Overview of Ceramics

- *Define ceramic materials*
- Find a few common examples of ceramic materials, with the correponding crystal structures.
- What are the types of bonds typically found in ceramic materials?
- What are typical applications of ceramic materials?

Key Mechanical Properties

- Strength
- ↑ Compressive strength (higher than metals and polymers)
- ↓ Tensile strength (typically low due to brittleness)
- Hardness
- ↑ High hardness (suitable for wear-resistant applications)
- Elasticity
- ↑ High elastic modulus (stiffness)
- ↓ Low ductility (little to no plastic deformation)

Linear elasticity

- Hooke's law

$$\varepsilon_{xx} = \frac{\sigma_{xx}}{E}$$

- Poisson's ratio

$$\nu = -\frac{\varepsilon_{yy}}{\varepsilon_{xx}}$$

$$\varepsilon_{yy} = -\nu\,\varepsilon_{xx} = -\nu\frac{\sigma_{xx}}{E} \qquad \varepsilon_{zz} = -\nu\,\varepsilon_{xx} = -\nu\frac{\sigma_{xx}}{E}$$

The maximum elastic strain that can be achieved in a polycrystalline ceramic prior to failure is typically 0.1% or so.

Ceramic fibers and bulk single crystals specially prepared to be nearly flaw free may have elastic tensile strains at fracture as great as 1%.

Response to shear loads and pressure

Application of shear stress $\sigma_{xy} = \sigma_{yx}.$

- Shear modulus or rigid modulus $\gamma_{xy} = \gamma_{yx} = \frac{\sigma_{xy}}{\mu}$
- Bulk modulus B: $B = -V\left(\frac{\partial p}{\partial V}\right)_T$ or $\boxed{B = -V\frac{dp}{dV}}$

Elastic Moduli of Polycrystalline Ceramics

Substance	Young's Modulus (GPa)	Shear Modulus (GPa)
Al_2O_3	402.8	163.0
Dy_2O_3	170.5	
Er_2O_3	186.3	
MgO	310.9	133.4
ThO_2	261.0	100.6
TiO_2	284.2	111.5

Variation of elastic constants with temperature

- Elastic constants of single crystals generally decrease slowly with increasing temperature

- As the temperature is decreased toward absolute zero, the slope of the curve of elastic constant as a function of temperature approaches zero, as required by the third law of thermodynamics.

- As the temperature increases toward the Debye temperature, the slope approaches a constant for many ceramics.

$$\boxed{E = E_0 - bT \exp\left(\frac{-T_0}{T}\right)}$$

Elastic properties of ceramics with porosity

- Many ceramics have some degree of porosity.

- Mechanical properties such as elastic moduli, strength, and toughness decrease with increasing porosity.

$$\boxed{\frac{E}{E_0} = 1 - bP}$$

where, P is the pore size

E is the elastic modulus of the porous material
E_0 is the elastic modulus of the fully dense material
P is the porosity
b is the shape factor that accounts for pore geometry

An important class of porous solids not properly regarded as solids with distributed porosity is the class of cellular solids (Homework: read about Cellular solids).

Defect-free solids are much stronger than the *real* solids (with defects) usually encountered.

Permanent deformation: creep

Here permanent deformation begins when stress is applied, slows down in rate, but continues for a long time before ultimate failure.

Transient and steady-state creep,
Generally occur in polycrystalline ceramics at low stresses and sufficiently high temperature.

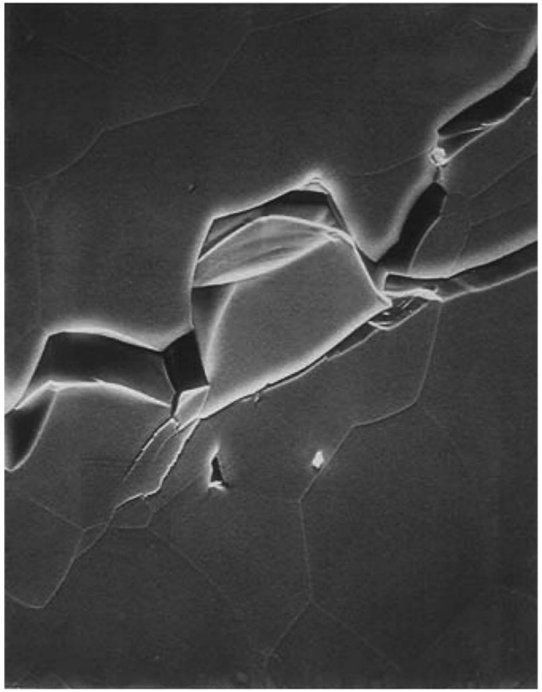
Fracture Behavior

Brittleness

- Lack of plastic deformation before failure
- Sudden, catastrophic fracture under stress

Crack Propagation

- Stress concentration at flaws or cracks
- Role of microcracks in failure



Micrograph showing pullout of bridge in wake of crack. (From Swanson et al., 1987)

Linear elastic fracture mechanics

- The strength of polycrystalline ceramics is usually much less than that of a corresponding perfect single crystal
- Understanding the strength of real polycrystalline ceramics requires understanding the behavior of microcracks under stress.
- Linear elastic fracture mechanics is a very useful theory that treats a crack in a continuous body while avoiding the detail of what happens on an atomic scale.

Concept of stress concentration

- Stress concentrations are usually discussed in terms of a thought experiment in which a flaw is introduced into a body that was originally under uniform stress.

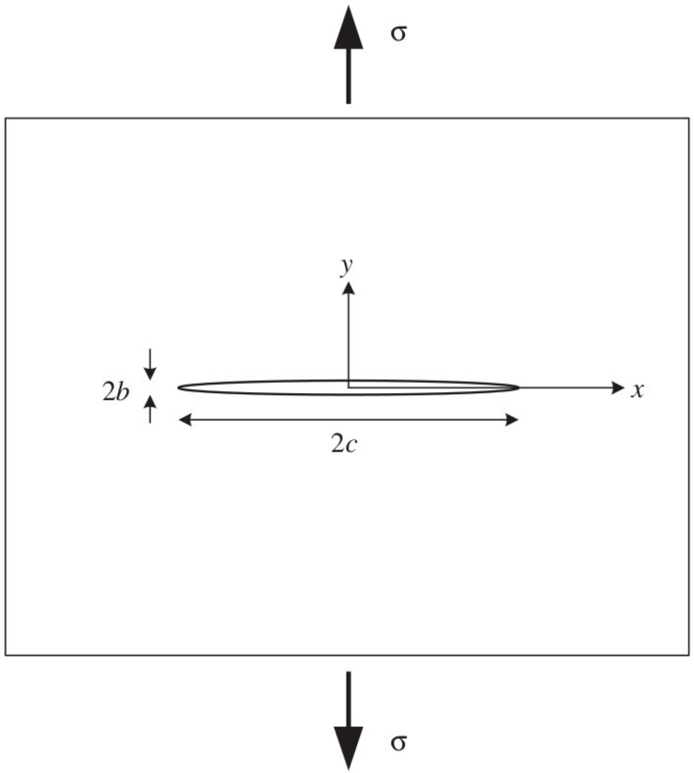
- Consider a sample initially under a uniform tensile stress, σ. If an elliptical flaw whose maximum length is perpendicular to the tensile stress is introduced, the stress will change, especially near the end of the flaw

- The equation of the ellipse defining the crack is

$$\boxed{\frac{x^2}{c^2} + \frac{y^2}{b^2} = 1}$$

- The radius of curvature at the end of the major axis of the ellipse is given by

$$\boxed{\rho = \frac{b^2}{c}}$$



Elliptical crack in plate subjected to uniaxial tensile stress σ.

Two-dimensional view of a sample with a flaw of length 2c in the x direction and a dimension 2b in the y direction

The maximum normal stress that appears anywhere in the plate is at the "tips" of the crack $(x = \pm c)$ and is in the y direction (σ_{yy}), that is, it is in the same direction as the externally applied stress σ.

This is given by:

$$\boxed{\underline{\sigma_{yy}} = \sigma\left(1 + \frac{2c}{b}\right) = \sigma\left[1 + 2\left(\frac{c}{\rho}\right)^{1/2}\right]}$$

develops because of presence of crack

This last expression of this equation contains only two characteristics of the elliptical crack: the length c and the radius of curvature at the end of the crack perpendicular to the initial stress, ρ.

To a good first approximation only the length of the crack perpendicular to the applied stress and the radius of curvature at the end of that length determine the maximum stress.

Toughness → Area under stress-strain curve until the fracture

Low Fracture Toughness

- Ceramics are prone to fracture under impact or stress in comparison with metals and polymers

Methods to Improve Toughness

- Toughening mechanisms (e.g., adding fibers, controlling grain size)
- Crack tip shielding by crack bridging (second-phase ductile ligament bridging)

Influence of Temperature

Thermal Shock Resistance

- Rapid temperature changes can cause fracture
- Applications requiring thermal stability (e.g., space shuttle tiles)

High-Temperature Strength

- Ceramics maintain strength at high temperatures (better than metals)