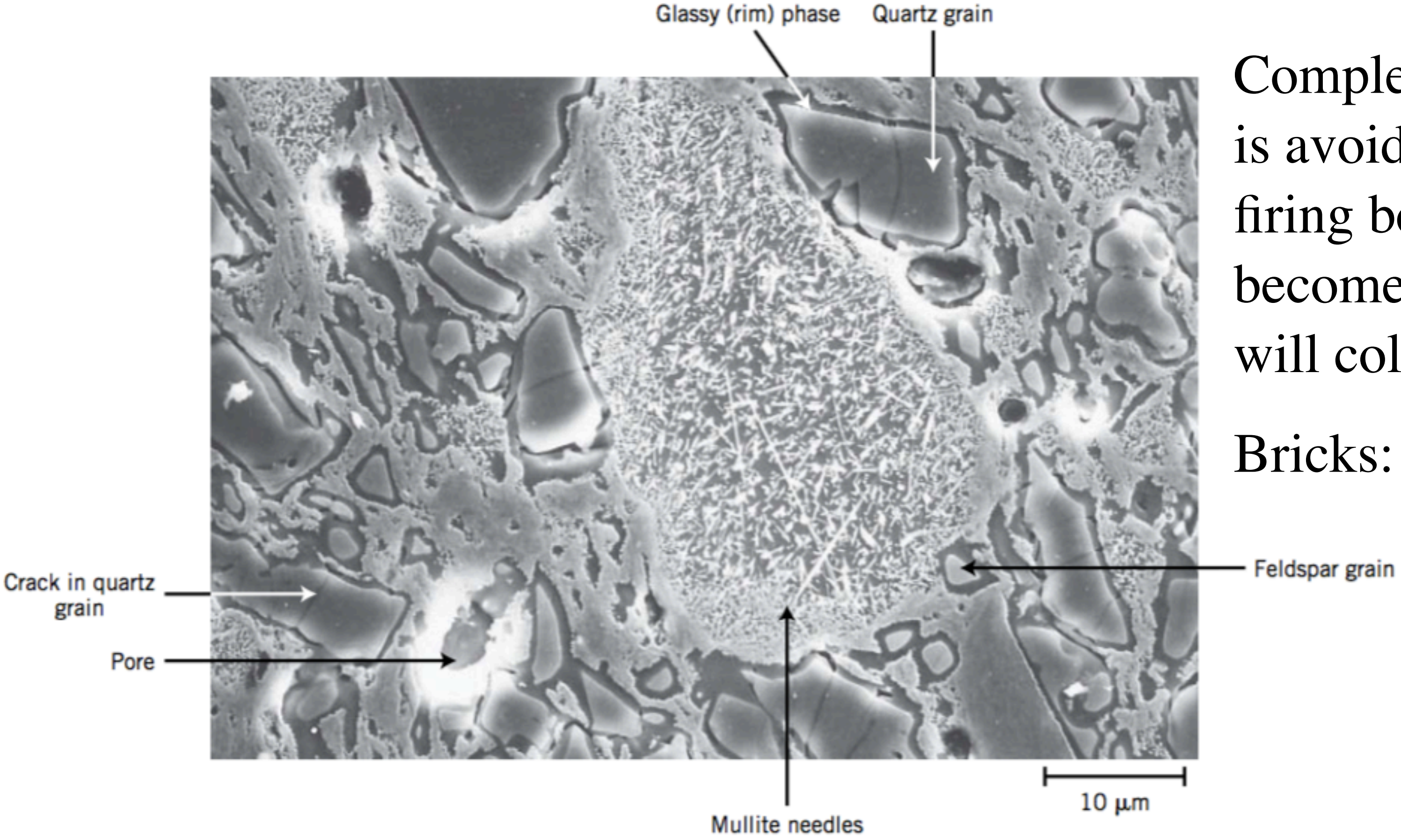


Figure 13.19 Scanning electron micrograph of a fired porcelain specimen (etched 15 s, 5°C, 10% HF) in which the following features may be seen: quartz grains (large dark particles), which are surrounded by dark glassy solution rims; partially dissolved feldspar regions (small unfeatured areas); mullite needles; and pores (dark holes with white border regions). Cracks within the quartz particles may be noted, which were formed during cooling as a result of the difference in shrinkage between the glassy matrix and the quartz. 1500×.
(Courtesy of H. G. Brinkies, Swinburne University of Technology, Hawthorn Campus, Hawthorn, Victoria, Australia.)

POWDER PRESSING

- Powder pressing: used to fabricate both clay and nonclay compositions, including electronic and magnetic ceramics, as well as some refractory brick products.

- A powdered mass, usually containing a small amount of water or other binder, is compacted into the desired shape by pressure.

- The degree of compaction is maximized and the fraction of void space is minimized by using coarse and fine particles mixed in appropriate proportions

- There are three basic powder-pressing procedures: uniaxial, isostatic (or hydrostatic), and hot pressing.

POWDER PRESSING

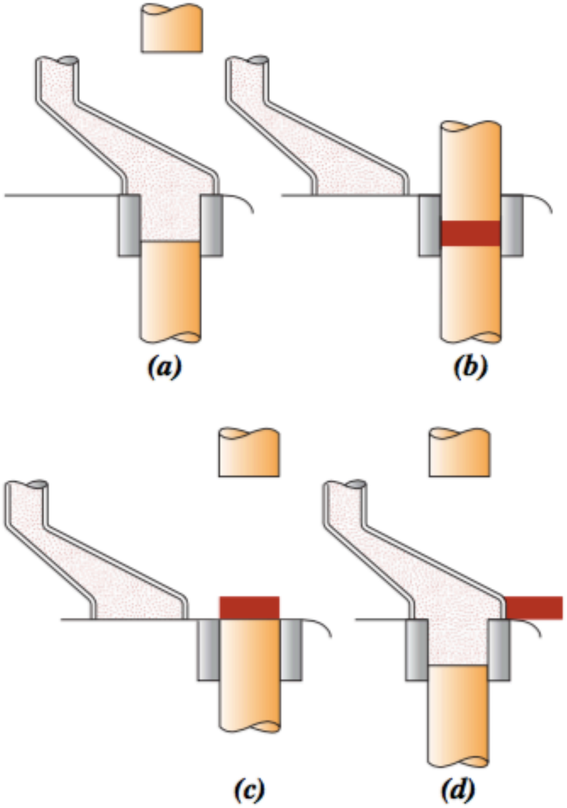


Figure 13.20 Schematic representation of the steps in uniaxial powder pressing. (*a*) The die cavity is filled with powder. (*b*) The powder is compacted by means of pressure applied to the top die. (*c*) The compacted piece is ejected by rising action of the bottom punch. (*d*) The fill shoe pushes away the compacted piece, and the fill step is repeated.
(From W. D. Kingery, *Ceramic Fabrication Processes,* p. 66. © 1958 Massachusetts Institute of Technology. By permission of The MIT Press.)

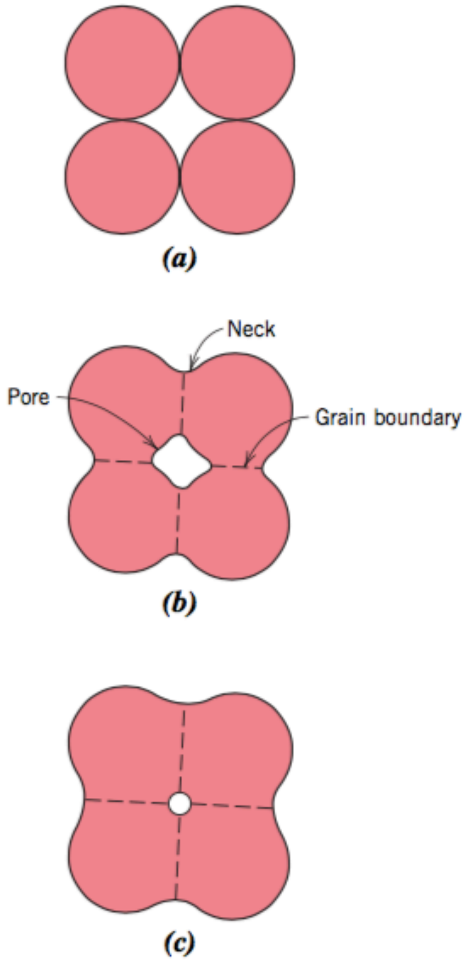


Figure 13.21 For a powder compact, microstructural changes that occur during firing. (*a*) Powder particles after pressing. (*b*) Particle coalescence and pore formation as sintering begins. (*c*) As sintering proceeds, the pores change size and shape.

TAPE CASTING

- In this technique, thin sheets of a flexible tape are produced by means of a casting process.
- These sheets are prepared from slips in many respects similar to those employed for slip casting.
- This type of slip consists of a suspension of ceramic particles in an organic liquid that also contains binders and plasticizers, which are incorporated to impart strength and flexibility to the cast tape.
- The actual tape is formed by pouring the slip onto a flat surface (of stainless steel, glass, a polymeric film, or paper); a doctor blade spreads the slip into a thin tape of uniform thickness.
- In the drying process, volatile slip components are removed by evaporation; this green product is a flexible tape that may be cut or into which holes may be punched prior to a firing operation. Tape thicknesses normally range between 0.1 and 2 mm

TAPE CASTING

Tape casting is widely used in the production of ceramic substrates that are used for integrated circuits and for multilayered capacitors.

Figure 13.23 Schematic diagram showing the tape-casting process using a doctor blade.
(From D. W. Richerson, *Modern Ceramic Engineering*, 2nd edition, Marcel Dekker, Inc., NY, 1992. Reprinted from *Modern Ceramic Engineering*, 2nd edition, p. 472 by courtesy of Marcel Dekker, Inc.)