(a) Quartz

(b) Clay

(c) Feldspar

Mix, add water, form, dry, fire

(d) Porcelain

Micrographs showing particles of (*a*) quartz, (*b*) clay, and (*c*) feldspar—the primary constituents of porcelain. In order to produce a porcelain object, these three ingredients are mixed in the proper proportions, water is added, and an object having the desired shape is formed (either by slip casting or hydroplastic forming). Next most of the water is removed during a drying operation, and the object is fired at an elevated temperature in order to improve its strength and impart other desirable properties. Decoration of this porcelain body is possible by applying a glaze to its surface.

(*d*) Scanning electron micrograph of a fired porcelain. 1500✕.

(*e*) and (*f*) Fired and glazed porcelain objets d'art.

[Figure (*a*) Courtesy Gregory C. Finn, Brock University; (*b*) courtesy of Hefa Cheng and Martin Reinhard, Stanford University; (*c*) courtesy of Martin Lee, University of Glasgow; (*d*) courtesy of H. G. Brinkies, Swinburne University of Technology, Hawthorn Campus, Hawthorn, Victoria, Australia; (*e*) and (*f*) from iStockphoto.]

(f)

(e)

WHY STUDY *Applications and Processing of Ceramics?*

It is important for the engineer to realize how the applications and processing of ceramic materials are influenced by their mechanical and thermal properties, such as hardness, brittleness, and high melting temperatures. For example, ceramic pieces normally cannot be fabricated using conventional metal-forming techniques (Chapter 11). As we discuss in this chapter, they are often formed using powder compaction methods, and subsequently fired (i.e., heat-treated).

In the processing/structure/properties/performance scheme, reasons for studying applications and processing of ceramics are as follows:

- During the processing of a glass-ceramic, it is necessary to melt and subsequently shape a viscous mass.

Melting and shaping procedures are facilitated with a knowledge of the temperature dependence of viscosity. The viscosity–temperature behavior of glasses is presented in this chapter.
- Another step in the processing of glass-ceramics is crystallization of the glass material. Crystallization is accomplished during cooling from an elevated temperature. We also explore in this chapter how rate of cooling affects degree of crystallization.
- In the crystallization process a noncrystalline material is transformed into a fine-grained polycrystalline one. Accompanying this transformation is an alteration in properties, which is also discussed.

Learning Objectives

After studying this chapter you should be able to do the following:

1. Describe the process that is used to produce glass-ceramics.
2. Name the two types of clay products, and give two examples of each.
3. Cite three important requirements that normally must be met by refractory ceramics and abrasive ceramics.
4. Describe the mechanism by which cement hardens when water is added.
5. Name and briefly describe four forming methods that are used to fabricate glass pieces.
6. Briefly describe and explain the procedure by which glass pieces are thermally tempered.
7. Briefly describe processes that occur during the drying and firing of clay-based ceramic ware.
8. Briefly describe/diagram the sintering process of powder particle aggregates.

13.1 INTRODUCTION

The preceding discussions of the properties of materials have demonstrated that there is a significant disparity between the physical characteristics of metals and ceramics. Consequently, these materials are used in totally 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, and the newly developed advanced ceramics. Figure 13.1 presents a taxonomy of these several types; some discussion is devoted to each in this chapter.
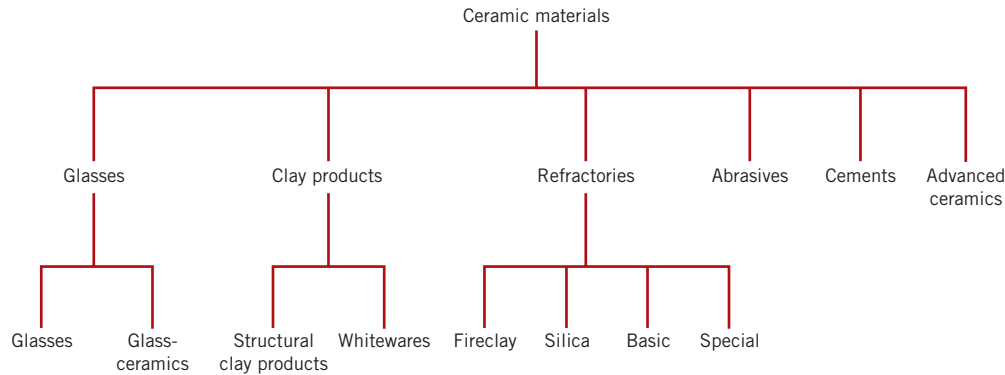
Figure 13.1 Classification of ceramic materials on the basis of application.

Types and Applications of Ceramics

13.2 GLASSES

The glasses are a familiar group of ceramics; containers, lenses, and fiberglass represent typical applications. As already mentioned, 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). The compositions of several common glass materials are contained in Table 13.1. Possibly the two prime assets of these materials are their optical transparency and the relative ease with which they may be fabricated.

13.3 GLASS-CERAMICS

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

Table 13.1 Compositions and Characteristics of Some of the Common Commercial Glasses

| Glass Type	Composition (wt%)						Characteristics and Applications
	SiO_2	Na_2O	CaO	Al_2O_3	B_2O_3	Other	
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

called **crystallization,** and the product is a fine-grained polycrystalline material that is often called a **glass-ceramic.** The formation of these small glass-ceramic grains is, in a sense, a phase transformation, which involves nucleation and growth stages. As a consequence, the kinetics (i.e., the rate) of crystallization may be described using the same principles that were applied to phase transformations for metal systems in Section 10.3. For example, dependence of degree of transformation on temperature and time may be expressed using isothermal transformation and continuous cooling transformation diagrams (Sections 10.5 and 10.6). The continuous cooling transformation diagram for the crystallization of a lunar glass is presented in Figure 13.2; the begin and end transformation curves on this plot have the same general shape as those for an iron–carbon alloy of eutectoid composition (Figure 10.25). Also included are two continuous cooling curves, which are labeled "1" and "2"; the cooling rate represented by curve 2 is much greater than that for curve 1. As also noted on this plot, for the continuous cooling path represented by 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. The other cooling curve (curve 2) just 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; for cooling rates less than this, some glass-ceramic material will form.

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.

Properties and Applications of Glass–Ceramics

Glass-ceramic materials have been designed to have the following characteristics: relatively high mechanical strengths; low coefficients of thermal expansion (to avoid thermal shock); relatively 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. Possibly the most attractive attribute of this class of materials is the ease with which they may be fabricated; conventional glass-forming techniques may be used conveniently in the mass production of nearly pore-free ware.

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). Also 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.)
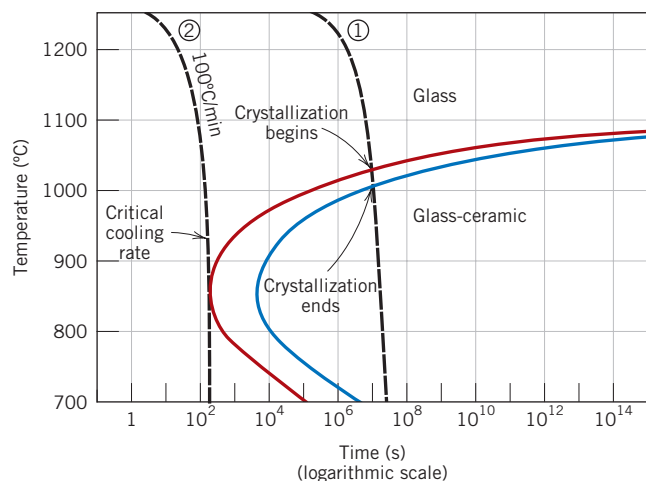
Glass-ceramics are manufactured commercially under the trade names of Pyroceram, CorningWare, Cercor, and Vision. The most common uses for these materials are as ovenware, tableware, oven windows, and range tops—primarily because of their strength and excellent resistance to thermal shock. They also serve as electrical insulators and as substrates for printed circuit boards and are used for architectural cladding and for heat exchangers and regenerators. A typical glass-ceramic is also included in Table 13.1.

✓ *Concept Check 13.1*

Briefly explain why glass-ceramics may not be transparent. *Hint:* you may want to consult Chapter 21.

[*The answer may be found at* www.wiley.com/college/callister *(Student Companion Site).*]

13.4 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.

structural clay product

whiteware

firing

Most of the clay-based products fall within two broad classifications: the **structural clay products** and the **whitewares.** Structural clay products include building bricks, tiles, and sewer pipes—applications in which structural integrity is important. The whiteware ceramics become white after the high-temperature **firing.** Included in this group are porcelain, pottery, tableware, china, and plumbing fixtures (sanitary ware). In addition to clay, many of these products also contain nonplastic ingredients, which influence the changes that take place during the drying and firing processes, and the characteristics of the finished piece (Section 13.10).

13.5 REFRACTORIES

refractory ceramic

Another important class of ceramics that are used in large tonnages is the **refractory ceramics.** The salient properties of these materials 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. Refractory materials are marketed in a variety of forms, but bricks are the most common. Typical applications include furnace linings for metal refining, glass manufacturing, metallurgical heat treatment, and power generation.

Of course, the performance of a refractory ceramic depends to a large degree on its composition. On this basis, there are several classifications—fireclay, silica, basic, and special refractories. Compositions for a number of commercial refractories are listed in Table 13.2. For many commercial materials, the raw ingredients consist of both large (or grog) 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

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

	Composition (wt%)							Apparent Porosity (%)
Refractory Type	Al_2O_3	SiO_2	MgO	Cr_2O_3	Fe_2O_3	CaO	TiO_2	
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.

brick; this phase may be predominantly either glassy or crystalline. 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 diminished. Of course, the optimum porosity depends on the conditions of service.

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. According to the SiO_2–Al_2O_3 phase diagram, Figure 12.27, over this composition range the highest temperature possible without the formation of a liquid phase is 1587°C (2890°F). Below this temperature the equilibrium phases present are mullite and silica (cristobalite). During refractory service use, the presence of a small amount of a liquid phase may be allowable without compromising mechanical integrity. Above 1587°C the fraction of liquid phase present will depend on refractory composition. Upgrading the alumina content will increase the maximum service temperature, allowing for the formation of a small amount of liquid.

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. Some control is normally maintained over the dimensional accuracy and stability of the finished product.

Silica Refractories

The prime ingredient for silica refractories, sometimes termed *acid refractories,* is silica. These materials, well known for their high-temperature load-bearing capacity, are commonly used in the arched roofs of steel- and glass-making furnaces; for these applications, temperatures as high as 1650°C (3000°F) may be realized. Under these conditions some small portion of the brick will actually exist as a liquid. The presence of even small concentrations of alumina has an adverse influence on the performance of these refractories, which may be explained by the silica–alumina phase diagram, Figure 12.27. 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°C

(2910°F). 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*) and are often used as containment vessels for them. On the other hand, 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.

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

Special Refractories

Yet other ceramic materials are used for rather specialized refractory applications. Some of these are relatively high-purity oxide materials, many of which may be produced with very little porosity. Included in this group are alumina, silica, magnesia, beryllia (BeO), zirconia (ZrO_2), and mullite ($3Al_2O_3$–$2SiO_2$). Others include carbide compounds, in addition to carbon and graphite. Silicon carbide (SiC) has been used for electrical resistance heating elements, as a crucible material, and in internal furnace components. Carbon and graphite are very refractory, but find limited application because they are susceptible to oxidation at temperatures in excess of about 800°C (1470°F). As would be expected, these specialized refractories are relatively expensive.

✓ *Concept Check 13.2*

Upon consideration of the SiO_2–Al_2O_3 phase diagram (Figure 12.27) for the following pair of compositions, which would you judge to be the more desirable refractory? Justify your choice.

    20 wt% Al_2O_3–80 wt% SiO_2
    25 wt% Al_2O_3–75 wt% SiO_2

[*The answer may be found at www.wiley.com/college/callister (Student Companion Site).*]

13.6 ABRASIVES

abrasive ceramic

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 utilized 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.

Abrasives are used in several forms—bonded to grinding wheels, as coated abrasives, and as loose grains. In the first case, the abrasive particles are bonded to a

Figure 13.3 Photomicrograph of an aluminum oxide bonded ceramic abrasive. The light regions are the Al_2O_3 abrasive grains; the gray and dark areas are the bonding phase and porosity, respectively. 100×. (From W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, *Introduction to Ceramics,* 2nd edition, p. 568. Copyright © 1976 by John Wiley & Sons. Reprinted by permission of John Wiley & Sons, Inc.)

100 μm
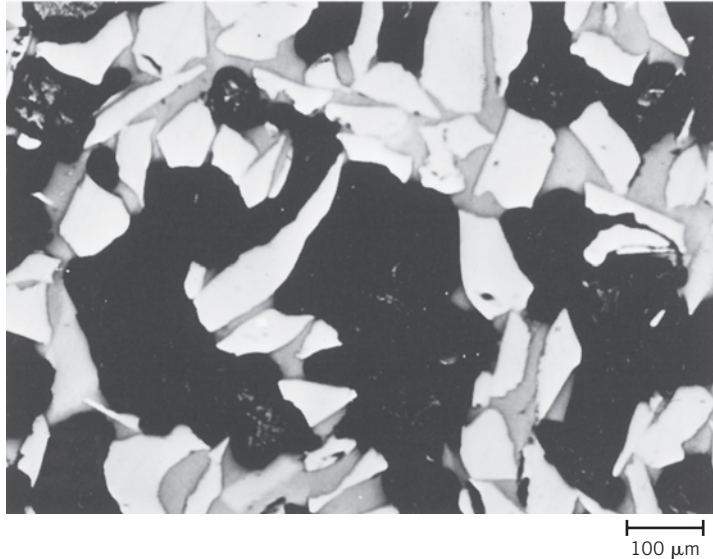
wheel by means of a glassy ceramic or an organic resin. The surface structure should contain some porosity; a continual flow of air currents or liquid coolants within the pores that surround the refractory grains prevents excessive heating. Figure 13.3 shows the microstructure of a bonded abrasive, revealing abrasive grains, the bonding phase, and pores.

Coated abrasives are those in which an abrasive powder is coated on some type of paper or cloth material; sandpaper is probably the most familiar example. Wood, metals, ceramics, and plastics are all frequently ground and polished using this form of abrasive.

Grinding, lapping, and polishing wheels often employ loose abrasive grains that are delivered in some type of oil- or water-based vehicle. Diamonds, corundum, silicon carbide, and rouge (an iron oxide) are used in loose form over a variety of grain size ranges.

13.7 CEMENTS

cement

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 expeditiously formed. Also, some of these materials act as a bonding phase that chemically binds particulate aggregates into a single cohesive structure. Under these circumstances, the role of the cement is similar to that of the glassy bonding phase that forms when clay products and some refractory bricks are fired. One important difference, however, is that the cementitious bond develops at room temperature.

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°C (2550°F) in a rotary

calcination

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.

Several different constituents are found in portland cement, the principal ones being tricalcium silicate ($3CaO$–SiO_2) and dicalcium silicate ($2CaO$–SiO_2). The setting and hardening of this material result from relatively complicated hydration reactions that occur among the various cement constituents and the water that is added. For example, one hydration reaction involving dicalcium silicate is as follows:

$$2CaO\text{–}SiO_2 + xH_2O \rightarrow 2CaO\text{–}SiO_2\text{–}xH_2O \qquad (13.1)$$

where x is variable and depends on how much water is available. These hydrated products are in the form of complex gels or crystalline substances that form the cementitious bond. Hydration reactions begin just as soon as water is added to the cement. These are first manifested as setting (i.e., the stiffening of the once-plastic paste), which takes place soon after mixing, usually within several hours. Hardening of the mass follows as a result of further hydration, a relatively slow process that may continue for as long as several years. It should be emphasized that the process by which cement hardens is not one of drying, but rather of hydration in which water actually participates in a chemical bonding reaction.

Portland cement is termed a *hydraulic cement* because its hardness develops by chemical reactions with water. It is used primarily in mortar and concrete to bind aggregates of inert particles (sand and/or gravel) into a cohesive mass; these are considered to be composite materials (see Section 16.2). Other cement materials, such as lime, are nonhydraulic; that is, compounds other than water (e.g., CO_2) are involved in the hardening reaction.

✓ *Concept Check 13.3*

Explain why it is important to grind cement into a fine powder.

[*The answer may be found at www.wiley.com/college/callister (Student Companion Site).*]

13.8 ADVANCED CERAMICS

Although the traditional ceramics discussed previously account for the bulk of the production, the development of new and what are termed *advanced ceramics* has begun and will continue to establish a prominent niche in our advanced technologies. In particular, electrical, magnetic, and optical properties and property combinations unique to ceramics have been exploited in a host of new products; some of these are discussed in Chapters 18, 20, and 21. Furthermore, advanced ceramics are utilized in optical fiber communications systems, in microelectromechanical systems (MEMS), as ball bearings, and in applications that exploit the piezoelectric behavior of a number of ceramic materials. Each of these will now be discussed.

Microelectromechanical Systems (MEMS)

microelectro-
mechanical system

Microelectromechanical systems (abbreviated *MEMS*) are miniature "smart" systems (Section 1.5) consisting of a multitude of mechanical devices that are integrated with large numbers of electrical elements on a substrate of silicon. The mechanical components are microsensors and microactuators. Microsensors collect environmental information by measuring mechanical, thermal, chemical, optical, and/or magnetic phenomena. The microelectronic components then process this sensory input and subsequently render decisions that direct responses from the

Figure 13.4 Scanning electron micrograph showing a linear rack gear reduction drive MEMS. This gear chain converts rotational motion from the top-left gear to linear motion to drive the linear track (lower right). Approximately 100×. (Courtesy Sandia National Laboratories, SUMMiT* Technologies, www.mems.sandia.gov.)

100 μm
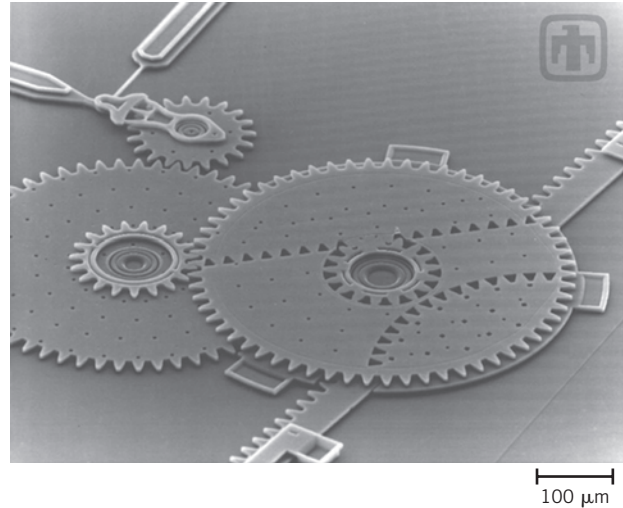
microactuator devices—devices that perform such responses as positioning, moving, pumping, regulating, and filtering. These actuating devices include beams, pits, gears, motors, and membranes, which are of microscopic dimensions, on the order of microns in size. Figure 13.4 is a scanning electron micrograph of a linear rack gear reduction drive MEMS.

The processing of MEMS is virtually the same as that used for the production of silicon-based integrated circuits; this includes photolithographic, ion implantation, etching, and deposition technologies, which are well established. In addition, some mechanical components are fabricated using micromachining techniques. MEMS components are very sophisticated, reliable, and minuscule in size. Furthermore, because the preceding fabrication techniques involve batch operations, the MEMS technology is very economical and cost effective.

There are some limitations to the use of silicon in MEMS. Silicon has a low fracture toughness ($\sim 0.90 \, \text{MPa} \sqrt{\text{m}}$) and a relatively low softening temperature (600°C) and is highly active to the presence of water and oxygen. Consequently, research is currently being conducted into using ceramic materials—which are tougher, more refractory, and more inert—for some MEMS components, especially high-speed devices and nanoturbines. The ceramic materials being considered are amorphous silicon carbonitrides (silicon carbide–silicon nitride alloys), which may be produced using metal organic precursors. In addition, fabrication of these ceramic MEMS will undoubtedly involve some of the traditional techniques discussed later in this chapter.

One example of a practical MEMS application is an accelerometer (accelerator/decelerator sensor) that is used in the deployment of air-bag systems in automobile crashes. For this application, the important microelectronic component is a freestanding microbeam. Compared to conventional air-bag systems, the MEMS units are smaller, lighter, and more reliable and are produced at a considerable cost reduction.

Potential MEMS applications include electronic displays, data storage units, energy conversion devices, chemical detectors (for hazardous chemical and biological agents and drug screening), and microsystems for DNA amplification and identification. There are undoubtedly many yet unforeseen uses of this MEMS technology, which will have a profound impact on our society in the future; these will probably overshadow the effects of microelectronic integrated circuits during the past three decades.

Optical Fibers

One new and advanced ceramic material that is a critical component in our modern optical communications systems is the **optical fiber.** The optical fiber is made of extremely high-purity silica, which must be free of even minute levels of contaminants and other defects that absorb, scatter, and attenuate a light beam. Very advanced and sophisticated processing techniques have been developed to produce fibers that meet the rigid restrictions required for this application. A discussion of optical fibers and their role in communications is provided in Section 21.14.

Ceramic Ball Bearings

Another new and interesting application of ceramic materials is in bearings. A bearing consists of balls and races that are in contact with and rub against one another when in use. In the past, both ball and race components traditionally have been made of bearing steels that are very hard and extremely corrosion resistant and may be polished to a very smooth surface finish. Over the past decade or so, silicon nitride (Si_3N_4) balls have begun replacing steel balls in a number of applications, because several properties of Si_3N_4 make it a more desirable material. In most instances races are still made of steel, because its tensile strength is superior to that of silicon nitride. This combination of ceramic balls and steel races is termed a *hybrid bearing*.

Because the density of Si_3N_4 is much less than that of steel (3.2 versus 7.8 g/cm^3), hybrid bearings weigh less than conventional ones; thus, centrifugal loading is less in the hybrids, with the result that they may operate at higher speeds (20% to 40% higher). Furthermore, the modulus of elasticity of silicon nitride is higher than for bearing steels (320 GPa versus about 200 GPa). Thus, the Si_3N_4 balls are more rigid and experience lower deformations while in use, which leads to reductions in noise and vibration levels. Lifetimes for the hybrid bearings are greater than for steel bearings—normally three to five times as great. The longer life is a consequence of the higher hardness of Si_3N_4 (75 to 80 HRC as compared to 58 to 64 HRC for bearing steels) and silicon nitride's superior compressive strength (3000 MPa versus 900 MPa), which results in lower wear rates. In addition, less heat is generated using the hybrid bearings, because the coefficient of friction of Si_3N_4 is approximately 30% that of steel; this leads to an increase in grease life. In addition, lower lubrication levels are required than for the all-steel bearings. Ceramic materials are inherently more corrosion resistant than metal alloys; thus, the silicon nitride balls may be used in more corrosive environments and at higher operating temperatures. Finally, because Si_3N_4 is an electrical insulator (bearing steels are much more electrically conductive), the ceramic bearings are immune to arcing damage.

Some of the applications that employ these hybrid bearings include inline skates, bicycles, electric motors, machine tool spindles, precision medical hand tools (e.g., high-speed dental drills and surgical saws), and textile, food-processing, and chemical equipment.

Also, all-ceramic bearings (having both ceramic races and balls) are now being used on a limited basis in applications requiring a high degree of corrosion resistance.

Significant research has gone into the development of this silicon nitride–bearing material. Some of the challenges that were encountered are as follows: processing/fabrication techniques to yield a pore-free material, fabrication of spherical pieces that require a minimum of machining, and a polishing/lapping technique to produce a smoother surface finish than steel balls.

MATERIALS OF IMPORTANCE

Piezoelectric Ceramics

A few ceramic materials (as well as some polymers) exhibit the unusual phenomenon of piezoelectricity[1]—electric polarization[2] (i.e., an electric field or voltage) is induced in the ceramic crystal when a mechanical strain (dimensional change) is imposed on it. The inverse piezoelectric effect is also displayed by this group of materials; that is, a mechanical strain results from the imposition of an electrical field.

Piezoelectric materials may be used as transducers between electrical and mechanical energies. One of the early uses of piezoelectric ceramics was in sonar, wherein underwater objects (e.g., submarines) are detected and their positions determined using an ultrasonic emitting and receiving system. A piezoelectric crystal is caused to oscillate by an electrical signal, which produces high-frequency mechanical vibrations that are transmitted through the water. Upon encountering an object, these signals are reflected back, and another piezoelectric material receives this reflected vibrational energy, which it then converts back into an electrical signal. Distance from the ultrasonic source and reflecting body is determined from the elapsed time between sending and receiving events.

More recently, the use of piezoelectric devices has grown dramatically as a consequence of increases in automation and consumer attraction to modern sophisticated gadgets. Applications that employ piezoelectric devices are found in the automotive, computer, commercial/consumer, and medical sectors. Some of these applications are as follows: automotive—wheel balances, seat belt buzzers, tread-wear indicators, keyless door entry, and airbag sensors; computer—microactuators for hard disks and notebook transformers; commercial/consumer—ink-jet printing heads, strain gauges, ultrasonic welders, and smoke detectors; medical—insulin pumps, ultrasonic therapy, and ultrasonic cataract-removal devices.

Commonly used piezoelectric ceramics include barium titanate ($BaTiO_3$), lead titanate ($PbTiO_3$), lead zirconate–titanate (PZT) [$Pb(Zr,Ti)O_3$], and potassium niobate ($KNbO_3$).

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[1] The piezoelectric phenomenon is described in more detail in Section 18.25.
[2] Electric polarization (explained in Sections 18.19 and 18.20) is the alignment of electric dipoles (Section 2.7) in a common direction, which gives rise to an electric field that is oriented in this same direction.

Fabrication and Processing of Ceramics

One chief concern in the application of ceramic materials is the method of fabrication. Many of the metal-forming operations discussed in Chapter 11 rely on casting and/or techniques that involve some form of plastic deformation. 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. A taxonomical scheme for the several types of ceramic-forming techniques is presented in Figure 13.5.