THERMAL SHOCK OF CERAMIC MATERIALS

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KEY WORDS: thermal shock, Young's modulus, thermal expansion coefficient

PREREQUISITE KNOWLEDGE: This demonstration is suitable for students in materials science at the high school or college levels. The students should understand elementary mechanics concepts, such as Young's Modulus of Elasticity.

OBJECTIVES: To demonstrate the concept of thermal shock in ceramic materials, and to illustrate the pertinent factors of materials selection.

EQUIPMENT AND SUPPLIES: Furnace capable of controlled temperatures up to 500°C; aluminum oxide rod or 2-hole thermocouple insulator, approx. 3 mm diameter x 10 cm long; water; tongs; black or blue ink.

PROCEDURE: Thermal shock is a mechanism often leading to the failure of ceramic materials. Many uses for ceramics involve high temperatures, and 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. Since the underlying material is still hot, the skin material is stretched 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.

After distributing aluminum oxide rods to the students urge them to manipulate and bend the rods with their hands. Soon, popping sounds will be heard in the classroom. These sounds demonsrate how a brittle material fails without warning, with no permanent strain, and at a low-strain value. Next, place about ten of the rods 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, then 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 carefully to avoid breaking. Again, urge the students to bend the rods and note that the rods are much weaker than before. Also, note from the partial penetration of the ink 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 at lower temperatures (down to about 300°C) crack density is lower and crack length is shorter. 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.

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. Since 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 the Young's modulus of elasticity (E). The thermal expansion is responsible for the failure-causing strain, so it should be as small as possible. The elastic modulus is a measure of the stress resulting from a given strain, so it 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 of 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 I. 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.

SAMPLE DATA SHEETS: If students quench specimens from a series of temperatures, data sheets might be constructed to record crack frequency as a function of quench temperature. Alternately, ceramic rods might be broken in 3-point bending on a testing machine, and the bending strength plotted as a function of quench temperature.

INSTRUCTOR NOTES: Provided above in Procedure. Follow usual safety precautions to avoid burns.

REFERENCES: Kingery, W. D., H. K. Bowen, D. R. Uhlmann, Introduction to Ceramics, Second Edition, John Wiley & Sons, New York, 1979, Ch. 16.

SOURCES OF SUPPLIES: The alumina should be >95% dense, but can be of any purity greater than 95%. One supplier is Coors Ceramics, Golden, CO.

Table I. Thermal Shock Index 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

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[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.

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