

# 1

## Introduction

### CHAPTER PREVIEW

In materials science we often divide materials into distinct classes. The primary classes of solid materials are ceramics, metals, and polymers. This classification is based on the types of atoms involved and the bonding between them. The other widely recognized classes are semiconductors and composites. Composites are combinations of more than one material and often involve ceramics, such as fiberglass. Semiconductors are materials with electrical conductivities that are very sensitive to minute amounts of impurities. As we will see later, most materials that are semiconductors are actually ceramics, for example, gallium nitride, the blue–green laser diode material.

In this chapter we will define what we mean by a “ceramic” and will also describe some of the general properties of ceramics. The difficulty when drawing generalizations, particularly in this case, is that it is always possible to find an exception to the rule. It is because of the wide range of properties exhibited by ceramics that they find application in such a variety of areas. A general theme throughout this book is the interrelationship between the way in which a ceramic is processed, its microstructure, and its properties. We give some examples of these interrelationships in this chapter to illustrate their importance.

### 1.1 DEFINITIONS

If you look in any introductory materials science book you will find that one of the first sections describes the classification scheme. In classical materials science, materials are grouped into five categories: metals, polymers, ceramics, semiconductors, and composites. The first three are based primarily on the nature of the interatomic bonding, the fourth on the materials conductivity, and the last on the materials structure—not a very consistent start.

*Metals*, both pure and alloyed, consist of atoms held together by the delocalized electrons that overcome the mutual repulsion between the ion cores. Many main-group elements and all the transition and inner transition elements are metals. They also include alloys—combinations of metallic elements or metallic and nonmetallic elements (such as in steel, which is an alloy of primarily Fe and C). Some commercial steels, such as many tool steels, contain ceramics. These are the carbides (e.g.,  $\text{Fe}_3\text{C}$  and  $\text{W}_6\text{C}$ ) that produce the hardening and enhance wear resistance, but also make it more brittle. The delocalized electrons give metals many of their characteristic properties (e.g., good thermal and electrical conductivity). It is because of their bonding that many metals have close packed structures and deform plastically at room temperature.

*Polymers* are macromolecules formed by covalent bonding of many simpler molecular units called mers.

Most polymers are organic compounds based on carbon, hydrogen, and other nonmetals such as sulfur and chlorine. The bonding between the molecular chains determines many of their properties. Cross-linking of the chains is the key to the vulcanization process that turned rubber from an interesting but not very useful material into, for example, tires that made traveling by bicycle much more comfortable and were important in the production of the automobile. The terms “polymer” and “plastic” are often used interchangeably. However, many of the plastics with which we are familiar are actually combinations of polymers, and often include fillers and other additives to give the desired properties and appearance.

*Ceramics* are usually associated with “mixed” bonding—a combination of covalent, ionic, and sometimes metallic. They consist of arrays of interconnected atoms; there are no discrete molecules. This characteristic distinguishes ceramics from molecular solids such as iodine crystals (composed of discrete  $\text{I}_2$  molecules) and paraffin wax (composed of long-chain alkane molecules). It also excludes ice, which is composed of discrete  $\text{H}_2\text{O}$  molecules and often behaves just like many ceramics. The majority of ceramics are compounds of metals or metalloids and nonmetals. Most frequently they are oxides, nitrides, and carbides. However, we also classify diamond and graphite as ceramics. These forms of carbon are inorganic in the most basic meaning of the term: they were

not prepared from the living organism. Richerson (2000) says “most solid materials that aren’t metal, plastic, or derived from plants or animals are ceramics.”

*Semiconductors* are the only class of material based on a property. They are usually defined as having electrical conductivity between that of a good conductor and an insulator. The conductivity is strongly dependent upon the presence of small amounts of impurities—the key to making integrated circuits. Semiconductors with wide band gaps (greater than about 3 eV) such as silicon carbide and boron nitride are becoming of increasing importance for high-temperature electronics, for example, SiC diodes are of interest for sensors in fuel cells. In the early days of semiconductor technology such materials would have been regarded as insulators. Gallium nitride (GaN), a blue–green laser diode material, is another ceramic that has a wide band gap.

*Composites* are combinations of more than one material or phase. Ceramics are used in many composites, often for reinforcement. For example, one of the reasons a B-2 stealth bomber is stealthy is that it contains over 22 tons of carbon/epoxy composite. In some composites the ceramic is acting as the matrix (ceramic matrix composites or CMCs). An early example of a CMC dating back over 9000 years is brick. These often consisted of a fired clay body reinforced with straw. Clay is an important ceramic and the backbone of the traditional ceramic industry. In concrete, both the matrix (cement) and the reinforcement (aggregate) are ceramics.

The most widely accepted definition of a ceramic is given by Kingery *et al.* (1976): “A ceramic is a nonmetallic, inorganic solid.” Thus all inorganic semiconductors are ceramics. By definition, a material ceases to be a ceramic when it is melted. At the opposite extreme, if we cool some ceramics enough they become superconductors. All the so-called high-temperature superconductors (HTSC) (ones that lose all electrical resistance at liquid-nitrogen temperatures) are ceramics. Trickier is glass such as used in windows and optical fibers. Glass fulfills the standard definition of a solid—it has its own fixed shape—but it is usually a supercooled liquid. This property becomes evident at high temperatures when it undergoes viscous deformation. Glasses are clearly special ceramics. We may crystallize certain glasses to make glass–ceramics such as those found in Corningware®. This process is referred to as “ceramming” the glass, i.e., making it into a ceramic. We stand by Kingery’s definition and have to live with some confusion. We thus define ceramics in terms of what they are not.

It is also not possible to define ceramics, or indeed any class of material, in terms of specific properties.

- We cannot say “ceramics are brittle” because some can be superplastically deformed and some metals can be more brittle: a rubber hose or banana at 77 K shatters under a hammer.

- We cannot say “ceramics are insulators” unless we put a value on the band gap ( $E_g$ ) where a material is not a semiconductor.
- We cannot say “ceramics are poor conductors of heat” because diamond has the highest thermal conductivity of any known material.

Before we leave this section let us consider a little history. The word ceramic is derived from the Greek *keramos*, which means “potter’s clay” or “pottery.” Its origin is a Sanskrit term meaning “to burn.” So the early Greeks used “keramos” when describing products obtained by heating clay-containing materials. The term has long included all products made from fired clay, for example, bricks, fireclay refractories, sanitaryware, and tableware.

In 1822, silica refractories were first made. Although they contained no clay the traditional ceramic process of shaping, drying, and firing was used to make them. So the term “ceramic,” while retaining its original sense of a product made from clay, began to include other products made by the same manufacturing process. The field of ceramics (broader than the materials themselves) can be defined as the art and science of making and using solid articles that contain as their essential component a ceramic. This definition covers the purification of raw materials, the study and production of the chemical compounds concerned, their formation into components, and the study of structure, composition, and properties.

## 1.2 GENERAL PROPERTIES

Ceramics generally have specific properties associated with them although, as we just noted, this can be a misleading approach to defining a class of material. However, we will look at some properties and see how closely they match our expectations of what constitutes a ceramic.

*Brittleness.* This probably comes from personal experiences such as dropping a glass beaker or a dinner plate. The reason that the majority of ceramics are brittle is the mixed ionic–covalent bonding that holds the constituent atoms together. At high temperatures (above the glass transition temperature) glass no longer behaves in a brittle manner; it behaves as a viscous liquid. That is why it is easy to form glass into intricate shapes. So what we can say is that most ceramics are brittle at room temperature but not necessarily at elevated temperatures.

*Poor electrical and thermal conduction.* The valence electrons are tied up in bonds, and are not free as they are in metals. In metals it is the free electrons—the electron gas—that determines many of their electrical and thermal properties. Diamond, which we classified as a ceramic in Section 1.1, has the highest thermal conductivity of any known material. The conduction mechanism is due to phonons, not electrons, as we describe in Chapter 34.

Ceramics can also have high electrical conductivity: (1) the oxide ceramic,  $\text{ReO}_3$ , has an electrical conductivity

at room temperature similar to that of Cu (2) the mixed oxide  $\text{YBa}_2\text{Cu}_3\text{O}_7$  is an HTSC; it has zero resistivity below 92 K. These are two examples that contradict the conventional wisdom when it comes to ceramics.

**Compressive strength.** Ceramics are stronger in compression than in tension, whereas metals have comparable tensile and compressive strengths. This difference is important when we use ceramic components for load-bearing applications. It is necessary to consider the stress distributions in the ceramic to ensure that they are compressive. An important example is in the design of concrete bridges—the concrete, a CMC, must be kept in compression. Ceramics generally have low toughness, although combining them in composites can dramatically improve this property.

**Chemical insensitivity.** A large number of ceramics are stable in both harsh chemical and thermal environments. Pyrex glass is used widely in chemistry laboratories specifically because it is resistant to many corrosive chemicals, stable at high temperatures (it does not soften until 1100 K), and is resistant to thermal shock because of its low coefficient of thermal expansion ( $33 \times 10^{-7} \text{K}^{-1}$ ). It is also widely used in bakeware.

**Transparent.** Many ceramics are transparent because they have a large  $E_g$ . Examples include sapphire watch

covers, precious stones, and optical fibers. Glass optical fibers have a percent transmission  $>96\% \text{km}^{-1}$ . Metals are transparent to visible light only when they are very thin, typically less than  $0.1 \mu\text{m}$ .

Although it is always possible to find at least one ceramic that shows atypical behavior, the properties we have mentioned here are in many cases different from those shown by metals and polymers.

### 1.3 TYPES OF CERAMIC AND THEIR APPLICATIONS

Using the definition given in Section 1.1 you can see that large numbers of materials are ceramics. The applications for these materials are diverse, from bricks and tiles to electronic and magnetic components. These applications use the wide range of properties exhibited by ceramics. Some of these properties are listed in Table 1.1 together with examples of specific ceramics and applications. Each of these areas will be covered in more detail later. The functions of ceramic products are dependent on their chemical composition and microstructure, which determines their properties. It is the interrelationship between

**TABLE 1.1 Properties and Applications for Ceramics**

Property	Example	Application
Electrical	$\text{Bi}_2\text{Ru}_2\text{O}_7$	Conductive component in thick-film resistors
	Doped $\text{ZrO}_2$	Electrolyte in solid-oxide fuel cells
	Indium tin oxide (ITO)	Transparent electrode
	SiC	Furnace elements for resistive heating
	$\text{YBaCuO}_7$	Superconducting quantum interference devices (SQUIDs)
	$\text{SnO}_2$	Electrodes for electric glass melting furnaces
Dielectric	$\alpha\text{-Al}_2\text{O}_3$	Spark plug insulator
	$\text{PbZr}_{0.5}\text{Ti}_{0.5}\text{O}_3$ (PZT)	Micropumps
	$\text{SiO}_2$	Furnace bricks
	(Ba,Sr)TiO <sub>3</sub>	Dynamic random access memories (DRAMs)
	Lead magnesium niobate (PMN)	Chip capacitors
Magnetic	$\gamma\text{-Fe}_2\text{O}_3$	Recording tapes
	$\text{Mn}_{0.4}\text{Zn}_{0.6}\text{Fe}_2\text{O}_4$	Transformer cores in touch tone telephones
	$\text{BaFe}_{12}\text{O}_{19}$	Permanent magnets in loudspeakers
	$\text{Y}_{2.66}\text{Gd}_{0.34}\text{Fe}_{4.22}\text{Al}_{0.68}\text{Mn}_{0.09}\text{O}_{12}$	Radar phase shifters
Optical	Doped $\text{SiO}_2$	Optical fibers
	$\alpha\text{-Al}_2\text{O}_3$	Transparent envelopes in street lamps
	Doped $\text{ZrSiO}_4$	Ceramic colors
	Doped (Zn,Cd)S	Fluorescent screens for electron microscopes
	$\text{Pb}_{1-x}\text{La}_x(\text{Zr}_z\text{Ti}_{1-z})_{1-x/4}\text{O}_3$ (PLZT)	Thin-film optical switches
	Nd doped $\text{Y}_3\text{Al}_5\text{O}_{12}$	Solid-state lasers
Mechanical	TiN	Wear-resistant coatings
	SiC	Abrasives for polishing
	Diamond	Cutting tools
	$\text{Si}_3\text{N}_4$	Engine components
	$\text{Al}_2\text{O}_3$	Hip implants
Thermal	$\text{SiO}_2$	Space shuttle insulation tiles
	$\text{Al}_2\text{O}_3$ and AlN	Packages for integrated circuits
	Lithium-aluminosilicate glass ceramics	Supports for telescope mirrors
	Pyrex glass	Laboratory glassware and cookware

structure and properties that is a key element of materials science and engineering.

You may find that in addition to dividing ceramics according to their properties and applications that it is common to class them as *traditional* or *advanced*.

Traditional ceramics include high-volume items such bricks and tiles, toilet bowls (whitewares), and pottery.

Advanced ceramics include newer materials such as laser host materials, piezoelectric ceramics, ceramics for dynamic random access memories (DRAMs), etc., often produced in small quantities with higher prices.

There are other characteristics that separate these categories.

*Traditional ceramics* are usually based on clay and silica. There is sometimes a tendency to equate traditional ceramics with low technology, however, advanced manufacturing techniques are often used. Competition among producers has caused processing to become more efficient and cost effective. Complex tooling and machinery is often used and may be coupled with computer-assisted process control.

*Advanced ceramics* are also referred to as “special,” “technical,” or “engineering” ceramics. They exhibit superior mechanical properties, corrosion/oxidation resistance, or electrical, optical, and/or magnetic properties. While traditional clay-based ceramics have been used for over 25,000 years, advanced ceramics have generally been developed within the last 100 years.

Figure 1.1 compares traditional and advanced ceramics in terms of the type of raw materials used, the forming

and shaping processes, and the methods used for characterization.

## 1.4 MARKET

Ceramics is a multibillion dollar industry. Worldwide sales are about \$100 billion ( $\$10^{11}$ ) per year; the U.S. market alone is over \$35 billion ( $\$3.5 \times 10^{10}$ ) annually. As with all economic data there will be variations from year to year. The *Ceramic Industry* (CI) is one organization that provides regular updates of sales through its annual *Giants in Ceramics* survey.

The general distribution of industry sales is as follows:

- 55% Glass
- 17% Advanced ceramics
- 10% Whiteware
- 9% Porcelain enamel
- 7% Refractories
- 2% Structural clay

In the United States, sales of structural clay in the form of bricks is valued at \$160M per month. However, financially, the ceramics market is clearly dominated by glass. The major application for glass is windows. World demand for flat glass is about 40 billion square feet—worth over \$40 billion.

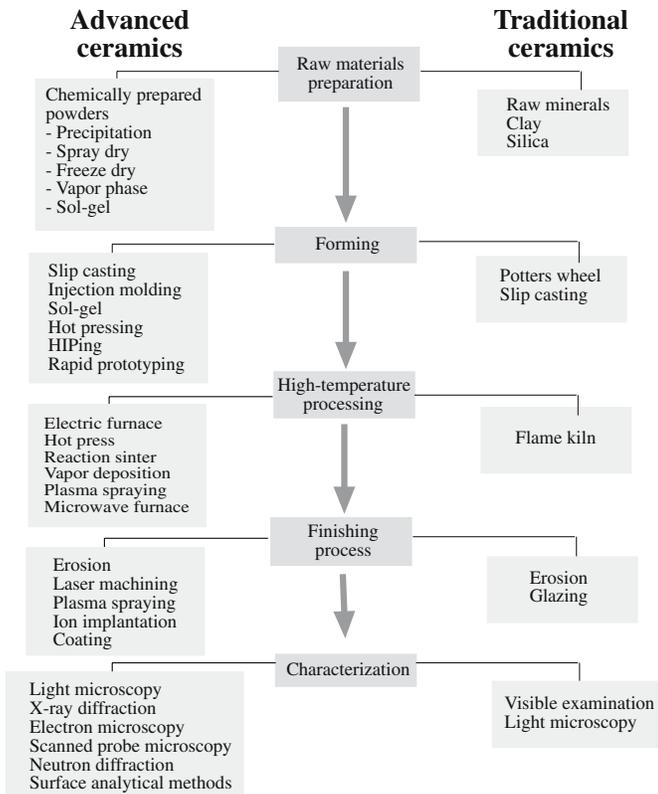
Overall market distribution in the United States is as follows:

- 32% Flat glass
- 18% Lighting
- 17% Containers
- 17% Fiber glass
- 9% TV tubes, CRTs
- 5% Consumer glassware
- 1% Technical/laboratory
- 1% Other

Advanced ceramics form the second largest sector of the industry. More than half of this sector is electrical and electronic ceramics and ceramic packages:

- 36% Capacitors/substrates/packages
- 23% Other electrical/electronic ceramics
- 13% Other
- 12% Electrical porcelain
- 8% Engineering ceramics
- 8% Optical fibers

High-temperature ceramic superconductors, which would fall into the category of advanced ceramics, are not presently a major market area. They constitute less than 1% of the advanced ceramics market. Significant growth has been predicted because of their increased use in microwave filters and resonators, with particular application in the area of cell phones.



**FIGURE 1.1** A comparison of different aspects of traditional and advanced ceramics.

Engineering ceramics, also called structural ceramics, include wear-resistant components such as dies, nozzles, and bearings. Bioceramics such as ceramic and glass-ceramic implants and dental crowns account for about 20% of this market. Dental crowns are made of porcelain and over 30 million are made in the United States each year.

Whiteware sales, which include sanitaryware (toilet bowls, basins, etc.) and dinnerware (plates, cups), account for about 10% of the total market for ceramics. The largest segment of the whiteware market, accounting for about 40%, is floor and wall tiles. In the United States we use about 2.5 billion ( $2.5 \times 10^9$ ) square feet of ceramic tiles per year. Annual sales of sanitaryware in the United States total more than 30 million pieces.

Porcelain enamel is the ceramic coating applied to many steel appliances such as kitchen stoves, washers, and dryers. Porcelain enamels have much wider applications as both interior and exterior paneling in buildings, for example, in subway stations. Because of these widespread applications it is perhaps not surprising that the porcelain enameling industry accounts for more than \$3 billion per year.

More than 50% of refractories are consumed by the steel industry. The major steelmaking countries are China, Japan, and the United States. Structural clay products include bricks, sewer pipes, and roofing tiles. These are high-volume low-unit-cost items. Each year about 8 billion bricks are produced in the United States with a market value of over \$1.5 billion.

## 1.5 CRITICAL ISSUES FOR THE FUTURE

Although glass dominates the global ceramics market, the most significant growth is in advanced ceramics. There are many key issues that need to be addressed to maintain this growth and expand the applications and uses of advanced ceramics. It is in these areas that there will be increasing employment opportunities for ceramic engineers and materials scientists.

*Structural ceramics* include silicon nitride ( $\text{Si}_3\text{N}_4$ ), silicon carbide ( $\text{SiC}$ ), zirconia ( $\text{ZrO}_2$ ), boron carbide ( $\text{B}_4\text{C}$ ), and alumina ( $\text{Al}_2\text{O}_3$ ). They are used in applications such as cutting tools, wear components, heat exchangers, and engine parts. Their relevant properties are high hardness, low density, high-temperature mechanical strength, creep resistance, corrosion resistance, and chemical inertness. There are three key issues to solve in order to expand the use of structural ceramics:

- Reducing cost of the final product
- Improving reliability
- Improving reproducibility

*Electronic ceramics* include barium titanate ( $\text{BaTiO}_3$ ), zinc oxide ( $\text{ZnO}$ ), lead zirconate titanate [ $\text{Pb}(\text{Zr}_x\text{Ti}_{1-x})\text{O}_3$ ], aluminum nitride ( $\text{AlN}$ ), and HTSCs. They are used in applications as diverse as capacitor dielectrics, varistors,

microelectromechanical systems (MEMS), substrates, and packages for integrated circuits. There are many challenges for the future:

- Integrating with existing semiconductor technology
- Improving processing
- Enhancing compatibility with other materials

*Bioceramics* are used in the human body. The response of these materials varies from nearly inert to bioactive to resorbable. Nearly inert bioceramics include alumina ( $\text{Al}_2\text{O}_3$ ) and zirconia ( $\text{ZrO}_2$ ). Bioactive ceramics include hydroxyapatite and some special glass and glass-ceramic formulations. Tricalcium phosphate is an example of a resorbable bioceramic; it dissolves in the body. Three issues will determine future progress:

- Matching mechanical properties to human tissues
- Increasing reliability
- Improving processing methods

*Coatings and films* are generally used to modify the surface properties of a material, for example, a bioactive coating deposited onto the surface of a bioinert implant. They may also be used for economic reasons; we may want to apply a coating of an expensive material to a lower cost substrate rather than make the component entirely from the more expensive material. An example of this situation would be applying a diamond coating on a cutting tool. In some cases we use films or coatings simply because the material performs better in this form. An example is the transport properties of thin films of HTSCs, which are improved over those of the material in bulk form. Some issues need to be addressed:

- Understanding film deposition and growth
- Improving film/substrate adhesion
- Increasing reproducibility

*Composites* may use ceramics as the matrix phase and/or the reinforcing phase. The purpose of a composite is to display a combination of the preferred characteristics of each of the components. In CMCs one of the principal goals has been to increase fracture toughness through reinforcement with whiskers or fibers. When ceramics are the reinforcement phase in, for example, metal matrix composites the result is usually an increase in strength, enhanced creep resistance, and greater wear resistance. Three issues must be solved:

- Reducing processing costs
- Developing compatible combinations of materials (e.g., matching coefficients of thermal expansion)
- Understanding interfaces

*Nanoceramics* can be either well established or at an early stage in their development. They are widely used in cosmetic products such as sunscreens, and we know they

are critical in many applications of catalysis, but their use in fuel cells, coatings, and devices, for example, is often quite new. There are three main challenges:

- Making them
- Integrating them into devices
- Ensuring that they do not have a negative impact on society

## 1.6 RELATIONSHIP BETWEEN MICROSTRUCTURE, PROCESSING, AND APPLICATIONS

The field of materials science and engineering is often defined by the interrelationship between four topics—synthesis and processing, structure and composition, properties, and performance. To understand the behavior and properties of any material, it is essential to understand its structure. Structure can be considered on several levels, all of which influence final behavior. At the finest level is the electron configuration, which affects properties such as color, electrical conductivity, and magnetic behavior. The arrangement of electrons in an atom influences how it will bond to another atom and this, in turn, impacts the crystal structure.

The arrangement of the atoms or ions in the material also needs to be considered. Crystalline ceramics have a very regular atomic arrangement whereas in noncrystalline or amorphous ceramics (e.g., oxide glasses) there is no long-range order, although locally we may identify similar polyhedra. Such materials often behave differently relative to their crystalline counterparts. Not only perfect lattices and ideal structures have to be considered but also the presence of structural defects that are unavoidable in all materials, even the amorphous ones. Examples of such defects include impurity atoms and dislocations.

Polycrystalline ceramics have a structure consisting of many grains. The size, shape, and orientation of the grains play a key role in many of the macroscopic properties of these materials, for example, mechanical strength. In most ceramics, more than one phase is present, with each phase having its own structure, composition, and properties. Control of the type, size, distribution, and amount of these phases within the material provides a means to control properties. The microstructure of a ceramic is often a result of the way it was processed. For example, hot-pressed ceramics often have very few pores. This may not be the case in sintered materials.

The interrelationship between the structure, processing, and properties will be evident throughout this text but are illustrated here by five examples.

1. The strength of polycrystalline ceramics depends on the grain size through the Hall–Petch equation. Figure 1.2 shows strength as a function of grain size for MgO. As the grain size decreases the strength increases. The grain size is determined by the size of the initial powder

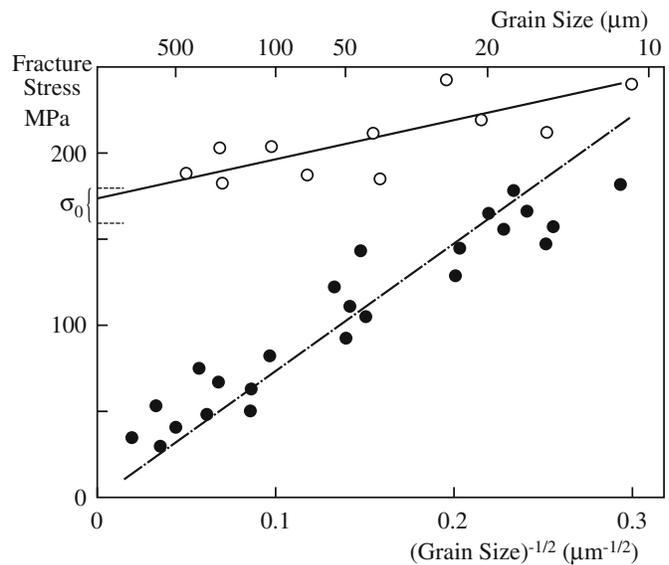


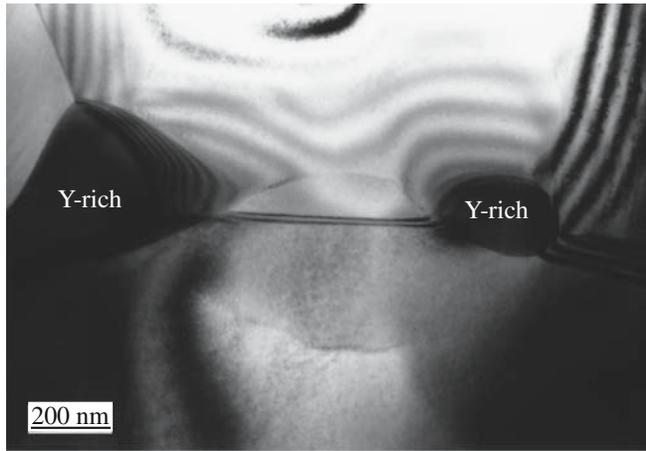
FIGURE 1.2 Dependence of fracture strength of MgO (at 20°C) on the grain size.

particles and the way in which they were consolidated. The grain boundaries in a polycrystalline ceramic are also important. The strength then depends on whether or not the material is pure, contains a second phase or pores, or just contains glass at the grain boundaries. The relationship is not always obvious for nanoceramics.

2. Transparent or translucent ceramics require that we limit the scattering of light by pores and second-phase particles. Reduction in porosity may be achieved by hot pressing to ensure a high-density product. This approach has been used to make transparent PLZT ceramics for electrooptical applications such as the flash-blindness goggles shown in Figure 1.3, developed during the 1970s



FIGURE 1.3 Pilot wearing the flash-blindness goggles (in the “off” position).

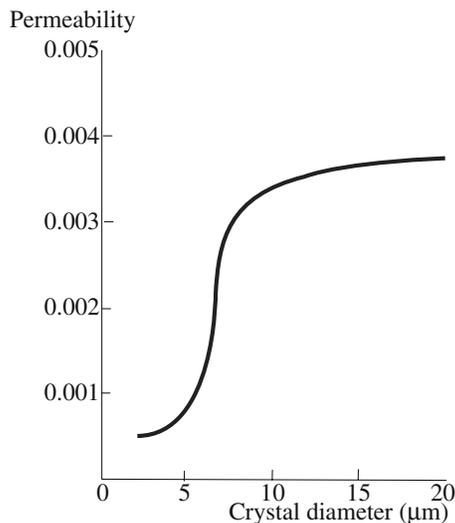


**FIGURE 1.4** TEM image of grain boundaries in AlN showing yttria-rich second-phase particles at the triple junctions.

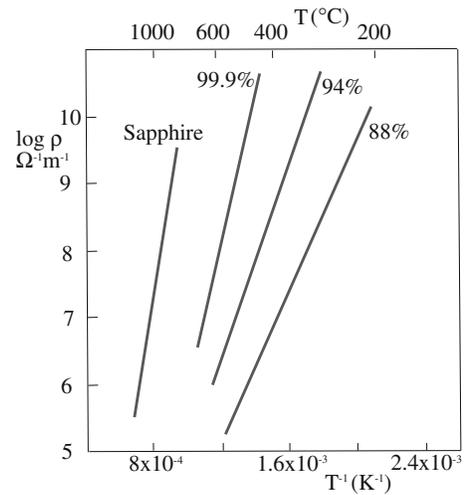
by Sandia National Laboratories in the United States for use by combat pilots.

3. Thermal conductivity of commercially available polycrystalline AlN is usually lower than that predicted by theory because of the presence of impurities, mainly oxygen, which scatter phonons. Adding rare earth or alkaline metal oxides (such as  $Y_2O_3$  and  $CaO$ , respectively) can reduce the oxygen content by acting as a getter. These oxides are mixed in with the AlN powder before it is shaped. The second phase, formed between the oxide additive and the oxide coating on the AlN grains, segregates to triple points as shown in Figure 1.4.

4. Soft ferrites such as  $Mn_{1-\delta}Zn_{\delta}Fe_2O_4$  are used in a range of different devices, for example, as the yoke that moves the electron beam in a television tube. The permeability of soft ferrites is a function of grain size as shown in Figure 1.5. Large defect-free grains are preferred because we need to have very mobile domain walls.



**FIGURE 1.5** The variation of permeability with average grain diameter of a manganese-zinc ferrite with uncontrolled porosity.



**FIGURE 1.6** Dependence of resistivity on temperature for different compositions of alumina.

Defects and grain boundaries pin the domain walls and make it more difficult to achieve saturation magnetization.

5. Alumina ceramics are used as electrical insulators because of their high electrical resistivity and low dielectric constant. For most applications pure alumina is not used. Instead we blend the alumina with silicates to reduce the sintering temperature. These materials are known as debased aluminas and contain a glassy silicate phase between alumina grains. Debased aluminas are generally more conductive (lower resistivity) than pure aluminas as shown in Figure 1.6. Debased aluminas (containing 95%  $Al_2O_3$ ) are used in spark plugs.

## 1.7 SAFETY

When working with any material, safety considerations should be uppermost. There are several important precautions to take when working with ceramics.

*Toxicity* of powders containing, for example, Pb or Cd or fluorides should be known. When shipping the material, the manufacturer supplies information on the hazards associated with their product. It is important to read this information and keep it accessible. Some standard resources that provide information about the toxicity of powders and the “acceptable” exposure levels are given in the References.

*Small particles* should not be inhaled. The effects have been well known, documented, and often ignored since the 1860s. Proper ventilation, improved cleanliness, and protective clothing have significantly reduced many of the industrial risks. Care should be taken when handling any powders (of both toxic and nontoxic materials). The most injurious response is believed to be when the particle size is  $<1 \mu m$ ; larger particles either do not remain suspended in the air sufficiently long to be inhaled or, if inhaled, cannot negotiate the tortuous passage of the upper

**TABLE 1.2 The Color Scale of Temperature**

<i>Color</i>	<i>Corresponding T</i>
Barely visible red	525°C
Dark red	700°C
Cherry red just beginning to appear	800°C
Clear red	900°C
Bright red, beginning orange	1000°C
Orange	1100°C
Orange-white	1200°C
Dull white	1300°C
Bright white	1400°C

respiratory tract. The toxicity and environmental impact of nanopowders have not been clearly addressed, but are the subject of various studies such as a recent report by the Royal Society (2004).

*High temperatures* are used in much of ceramic processing. The effects of high temperatures on the human body are obvious. What is not so obvious is how hot something actually is. Table 1.2 gives the color scale for temperature. From this tabulation you can see that an alumina tube at 400°C will not show a change in color but it will still burn skin. Other safety issues involved with furnaces are given in Chapter 9.

*Organics* are used as solvents and binders during processing. Traditionally, organic materials played little role in ceramic processing. Now they are widely used in many forms of processing. Again, manufacturers will provide safety data sheets on any product they ship. This information is important and should always be read carefully.

As a rule, the material safety data sheets (MSDS) should be readily accessible for all the materials you are

using; many states require that they are kept in the laboratory.

## 1.8 CERAMICS ON THE INTERNET

There is a great deal of information about ceramics on the Internet. Here are some of the most useful web sites.

- [www.FutureCeramics.com](http://www.FutureCeramics.com) The web site for this text.
- [www.acers.org](http://www.acers.org) The American Ceramic Society, membership information, meetings, books.
- [www.acers.org/cic/propertiesdb.asp](http://www.acers.org/cic/propertiesdb.asp) The Ceramic Properties Database. This database has links to many other sources of property information including the NIST and NASA materials databases.
- [www.ceramics.com](http://www.ceramics.com) Links to many technical and industrial sites.
- [www.ceramicforum.com](http://www.ceramicforum.com) A web site for the ceramics professional.
- [www.ecers.org](http://www.ecers.org) The European Ceramics Society.
- [www.ceramicsindustry.com](http://www.ceramicsindustry.com) Source of industry data.
- [www.porcelainenamel.com](http://www.porcelainenamel.com) The Porcelain Enamel Institute.

## 1.9 ON UNITS

We have attempted to present all data using the Système International d'Unités (SI). The basic units in this system are listed in Table 1.3 together with derived quantities. The primary exceptions in which non-SI units are encountered is in the expression of small distances and wavelengths

**TABLE 1.3 SI Units**

<b>SI Base Units</b>		
<i>Base quantity</i>	<i>Name</i>	<i>Symbol</i>
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd
<b>SI-Derived Units</b>		
<i>Derived quantity</i>	<i>Name</i>	<i>Symbol</i>
Area	square meter	m <sup>2</sup>
Volume	cubic meter	m <sup>3</sup>
Speed, velocity	meter per second	m/s
Acceleration	meter per second squared	m/s <sup>2</sup>
Wave number	reciprocal meter	m <sup>-1</sup>
Mass density	kilogram per cubic meter	kg/m <sup>3</sup>
Specific volume	cubic meter per kilogram	m <sup>3</sup> /kg
Current density	ampere per meter	A/m <sup>2</sup>
Magnetic field strength	ampere per meter	A/m
Amount-of-substance concentration	mole per cubic meter	mol/m <sup>3</sup>
Luminance	candela per square meter	cd/m <sup>2</sup>
Mass fraction	kilogram per kilogram	kg/kg = 1

**TABLE 1.3** *Continued*

**SI-Derived Units with Special Names and Symbols**

<i>Derived quantity</i>	<i>Name</i>	<i>Symbol</i>	<i>Expression in terms of other SI units</i>	<i>Expression in terms of SI base units</i>
Plane angle	radian	rad	—	$m \cdot m^{-1} = 1$
Solid angle	steradian	sr	—	$m^2 \cdot m^{-2} = 1$
Frequency	hertz	Hz	—	$s^{-1}$
Force	Newton	N	—	$m \cdot kg \cdot s^{-2}$
Pressure, stress	pascal	Pa	$N/m^2$	$m^{-1} \cdot kg \cdot s^{-2}$
Energy, work, quantity of heat	joule	J	$N \cdot m$	$m^2 \cdot kg \cdot s^{-2}$
Power, radiant flux	watt	W	$J/s$	$m^2 \cdot kg \cdot s^{-3}$
Electric charge, quantity of electricity	coulomb	C	—	$s \cdot A$
Electric potential difference, electromotive force	volt	V	$W/A$	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$
Capacitance	farad	F	$C/V$	$m^{-2} \cdot kg^{-1} \cdot s^4 \cdot A^2$
Electric resistance	ohm	$\Omega$	$V/A$	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$
Electric conductance	siemens	S	$A/V$	$m^{-2} \cdot kg^{-1} \cdot s^3 \cdot A^2$
Magnetic flux	weber	Wb	$V \cdot s$	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}$
Magnetic flux density	tesla	T	$Wb/m^2$	$kg \cdot s^{-2} \cdot A^{-1}$
Inductance	henry	H	$Wb/A$	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$
Celsius temperature	degree Celsius	$^{\circ}C$	—	K
Luminous flux	lumen	lm	$cd \cdot sr$	$m^2 \cdot m^{-2} \cdot cd = cd$
Illuminance	lux	lx	$lm/m^2$	$m^2 \cdot m^{-4} \cdot cd = m^{-2} cd$
Activity (of a radionuclide)	becquerel	Bq	—	$s^{-1}$
Absorbed dose, specific energy (imparted), kerma	gray	Gy	$J/kg$	$m^2 \cdot s^{-2}$
Dose equivalent	sievert	Sv	$J/kg$	$m^2 \cdot s^{-2}$
Catalytic activity	katal	kat	—	$s^{-1} mol$

**SI-Derived Units with Names and Symbols That Include Other SI-Derived Units**

<i>Derived quantity</i>	<i>Name</i>	<i>Symbol</i>
Dynamic viscosity	pascal second	Pa·s
Moment of force	newton meter	N·m
Surface tension	newton per meter	N/m
Angular velocity	radian per second	rad/s
Angular acceleration	radian per second squared	rad/s <sup>2</sup>
Heat flux density, irradiance	watt per square meter	W/m <sup>2</sup>
Heat capacity, entropy	joule per kelvin	J/K
Specific heat capacity, specific entropy	joule per kilogram kelvin	J kg <sup>-1</sup> K <sup>-1</sup>
Specific energy	joule per kilogram	J/kg
Thermal conductivity	watt per meter kelvin	W m <sup>-1</sup> K <sup>-1</sup>
Energy density	joule per cubic meter	J/m <sup>3</sup>
Electric field strength	volt per meter	V/m
Electric charge density	coulomb per cubic meter	C/m <sup>3</sup>
Electric flux density	coulomb per square meter	C/m <sup>2</sup>
Permittivity	farad per meter	F/m
Permeability	henry per meter	H/m
Molar energy	joule per mole	J/mol
Molar entropy, molar heat capacity	joule per mole Kelvin	J mol <sup>-1</sup> K <sup>-1</sup>
Exposure (X and $\gamma$ rays)	coulomb per kilogram	C/kg
Absorbed dose rate	gray per second	Gy/s
Radiant intensity	watt per steradian	W/sr
Radiance	watt per square meter steradian	W m <sup>-2</sup> sr <sup>-1</sup>
Catalytic (activity) concentration	katal per cubic meter	kat/m <sup>3</sup>

where the Å (angstrom) is used by electron microscopists and X-ray crystallographers and the eV (electron volt) is used as a unit of energy for band gaps and atomic binding energies. We have not used the former but do use the latter for convenience. In the ceramics industry customary U.S. units are commonly encountered. For example, tempera-

ture is often quoted in Fahrenheit ( $^{\circ}F$ ) and pressure in pounds per square inch (psi). Conversions between SI units and some of the special British and U.S. units are provided in Table 1.4.

The SI base unit of temperature is the kelvin, K. We use both K and  $^{\circ}C$  in this text. The degree Celsius is equal

**TABLE 1.4 Conversion Factors between SI Base Units and SI-Derived Units and Other Systems**

<i>SI units</i>	<i>Related units</i>	<i>Special British and U.S. units</i>
Length: 1 m	$10^{10}$ Å	3.28 ft
Mass: 1 kg 1 t		2.205 lb 0.984 U.K. (long) ton 1.103 U.S. (short) ton
Time: 1 s		$2.778 \times 10^{-4}$ h, $1.667 \times 10^{-2}$ min
Absolute temperature: $y$ K	$y - 273.15$ °C	$32 + 1.8(y - 273.15)$ °F
Area: 1 m <sup>2</sup>	10 <sup>4</sup> cm <sup>2</sup>	10.76 ft <sup>2</sup>
Volume: 1 m <sup>3</sup>	10 <sup>6</sup> cm <sup>3</sup>	35.3 ft <sup>3</sup>
Density: 1 kg/m <sup>3</sup>	10 <sup>-3</sup> g/cm <sup>3</sup>	$6.24 \times 10^{-2}$ lb/ft <sup>3</sup>
Force: 1 N 9.807 N	10 <sup>5</sup> dyn 1 kgf (kilogram force)	— 2.205 lbf
Pressure, stress: 10 <sup>5</sup> Pa	1 bar; 750 mmHg (torr)	14.5 psi 0.987 atm
Energy, work, quantity of heat 1 J 105.5 MJ 0.1602 aJ	10 <sup>7</sup> erg or 0.239 cal — 1 eV	— 10 <sup>5</sup> Btu —
Power: 1 W	0.86 kcal/h	$1.341 \times 10^{-3}$ hp
Dynamic viscosity: 1 dPa·s	1 P (poise) 10 <sup>2</sup> cP	—
Surface tension, surface energy: 1 N/m	10 <sup>3</sup> dyn/cm 10 <sup>3</sup> erg/cm <sup>2</sup>	—
Magnetic field strength: 1 A/m	$4\pi \times 10^{-3}$ oersted	—
Magnetic flux density: 1 T	10 <sup>4</sup> G (gauss)	—

in magnitude to the kelvin, which implies that the numerical value of a temperature difference or temperature interval whose value is expressed in °C is equal to the numerical value of the same temperature difference or interval when its value is expressed in K.

Several of the figures that we have used were obtained from sources in which the original data were not in SI units. In many cases we have converted the units into SI using conversions and rounding in accordance with ASTM Standard E 380. Any variations from this procedure are noted in the appropriate place.

The decade power notation is a convenient method of representing large and small values within the SI units. Examples that you will encounter in this book include nm (10<sup>-9</sup> m) and pF (10<sup>-12</sup> F). The full decade power notation scheme is given in Table 1.5.

**TABLE 1.5 Decade Power Notation<sup>a</sup>**

<i>Factor</i>	<i>Prefix</i>	<i>Symbol</i>	<i>Factor</i>	<i>Prefix</i>	<i>Symbol</i>
10 <sup>24</sup>	yotta	Y	10 <sup>-1</sup>	deci	d
10 <sup>21</sup>	zetta	Z	10 <sup>-2</sup>	centi	c
10 <sup>18</sup>	exa	E	10 <sup>-3</sup>	milli	m
10 <sup>15</sup>	peta	P	10 <sup>-6</sup>	micro	μ
10 <sup>12</sup>	tera	T	10 <sup>-9</sup>	nano	n
10 <sup>9</sup>	giga	G	10 <sup>-12</sup>	pico	p
10 <sup>6</sup>	mega	M	10 <sup>-15</sup>	femto	f
10 <sup>3</sup>	kilo	k	10 <sup>-18</sup>	atto	a
10 <sup>2</sup>	hecto	h	10 <sup>-21</sup>	zepto	z
10 <sup>1</sup>	deca	da	10 <sup>-24</sup>	yocto	y

<sup>a</sup>Factors that are not powers of 1000 are discouraged.

## CHAPTER SUMMARY

We adopted the definition of a ceramic as a *nonmetallic, inorganic solid*. This definition encompasses a wide range of materials, many of which you might find are described as semiconductors elsewhere. The definition of ceramics we adopted is not quite complete in that glass—which behaves at room temperature and below like a solid but has the structure of a liquid—is actually a very important ceramic. More than half the ceramic industry is devoted to producing glass. The second largest segment of the ceramics market is in advanced (also called special, engineering, or technical) ceramics. This area is exciting and includes many of the newer materials such as HTSCs, bioceramics, and nanoceramics. These areas are predicted to experience significant growth.

## PEOPLE IN HISTORY

In most of the chapters we will include a short section relating to the history of the topic, usually one-line biographies of our heroes in the field—some of those who have defined the subject. If the section is a little short in some chapters, the names/events may be listed in another chapter. The purpose of this section is to remind you that although our subject is very old, it is also quite young and many of the innovators never thought of themselves as ceramists.

## REFERENCES

In the reference sections throughout the book we will list general references on the overall theme of the chapter and specific references that are the source of information referenced in the chapter. If a general reference is referred to specifically in the chapter, we will not generally repeat it.

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## JOURNALS

- Bulletin of the American Ceramic Society*, published by the American Ceramic Society (ACerS). News, society information, industry updates, and positions. Free to society members.
- Ceramic Industry*, published by Business News Publishing Co., Troy, MI. Information on manufacturing. Designed mainly for the ceramist in industry.
- Ceramics International*
- Glass Technology*, published by The Society of Glass Technology, Sheffield, UK.
- Journal of the American Ceramic Society*, house journal of the ACerS contains peer-reviewed articles, published monthly.
- Journal of the European Ceramics Society*, house journal of the European Ceramic Society published by Elsevier.
- Journal of Non-Crystalline Solids*
- Physics and Chemistry of Glasses*
- Transactions of the British Ceramic Society*

## CONFERENCE PROCEEDINGS

- American Ceramic Society Transactions*
- Ceramic Engineering and Science Proceedings*. Published by the American Ceramic Society; each issue is based on proceedings of a conference.

## USEFUL SOURCES OF PROPERTIES DATA, TERMINOLOGY, AND CONSTANTS

- Engineered Materials Handbook*, Volume 4, *Ceramics and Glasses* (1991), volume chairman Samuel J. Schneider, Jr., ASM International, Washington, D.C.
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## SAFETY

- Chemical Properties Handbook* (1999), edited by C.L. Yaws, McGraw-Hill, New York. Gives exposure limits for many organic and inorganic compounds, pp. 603–615.
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- Hazardous Chemicals Desk Reference*, 5th edition (2002), edited by R.J. Lewis, Sr., Van Nostrand Reinhold, New York. Shorter version of the next reference.
- Sax's Dangerous Properties of Industrial Materials*, 11th edition (2004), edited by R.J. Lewis, Sr., Wiley, New York. A comprehensive resource in several volumes available in most libraries.
- The Occupational Safety and Health Administration (OSHA) of the U.S. Department of Labor web site on the internet is a comprehensive resource on all safety issues, [www.osha.gov](http://www.osha.gov).

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## EXERCISES

- 1.1 Which of the following materials could be classified as a ceramic. Justify your answer. (a) Solid argon (Ar); (b) molybdenum disilicide ( $\text{MoSi}_2$ ); (c) NaCl; (d) crystalline sulfur (S); (e) ice; (f) boron carbide ( $\text{B}_4\text{C}$ ).
- 1.2 Is silicone rubber (widely used as a caulking material in bathrooms and kitchens) a ceramic or a polymer? Explain your reasoning.
- 1.3 There are several different phases in the Fe-C system. One phase is the  $\gamma$ -Fe (austenite), which can contain up to about 8 atomic % C. Another phase is cementite, which contains 25 atomic % C. Are either of these two phases a ceramic? Justify your answer.
- 1.4 The following definition has been proposed: "All ceramics are transparent to visible light." Is this a good way of defining a ceramic? Explain your reasoning.
- 1.5 In the distribution of industry sales of advanced ceramics (Section 1.4), 13% was listed as "Other." Suggest applications that might be included in this group.
- 1.6 Ceramic tile accounts for about 15% of the floor tile market. (a) What alternatives are available? (b) What advantages/disadvantages do ceramics have over the alternatives? (c) What factors do you think influence the total amount of ceramic floor tiles used?
- 1.7 Gerber, the baby food manufacturer, is replacing most of its glass baby food jars with plastic. Miller Brewing Co. now sells some of its popular beers in plastic containers. Compare glass and plastics in terms of their application for packaging food and beverages.
- 1.8 The steel industry is the major consumer of refractories. What other industries might be users of this ceramic product?
- 1.9 Pearls and garnets are both examples of gems. We classify garnet as a ceramic. Would you classify pearl as a ceramic? Briefly justify your answer.
- 1.10 Some nuclear reactors use MOX fuel. What is MOX and is it a ceramic?