Lecture Outline

- Mechanical properties of ceramics
- Applications of ceramics
- Fabrication of Glasses
- Glass properties
- Processing of Ceramics

Mechanical properties of ceramics

- Ceramic materials are notorious for their *lack of ductility*.
- In general, they are ……., but …….
- Plastic deformation (slip) is essentially non-existent.
- Mechanical behavior is dictated by the **Griffith theory** of brittle fracture

Griffith Theory:

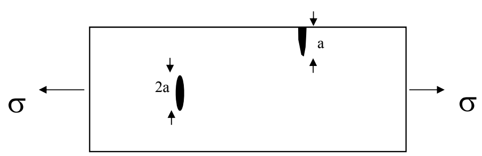
All ceramics are assumed to contain pre-existing microscopic defects (*voids, cracks, grain corners*) that act as stress concentrators. The local stress at the tip of a pre- existing flaw increases with decreasing tip radius of curvature and with increasing crack length according to:

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

σ_o = nominal stress
ρ_t = tip radius
a = the length of an external crack or **half** the length of an internal one

Crack propagation occurs when σ_m exceeds the local tensile strength.

Mechanical properties of ceramics



Plane strain fracture toughness, K_{ic}, is a measure of a material's ability to resist fracture when a crack is present.

$$K_{ic} = Y\sigma_f\sqrt{\pi a}$$

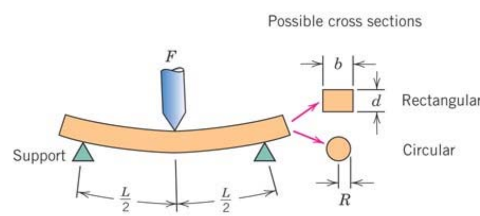
Y = a dimensionless constant (usually ≈ 1)
σ_f = fracture stress (MPa)
a = the length of an external crack or half the length of the internal one.
K_{ic} = Plane strain fracture toughness (*for most ceramics is less than 10 MPa.m$^{1/2}$*)

Values for K_{ic} for ceramic materials are usually *at least* an order of magnitude less than that for metals (*1/10 of that for metal*).

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

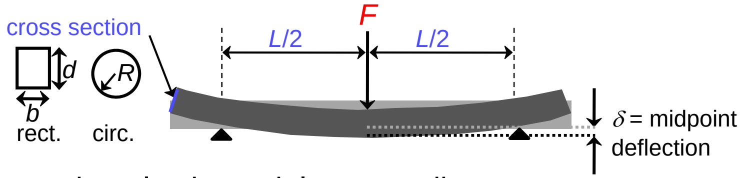
For these reasons, the mechanical properties are determined using a different approach, the ………..……………….:



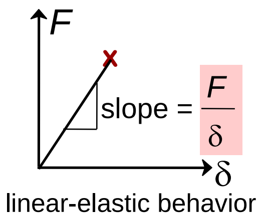
- specimen geometry is either circular or rectangular cross section
- during the test, the top surface is under compression while the bottom surface is under tension
- maximum tensile stress occurs on the bottom surface, just below the top loading point

MEASURING ELASTIC MODULUS

- Room temperature behavior is usually elastic, with brittle failure.
- 3-Point Bend Testing often used.
  - as mentioned earlier because tensile tests are difficult for brittle materials.



- Determine elastic modulus according to:

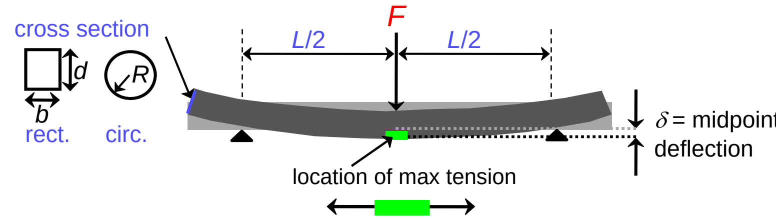


$$E = \frac{F}{\delta}\frac{L^3}{4bd^3} \quad \text{(rect. cross section)}$$

$$E = \frac{F}{\delta}\frac{L^3}{12\pi R^4} \quad \text{(circ. cross section)}$$

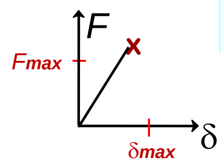
MEASURING STRENGTH

- 3-point bend test to measure room temperature strength.



- Flexural strength:

$$\sigma_{fs} = \sigma_m^{fail} = \frac{1.5F_{max}L}{bd^2} \text{ (rect.)} = \frac{F_{max}L}{\pi R^3}$$



- Typical values:

Material	σ_{fs} (MPa)	E(GPa)
Si nitride	250-1000	304
Si carbide	100-820	345
Al oxide	275-700	393
glass (soda-lime)	69	69

Data from Table 12.5, *Callister & Rethwisch 8e.*

Mechanical Properties of Ceramics

The stress at fracture, s_{fs}, *(flexural strength, modulus of rupture, fracture strength, or bend strength)* is given by:

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

for samples with ……………. cross sections, where,

F_f: is the load at fracture,

L: is the distance between lower supports,

b and d: are the width and thickness.

Or

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

for samples with ………. cross sections, where,

R: is the radius of the sample.

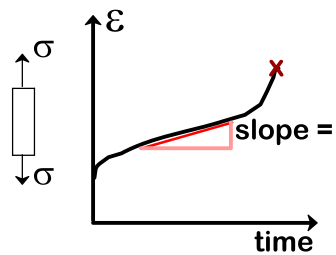
Example

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

Measuring Elevated Temperature Response

- Elevated Temperature Tensile Test ($T > 0.4\,T_{melt}$).

  creep test



slope = $\dot{\varepsilon}_{ss}$ = steady-state creep rate

Generally,

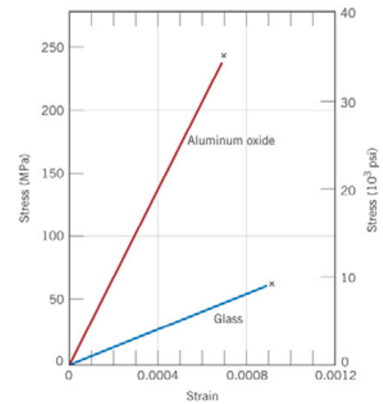
$$\dot{\varepsilon}_{ss}^{ceramics} < \dot{\varepsilon}_{ss}^{metals} << \dot{\varepsilon}_{ss}^{polymers}$$

Mechanical Properties of Ceramics

note the complete absence of plastic deformation. Why?

because slip is more difficult in ceramic materials than in metals.

Recall:
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.



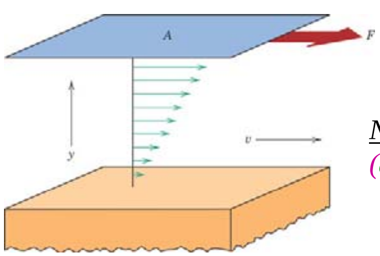
Typical results for three point bend test for alumina and glass

In covalent ceramics strong bonding does not allow slip to occur.

Mechanical Properties of Ceramics

Non-crystalline ceramic:

- there is no regular crystalline structure → no dislocations.
- Materials deform by viscous flow, i.e. by breaking and reforming of atomic bonds, allowing ions/atoms to slide past each other (like in a liquid).
- Viscosity is a measure of glassy material's resistance to deformation.



$$\eta = \frac{\tau}{dv/dx} = \frac{F/A}{dv/dx}$$

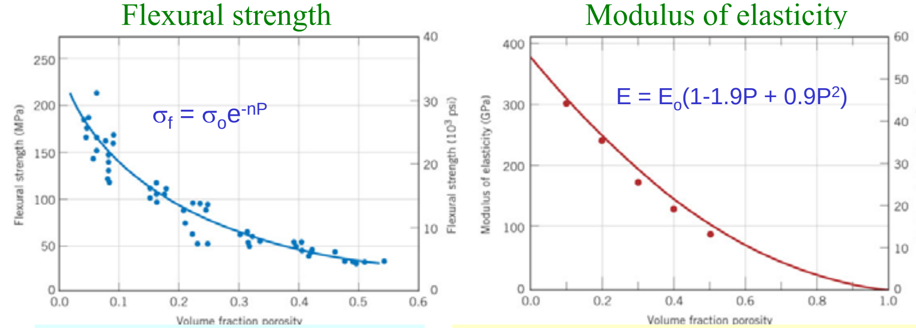
Note: *η is proportional to the applied stress (deformation rate)*

Viscosity (η) of material measures resistance to deformation (oils - glasses etc)

- Units are Poise (P) and Pa-s
  - LOW: water 10^{-3} Pa-s
  - HIGH: glass at RT 10^{16}Pa-s

POROSITY EFFECTS on Mechanical Properties of Ceramic Materials

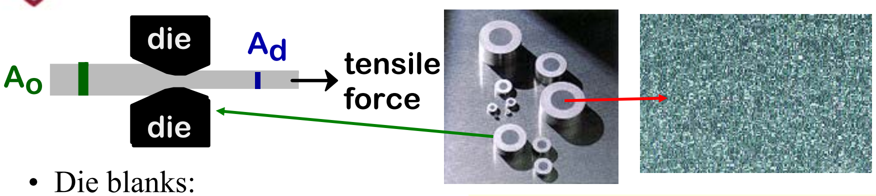
- ***Many ceramics are made from powders and contain some pores (holes).***
- Porosity affects both flexural strength and modulus of elasticity.



σ_o and n are experimental constants *E_o is elastic modulus of fully dense material*

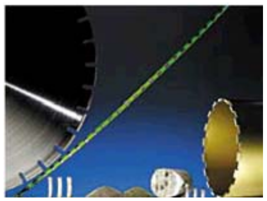
Influence of porosity on flexural strength and modulus of elasticity for Al_2O_3

Applications of Ceramics



- Die blanks:
  - Need wear resistant properties!
- Die surface:
  - 4 μm polycrystalline diamond particles that are sintered on to a cemented tungsten carbide substrate.


oil drill bits


blades

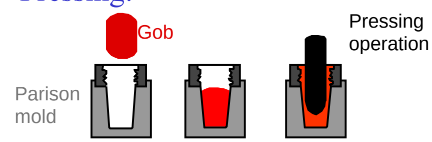
- Tools:
  - for grinding
  - for cutting
  - for oil drilling

Ceramic Fabrication Methods

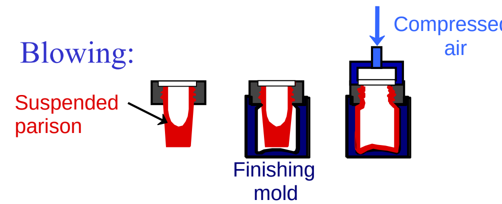
- Ceramics cannot be easily melted and are difficult to contain (high T_m).
- Ceramics cannot be plastically deformed into shape easily (brittle).
- Ceramics are usually hard materials and machining is slow and expensive

Glass Forming

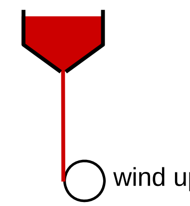
Pressing:



Blowing:

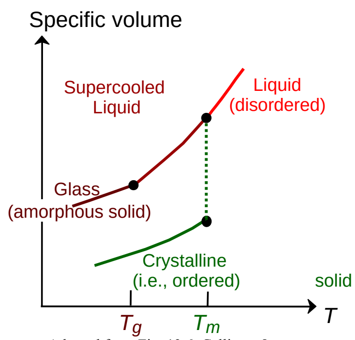


Fiber drawing:



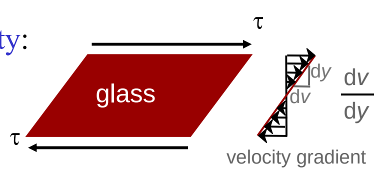
Glass Properties

- Specific volume (1/ρ) vs Temperature (T):



Adapted from Fig. 13.6, Callister, 8e.

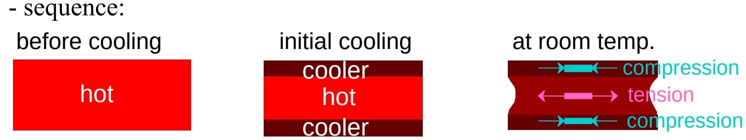
- Crystalline materials:
  - crystallize at melting temp, T_m
  - have abrupt change in spec. vol. at T_m
- Glasses:
  - do not crystallize
  - spec. vol. varies smoothly with T
  - Glass transition temp, T_g
- Recall that Viscosity:
  - relates shear stress & velocity gradient:
  - has units of (Pa-s)



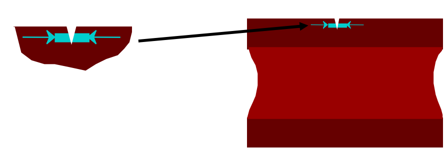
$$\eta = \frac{\tau}{dv/dy}$$

Heat Treating Glass

- Annealing:
  - removes internal stresses caused by uneven cooling.
- Tempering:
  - puts surface of glass part into compression
  - suppresses growth of cracks from surface scratches.
  - sequence:



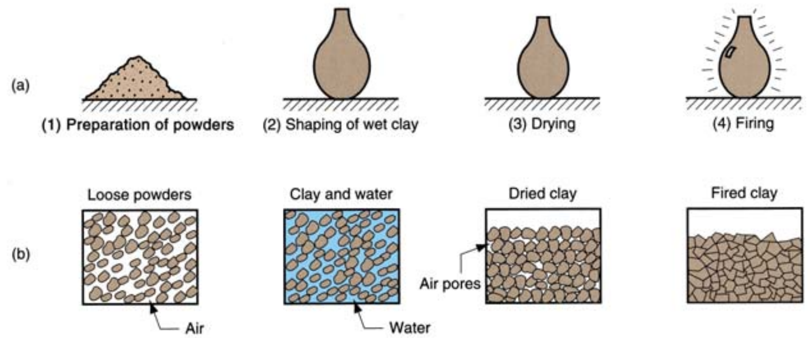
-- Result: surface crack growth is suppressed.



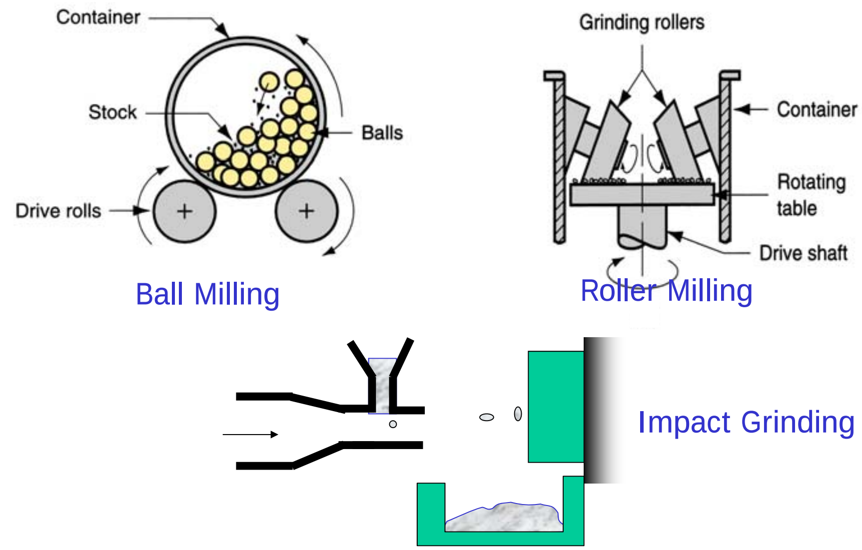
Traditional Ceramic Processing

- Processing sequence
  - Preparing powders
  - Shaping of wet clay
  - Drying
  - Firing
- Preparation of Raw Materials
  - Crushing and Grinding *(micron size particles)*

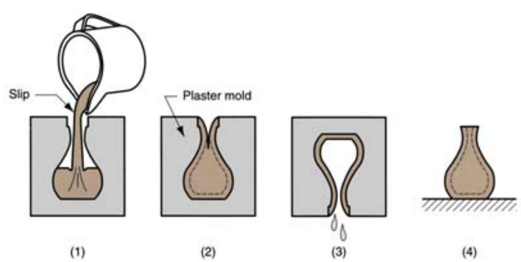
The more water in the mixture, the easier to form. But cracking during drying and sintering.



Grinding



Shaping: *Slip Casting*



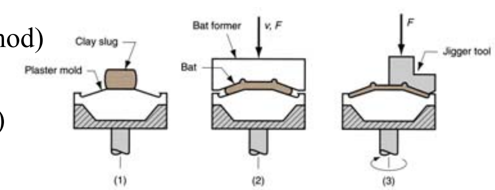
- A suspension of ceramic powders in water, called a *slip*, is poured into a porous plaster of paris mold so that water from the mix is absorbed into the plaster to form a firm layer of clay at the mold surface
- The slip composition is 25% to 40% water

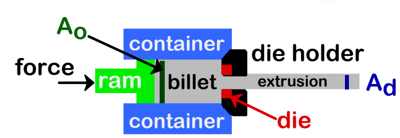
Drying:

- Water must be removed from the clay piece *before firing*
- Shrinkage is a problem during drying because water contributes volume to the piece, and the volume is reduced when it is removed

Shaping: *Plastic Forming*

- The starting mixture must have a plastic consistency, with ………% water
- Variety of manual and mechanized methods
- Hand modeling (manual method)
- Jiggering (mechanized)
- Plastic pressing (mechanized)
- Extrusion (mechanized)

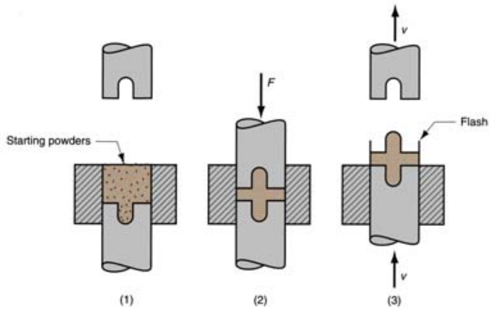




– Manual methods use clay with **……. water** because it is more easily formed (*More water means greater shrinkage in drying*)

– Mechanized methods generally use a mixture with less water so starting clay is stiffer

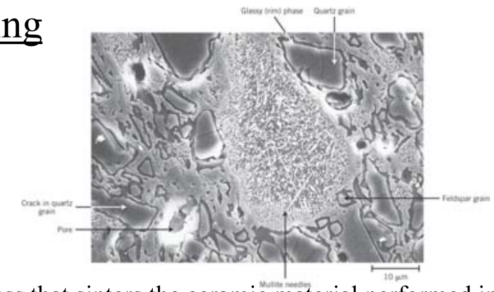
Pressing Processes



Semi-dry Pressing: Uses high pressure to overcome the clay's low plasticity and force it into a die cavity

- Dry Pressing: process sequence is similar to semi-dry pressing - the main distinction is that the water content of the starting mix is < 5%
- Dies must be made of hardened tool steel or cemented carbide to reduce wear since dry clay is very abrasive
- No drying shrinkage occurs, **so drying time is ………….** and **good dimensional accuracy** is achieved in the final product
- Typical products: bathroom tile, electrical insulators, refractory brick, and other simple geometries

Firing and Glazing

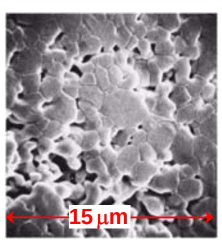


- **Firing:** Heat treatment process that sinters the ceramic material performed in a furnace called a kiln
- Bonds are developed between the ceramic grains which leads to densification and reduction of porosity. Hence additional **shrinkage** occurs.
- In the firing of traditional ceramics, a glassy phase forms among the crystals which acts as a binder
- **Glazing:** Application of a ceramic surface coating to make the piece more impervious to water and enhance its appearance
- The usual processing sequence with glazed ware is:
  1. Fire the piece once before glazing to harden the body of the piece
  2. Apply the glaze
  3. Fire the piece a second time to harden the glaze

Particulate Forming

- Sintering: useful for both clay and non-clay compositions.
- Procedure:
  - grind to produce ceramic and/or glass particles
  - inject into mold
  - press at elevated T to reduce pore size.
- Aluminum oxide powder:
  - sintered at 1700°C for 6 minutes.

Usually sintering is performed at ……….. of melting temp.



Adapted from Fig. 13.15, *Callister 6e*. (Fig. 13.15 is from W.D. Kingery, H.K. Bowen, and D.R. Uhlmann, *Introduction to Ceramics*, 2nd ed., John Wiley and Sons, Inc., 1976, p. 483.)

Next time

Polymers