Mat E 272

Lectures 24a: Mechanical Properties of Ceramics and Ceramic Processing

December 4, 2001

Mechanical properties of ceramics

Ceramic materials are notorious for their lack of ductility. In general, they are strong in compression, but possess low fracture toughness; plastic deformation (slip) is essentially non-existent. Mechanical behavior is described by the Griffith theory of brittle fracture:

All ceramics are assumed to contain pre-existing microscopic defects (voids, cracks, grain corners) that act as stress concentrators. The local stress at the tip of a pre-existing flaw increases with decreasing tip radius of curvature and with increasing crack length according to

$$\sigma_m = 2\sigma_o \left(\frac{a}{\rho_t} \right)^{\frac{1}{2}}$$

Crack propagation occurs when σ_m exceeds the local tensile strength. Plane strain fracture toughness, K_{ic}, is a measure of a material's ability to resist fracture when a crack is present. Recall,

$$K_{Ic} = Y\sigma\sqrt{\pi a}$$

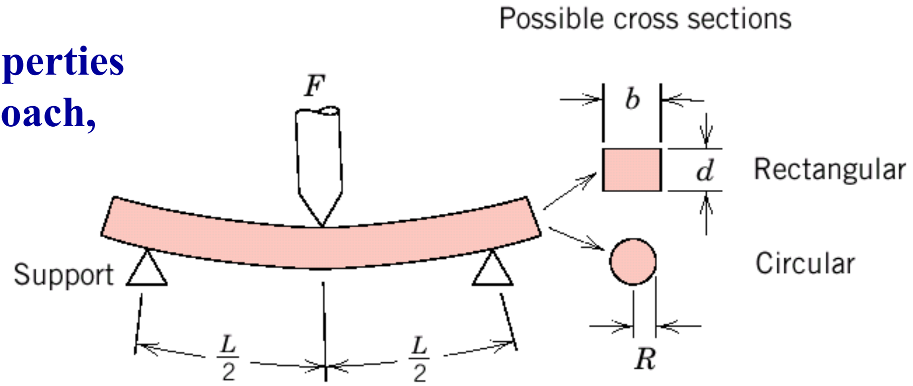
Values for K_{ic} for ceramic materials are usually (at least) an order of magnitude less than that for metals. Since there is no stress amplification under compression, ceramics are usually used under compressive loading.

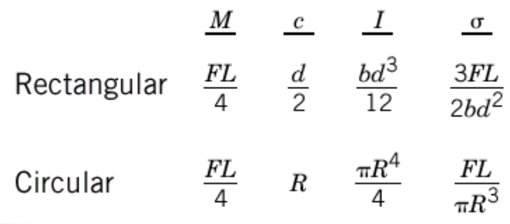
Mechanical properties of ceramics

Recall in the case of metals, mechanical properties were determined from tensile tests, in which a stress-strain curve is generated. Ceramics are not normally tested in tension because:

- **it is difficult to machine to the required geometry**
- **it is difficult to grip brittle materials without inducing fracture**
- **ceramics typically fail after only ~ 0.1% strain**

For these reasons, the mechanical properties are determined using a different approach, the three point bend test:





	M	c	I	σ
Rectangular	$\frac{FL}{4}$	$\frac{d}{2}$	$\frac{bd^3}{12}$	$\frac{3FL}{2bd^2}$
Circular	$\frac{FL}{4}$	R	$\frac{\pi R^4}{4}$	$\frac{FL}{\pi R^3}$

σ = stress = $\frac{Mc}{I}$

where M = maximum bending moment
c = distance from center of specimen to outer fibers
I = moment of inertia of cross section
F = applied load

Mechanical properties of ceramics

Three point bend test:

- **specimen geometry is circular or rectangular cross section**
- **during the test, the top surface is under compression while the bottom surface is under tension**
- **maximum tensile stress occurs on the bottom surface, just below the top loading point**
- **the stress at fracture, σ_{fs}, (a.k.a. *flexural strength, modulus of rupture, fracture strength, or bend strength*) is given by**

$$\sigma_{fs} = \frac{3F_f L}{2bd^2}$$

for samples with rectangular cross sections, and

F_f is the load at fracture, L the distance between lower supports,
b and d are the width and thickness.

$$\sigma_{fs} = \frac{F_f L}{\pi R^3}$$

for samples with circular cross sections

F_f is the load at fracture, L the distance between lower supports,
R is the radius of the specimen.

Example - solved problem

A three-point transverse bend test is applied to an alumina cylinder with a reported flexural strength of 390 MPa (56 ksi). If the specimen radius is 2.5 mm (0.10") and the support point separation distance is 30 mm (1.2"), estimate whether or not the specimen would fracture when a load of 620 N (140 lb$_f$) is applied.

Solution:

Using Equation (**13.3b**), one can calculate the value of **σ; ** if this value is greater than σ_{fs} (390 MPa), then fracture is expected.

$$\sigma_{fs} = \frac{F_f L}{\pi R^3}$$

for samples with circular cross sections

Where F_f is the load, L the distance between lower supports, and R is the radius of the specimen.

$$\sigma = \frac{FL}{\pi R^3} = \frac{(620N)(30\times10^{-3}m)}{\pi(2.5\times10^{-3}m)} = 379 \times 10^6 \text{ N/m}^2 = 379 \text{ MPa } (53.5\text{ksi})$$

Since this value is less than the given value of σ_{fs} (390 MPa), fracture is **not** predicted.

Mechanical properties of ceramics

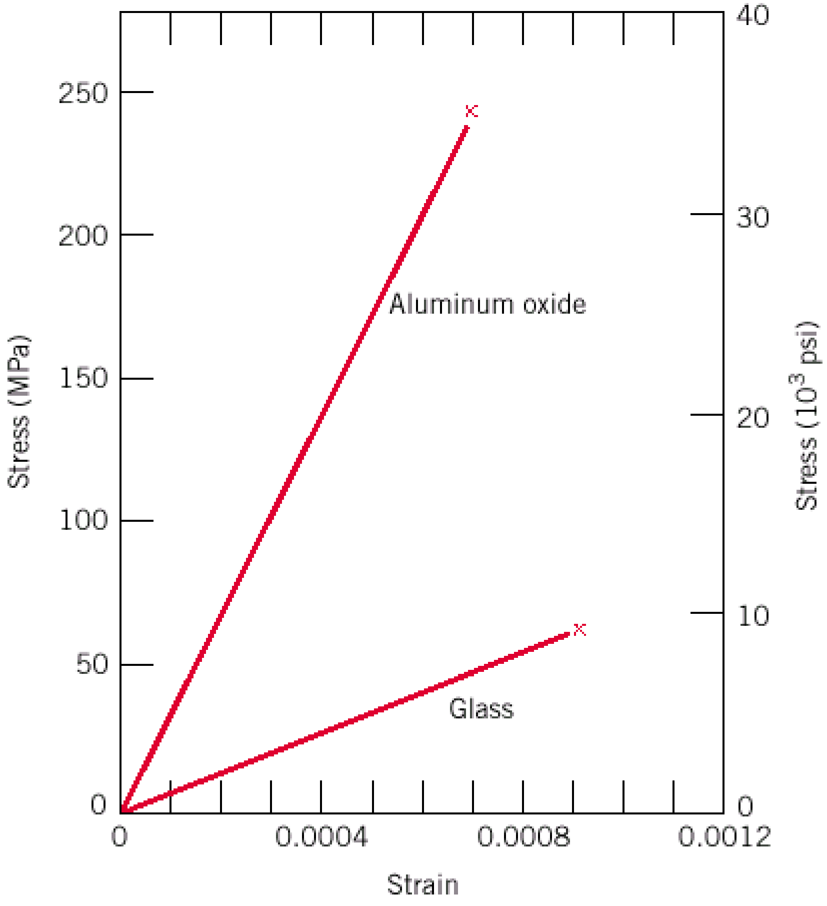
Typical results for three point bend test:

note the complete absence of plastic deformation

why…?

…because slip is more difficult in ceramic materials than in metals. For slip to occur, the atoms in one plane must "slide" over the atoms in an adjoining plane. In the case of ceramic materials, the atoms are charged ions, and a strong electrostatic repulsion prevents ions of the same charge from coming in close proximity to one another.

Al_2O_3 and glass

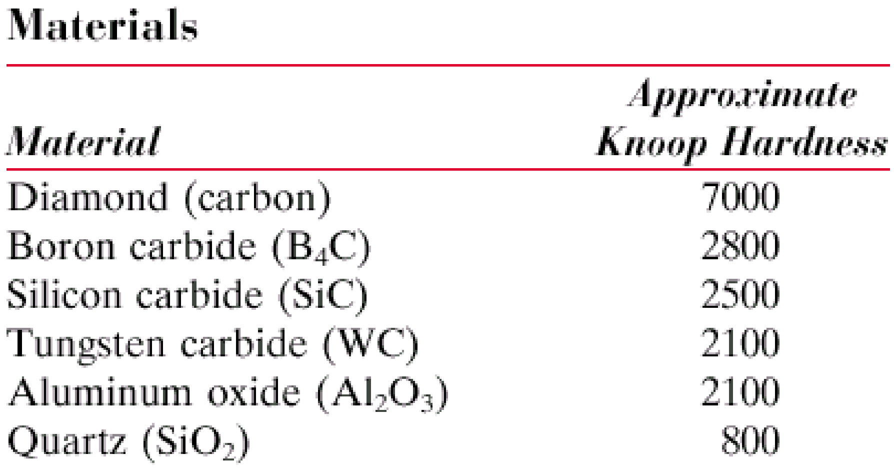


Mechanical properties of ceramics

A word about hardness of ceramic materials:

many ceramic materials exhibit significantly higher hardness values than metals; this property enables a large number of abrasion-related applications (sanding, cutting, grinding, finishing)

Chemically-modified $AlMgB_{14}$ has been shown to possess a hardness as high as 4600 on this scale.



Materials

Material	*Approximate Knoop Hardness*
Diamond (carbon)	7000
Boron carbide (B_4C)	2800
Silicon carbide (SiC)	2500
Tungsten carbide (WC)	2100
Aluminum oxide (Al_2O_3)	2100
Quartz (SiO_2)	800

Ceramic Processing

Because of their inherent lack of ductility, ceramic materials cannot be formed by drawing, rolling, swaging, or extrusion methods*. Moreover, their high melting temperature places additional restrictions on the type of material used to contain molten ceramics. As a result, many ceramic materials are prepared through powder processing techniques.

1) Raw materials

Clays and other natural raw materials are crushed and ground to a specified particle size range and chemically treated to separate phases & compounds and to achieve desired purity.

2) Forming

Addition of water and/or plasticizers allows the paste to be formed into the desired shape. Some of the most common forming methods for ceramics include slip casting, pressing, tape casting and injection molding.

* without use of a binder or plasticizer

Ceramic Processing

3) Firing

After the particles are formed, these "green" ceramics undergo a heat-treatment (called firing or sintering) to produce a rigid, finished product Some ceramic products such as electrical insulators, dinnerware and tile may then undergo a glazing process. Some ceramics for advanced applications may undergo a machining and/or polishing step in order meet specific engineering design criteria.

Processing of glass

The processing of glass is different than for ceramics. In glass production, raw materials such as silica, lime, and soda ash are melted in a furnace, then formed into the desired shape (i.e.; plate, fiber, bottle, etc.) while molten. After the molten glass is formed, it is quickly cooled, "freezing" the glass into place to form the finished product. The glass may undergo additional processing steps such as cutting, etching, coating, grinding, decorating, or heat treating (tempering).

Ceramic Processing

Powder consolidation

Uniaxial Pressing / Isostatic Pressing

- Powder may be mixed with a binder, an organic substance that acts as a weak glue.
- Powder is then pressed into a solid of the desired shape.

  Uniaxial (uni-directional loading) pressing is limited to simple shapes.

  Isostatic (3-dimensional loading) pressing provides more uniform compaction of more complicated shapes.

- May be accomplished either with (*hot pressing*) or without (*cold pressing*) simultaneous application of heat
- Objective is to achieve the highest possible density

  65 - 85 % of theoretical for cold pressing (normally involves a subsequent *sintering* step)

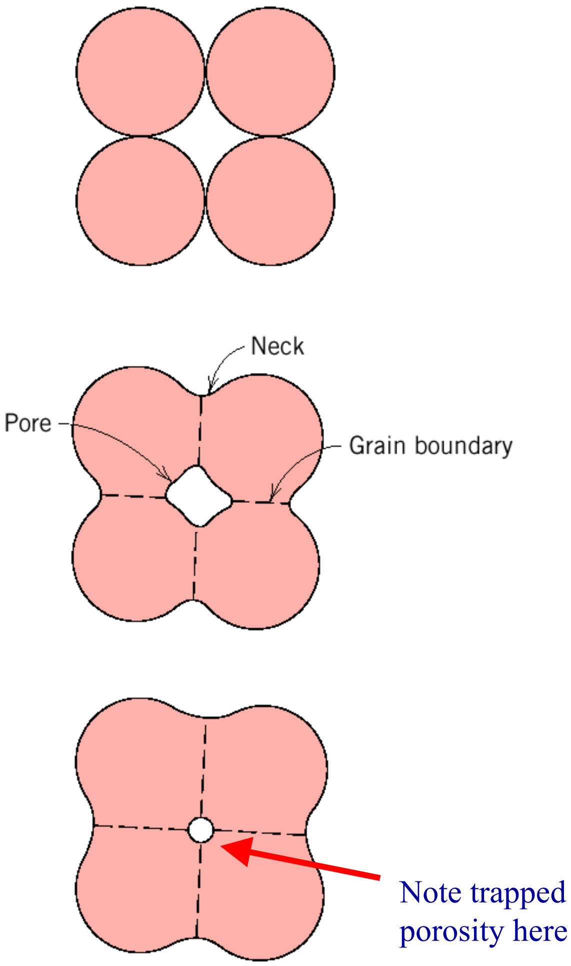
  90 - 100 % of theoretical for hot pressing

Ceramic Processing

Powder consolidation

Sintering

- Ceramic powder is mixed with a binder which holds the powder together and pressed into a mold of the desired shape.
- The powder compact is removed from the mold and heated to a high temperature where the powder particles coalesce or *sinter* into a solid object.
- Sintering occurs by the <u>diffusion of atoms</u> in the solid



Note trapped porosity here

Ceramic Processing

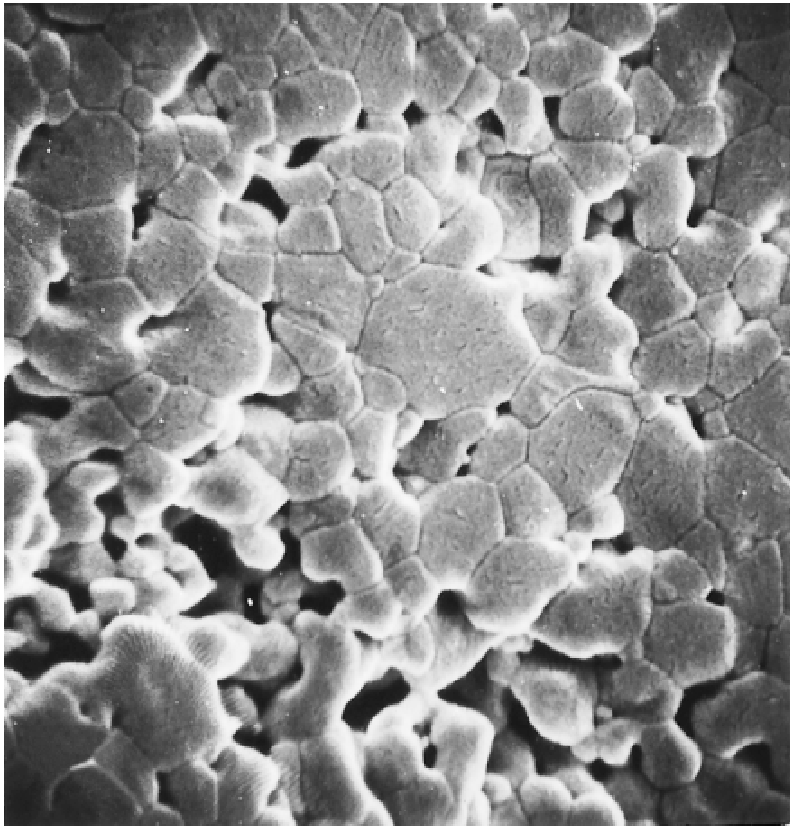
Powder consolidation

Sintering

This is a scanning electron micrograph of a specimen of Al_2O_3 that was sintered for 6 minutes at 1700°C.

Note the entrapped porosity and the grain boundaries separating single crystal grains.

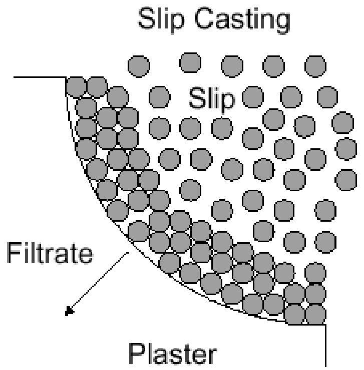
The entrapped porosity makes it almost impossible to achieve fully dense compacts. A considerable amount of processing research has been applied to the elimination of this type of porosity



Magnification = 5000X

Ceramic Processing

Powder consolidation



Slip Casting

- A plaster of paris mold is prepared.

  Plaster of paris is porous and absorbs water.

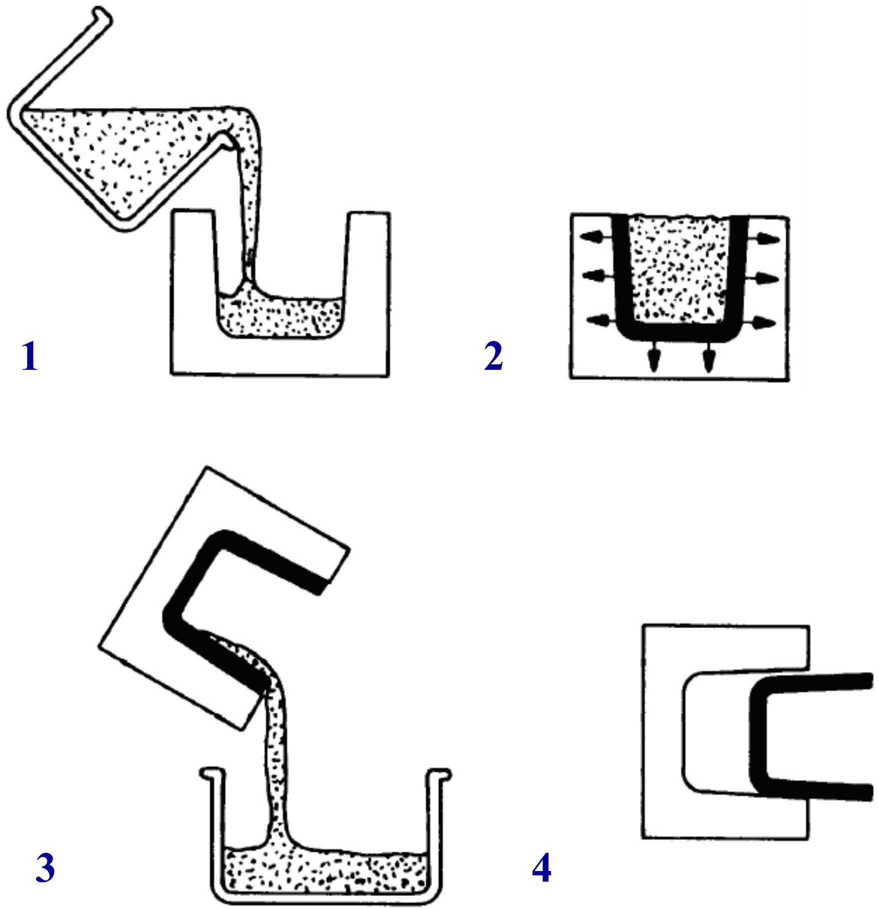
- A slurry of the powder and water is prepared, which is called the *slip*.
- The slip is poured into the plaster of paris mold.
- The mold absorbs the water and the powder is deposited on the inside of the mold.
- The mold is split and the powder compact is removed.
- The powder compact is *sintered*.
- Slip casting allows complex shaped parts to be fashioned.

  Toilet bowls and sinks (sanitary whitewares) are usually made by slip casting.

Ceramic Processing

Powder consolidation

Slip Casting



Ceramic Processing

Powder consolidation

Reaction bonding

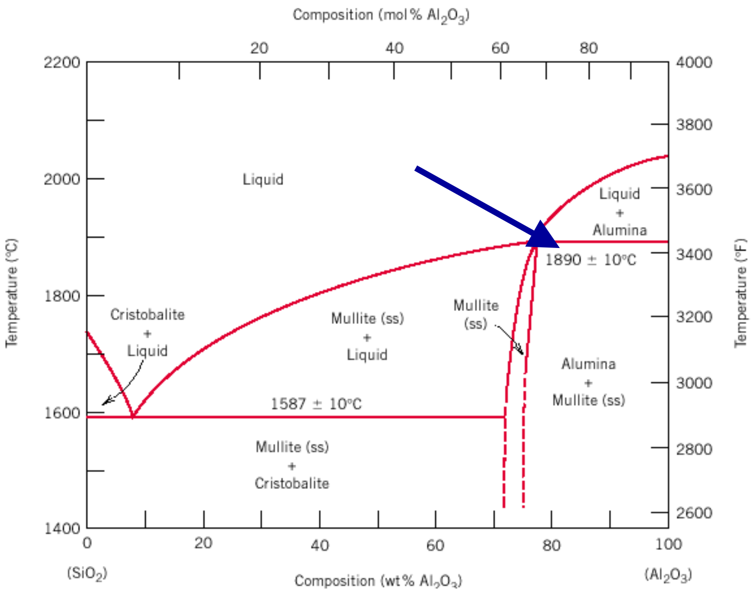
- Many important ceramic compounds such as silicon nitride (Si_3N_4) are made by *reaction bonding*.
- Silicon powder is formed into the desired shape.
- It is then *reacted* at high temperatures with nitrogen gas to form silicon nitride.

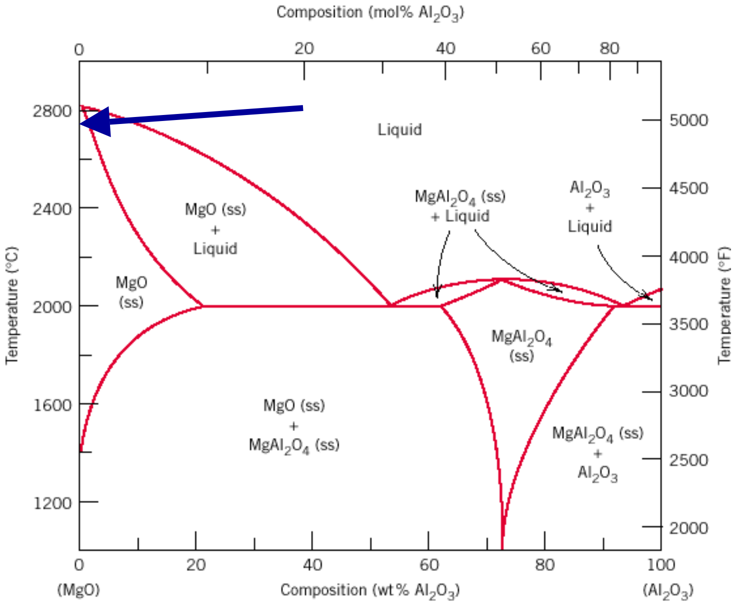
Example problem

For the SiO_2 - Al_2O_3 system, what is the maximum temperature that is possible without the formation of a liquid phase? At what composition or over what range of compositions will this maximum temperature be achieved? What are the maximum temperatures and range of compositions corresponding to the MgO - Al_2O_3 system?

(a) According to the relevant phase diagram, the maximum temperature is 1890°C, which is possible for compositions between about 77 and virtually 100 wt% Al_2O_3:

(b) For the MgO-Al_2O_3 system, the maximum temperature without the formation of a liquid phase is approximately 2800°C which is possible for pure MgO.





Want more information?

Suggested references on ceramic materials and processing:

Introduction to the Principles of Ceramic Processing, J.S. Reed, John Wiley & Sons, NY, 1989.

Introduction to Ceramics, W.D. Kingery, H.K. Bowen and D.R. Uhlmann. 2nd Edition, John Wiley & Sons, NY,1976.

Clay and Ceramic Raw Materials, W.E. Worrall, Applied Science Publishers, London, 1975.

Fine Ceramics, F.H. Norton, Krieger, Malabar, FL, 1978.

Ceramic Processing Before Firing, G.Y. Onoda Jr and L.L. Hench, Wiley-Interscience, NY, 1978.