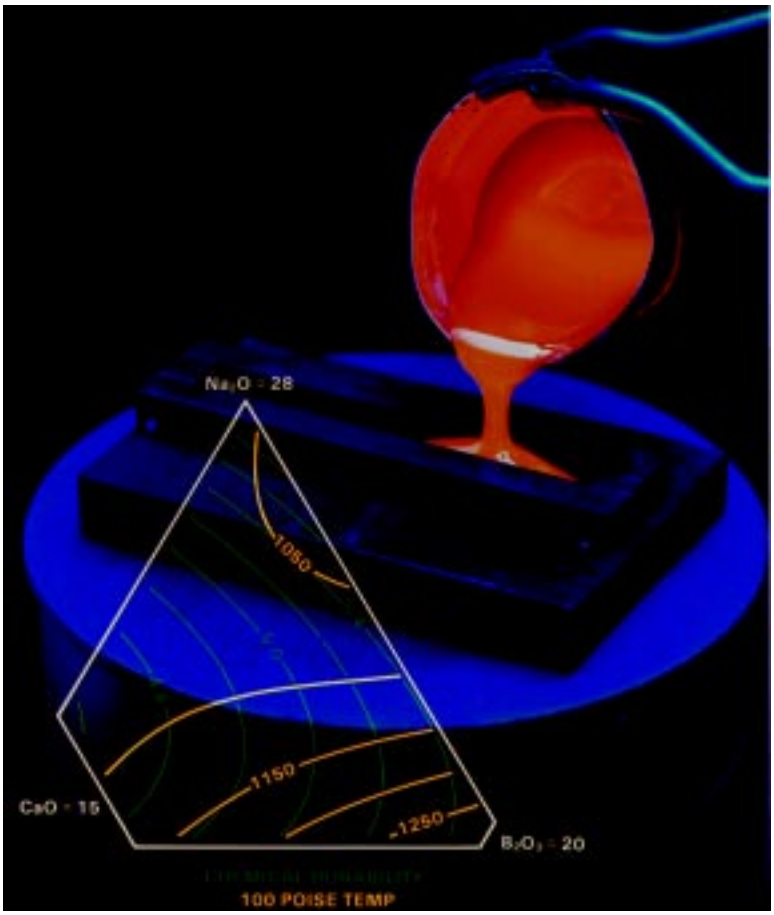
Ceramics

Introduction

Ceramics are non-metallic and inorganic and are made from raw materials that are either mined from the earth or chemically synthesized. They are hard, generally resistant to heat and most chemicals, and lighter than most metals.

Traditional ceramic materials include glass windows, insulating bricks, pottery, and china. However, the fiber-optic phone lines that provide today's clear voice communication are also ceramic, products of high-technology glassmaking. Likewise, the space shuttle is insulated against the searing heat generated as it returns from near space through the earth's atmosphere. Its aluminum hull is shielded by incredibly light bricks made from tiny glass fibers.

Ceramics are compounds that are generally formed by reacting a metal with other elements such as oxygen, nitrogen, carbon, or silicon.



The bonding is usually ionic and is very strong, making ceramics comparatively stable chemically. (Ionic means the joining of a positively charged atom to a negatively charged atom, usually metal atoms to non-metallic atoms.) This ionic bonding occupies the outer electrons of the metal, making the electrons incapable of moving in an electric field; thus, most ceramics are poor conductors of electricity. Ceramics also include glasses, which are composed of metals, oxygen, and silicon. By their nature, glasses do not crystallize as other ceramics do. As they cool from the liquid state, they become progressively stiffer until they are solid, which gives them different properties from other materials, such as not having a definite melting point.

Where resistance to extreme temperatures or molten metals is desired, ceramic materials emerge as extremely important. Without ceramics, it would probably be impossible to melt or cast metals; other materials will not resist the heat or chemical environment, and other materials allow heat to leak away, because they are not effective insulators like ceramics.

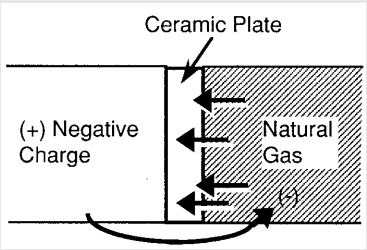
The powerful bonding forces in ceramics have some negative features, one of them being brittleness. Ceramics cannot be bent like metals or most other common materials, and they tend to break without warning. Tiny surface defects, too small to cause much of a problem with a metal, can greatly reduce the strength of a ceramic material. In a metal, flow at the defect location would reduce the effect of that defect; this flow is not possible in a ceramic. So cracks stay sharp and ceramics break instead of bend. (Metallic flow is the movement of one plane of atoms over another.)

Humankind first made ceramics in ancient times. Fire, probably at that time a relatively new discovery, was used to make clay vessels less likely to revert to a gooey mess when contacted by water. During this firing process, materials in the clays reacted, forming small amounts of glass that cemented the rest of the materials together. Glass was born in similar fireside experiments, and in Roman times, was more precious than gemstones and used similarly for decoration.

The future of ceramic materials is even more interesting. Scientists have created ceramics that, while not as tough as metals, are many times tougher than those made just a few years ago. These tough materials are being used increasingly as parts in automobile engines because of their lightness and resistance to wear.

Other ceramics have been made electrically conductive or able to allow oxygen ions to penetrate them. Both of these characteristics are needed for high-temperature fuel cells that can convert fuels such as natural gas directly to electricity more efficiently then any other method (see Figure 6.1).

Ceramics are being formed by methods similar to those used for mass production of plastic parts, so that increasingly intricate parts can be made cheaply. All these developments combined ensure that ceramics will continue to play important roles in modern life.



Oxygen atoms (-) negative charge flow through ceramic to combine with (+) positively charged particles. An electric potential is created and electricity is “birthed.”

Figure 6.1. Electrically Conductive High-Temperature Fuel Cell

Thermal Shock
Instructor Notes

Reliability

This experiment works well if the materials are the same as what is described herein.

Estimated Time for Activity

One class period.*

Teacher Tips

1. Thermal shock is a mechanism often leading to the failure of ceramic materials. Many uses for ceramics involve high temperature. If the temperature of a ceramic is rapidly changed, failure may occur. Thermal shock failures may occur during rapid cooling or during rapid heating. As an example, consider rapid cooling, which is easier to visualize. If a ceramic material is cooled suddenly, the surface material will approach the temperature of the cooler environment. In doing so, it will experience thermal contraction. Because the underlying material is still hot, the skin material stretches and so experiences tensile stress. If the resulting strain is high enough (0.01% to 0.1% for most ceramics), the ceramic will fail from the surface, and cracks will propagate inward. Even if these cracks do not cause immediate failure, the ceramic will be severely weakened and may fail from mechanical overload of forces it would normally withstand.
2. When comparing different ceramics for thermal shock applications, it is common to use a figure of merit or index of thermal shock performance. This is a number (ratio) that is useful for both choosing materials and for visualizing the thermal shock process. Because the index should be high for a thermal shock resistant ceramic, its numerator should contain properties that are numerically large when good thermal shock performance is exhibited by a material. Tensile strength (S) and thermal conductivity (K) are therefore placed in the numerator, the former for obvious reasons and the latter because a high value of thermal conductivity tends to decrease thermal gradients, other factors being equal. The denominator of the thermal shock index is composed of the thermal expansion coefficient (A) and Young's Modulus (E), which is a measure of

*One class period is approximately 1 hour.

the stress resulting from a given strain. These numbers should be a low value for good thermal shock performance. Combining these factors,

$$\text{Thermal Shock Index (TSI)} = \frac{SK}{AE}$$

Where the units of measurement should be consistent within a given comparison.

In the case of common glasses, all the properties except thermal expansion fall into a relatively narrow range. By choosing a glass with low thermal expansion, thermal shock failure can be avoided in most cases. See, for example, the index values for soda-lime glass, borosilicate glass, and fused silica in Table 6.1. Note the large difference between the thermal shock indices of aluminum oxide and graphite. This difference is backed by experience; it is extremely difficult to cause graphite to fail by thermal shock, principally because its Young's modulus is so low and its thermal conductivity is high.

Table 6.1. Thermal Shock Index (TSI) for Some Common Ceramic Materials

Material	K,[1] W/cm-°C	S, MPa	A, °C^{-1}, x 10^{-6}	E, GPa	TSI
Soda-lime-silica glass	2E-2	68[2]	9.2	69	2.1
Borosilicate glass	2E-2	68	3.3	63	6.5
Fused SiO_2	6E-2	68	0.6	72	94
Aluminum Oxide	3E-1	204	5.4	344	33
Graphite[3]	1.4	8.7	3.8	7.7	416

(1) Thermal conductivity and expansion coefficients from *Thermophysical Properties of Matter*, Y. S. Touloukian, ed., Plenum Press, New York, 1970.
(2) Because glass tensile strength is so dependent on surface condition, a single "reasonable" value was chosen for all glass strengths.
(3) Values are typical of nuclear-grade graphite, from *Industrial Graphite Engineering*, Union Carbide Corp., 1959

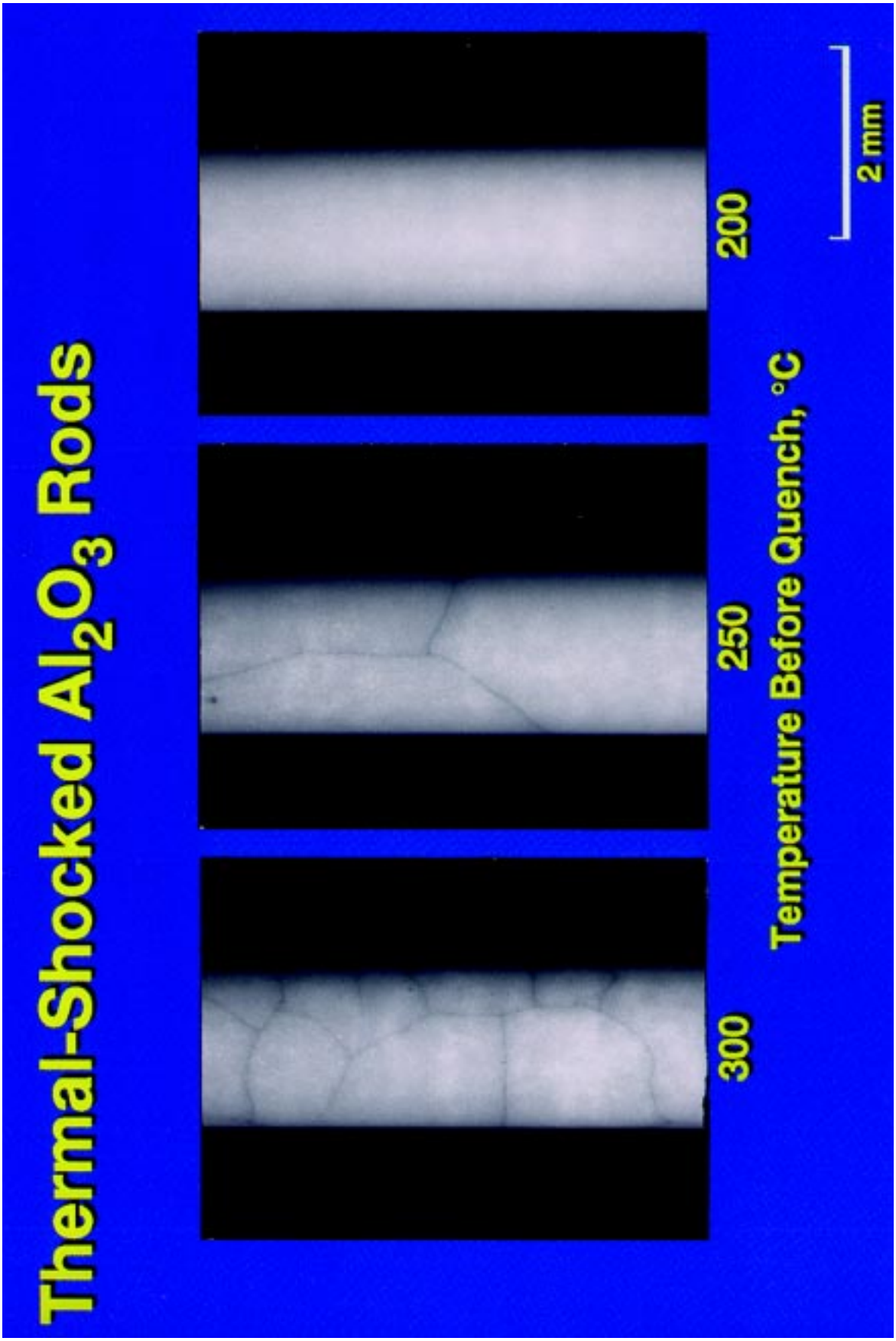
Teacher Tips for Demonstration

1. Thrown into water (quench), the water changes to steam.
2. Steam forms at the surface of the specimen, absorbing energy (539 calories per gram).
3. This causes the surface to cool to 100°C, almost instantly.
4. The result is a shrinking surface encasing a large, hot specimen, causing thermal shock and cracking.
5. The temperature difference and coefficient of thermal expansion of the material determines the amount that the material will crack.
6. The larger the TSI value, the more likely the material will withstand thermal shock.

Extension Activity

A similar thermal shock experiment to demonstrate follows:

Place about 10 aluminum oxide rods, 3 mm x 10 cm in length, into a stainless-steel beaker or a small metal pan and heat to 500°C in a suitable furnace. Remove the container from the furnace, and quickly quench the rods in a bucket of water. Dry them overnight at about 100°C. The following day, dip the rods in ink, which acts as a crude dye penetrant to make any cracking visible. Wipe excess ink from the rods, handling care-fully to avoid breaking. Note, if broken, the partial penetration of the ink shows that the cracks do not extend into the centers of the rods. This is because the cracks start at the surface in a tensile stress area, but propagate into regions of lower stress until they stop. When a quench is performed on rods heated at lower temperatures (down to about 300°C) crack density is lower and crack depth is shorter (see attached Figures of Al_2O_3 rods). A quench temperature that is lower still will not result in any detectable damage. This temperature is not a constant, but is a function of both configuration and material heated at designated temperatures and quenched). The alumina should be >95% dense, but can be of any purity greater than 95%.


Thermal-Shocked Al_2O_3 Rods
300
250
200
Temperature Before Quench, °C
2 mm