Mechanical Properties of Ceramics

Mechanical Properties

Properties obtain from a response or deformation due to an applied load or force.

Example: Strength, hardness, toughness, elasticity, plasticity, brittleness, and ductility and malleability

Stress and Strain Diagram: Brittle material

•Materials that fail in tension at relatively low values of strain are classified as brittle materials.

• Examples are concrete, stone, cast iron, glass, ceramic materials, and many common metallic alloys.

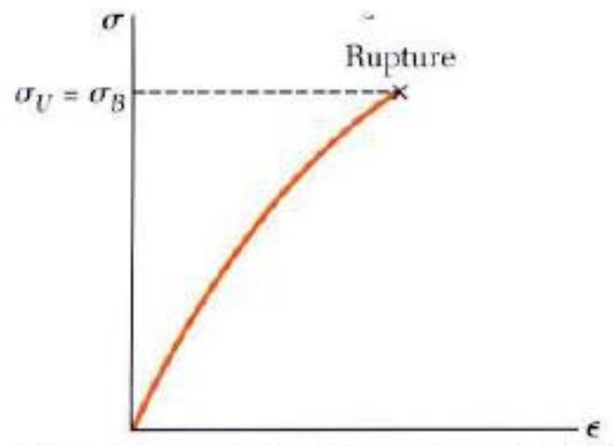
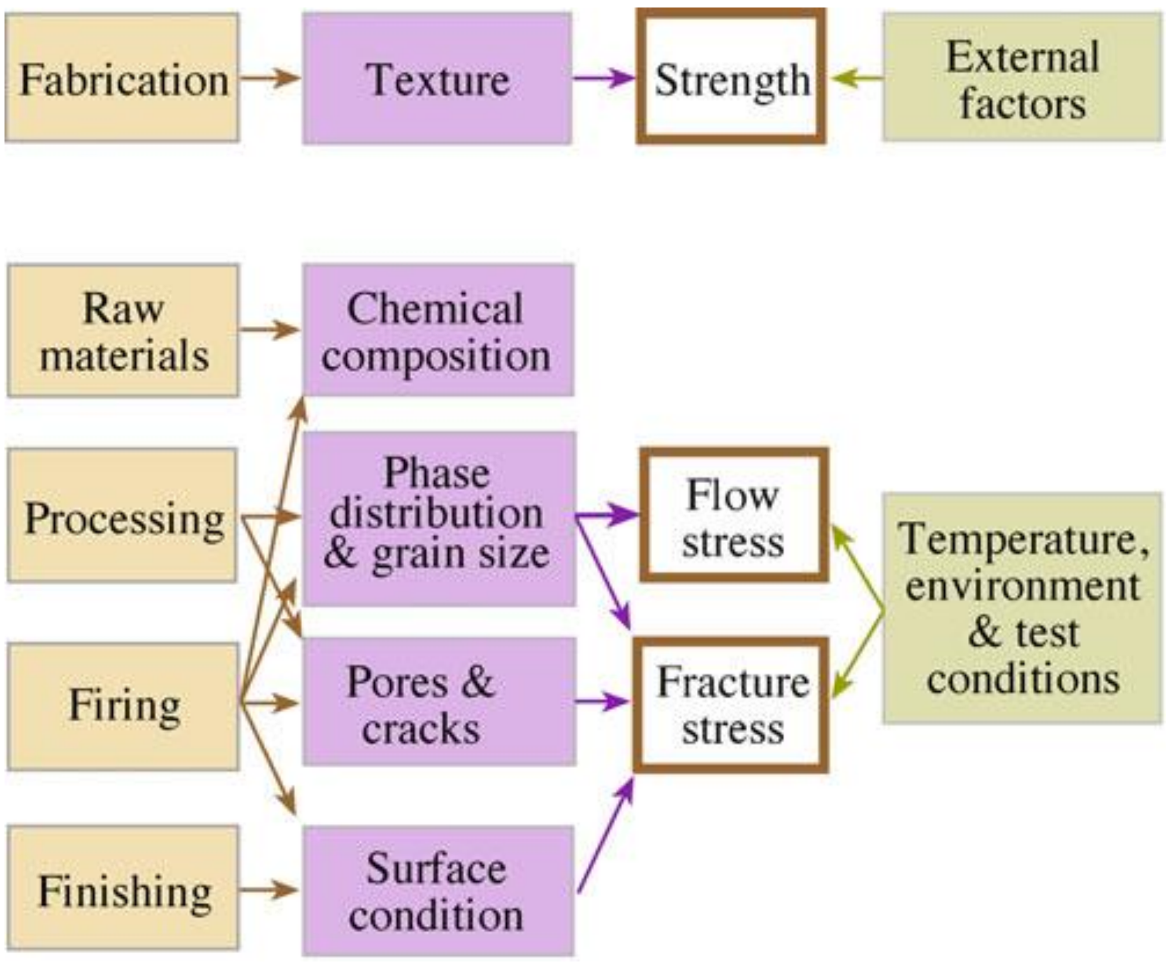


Fig. 2.11 Stress-strain diagram for a typical brittle material.

Brittle Fracture

- Ceramics failed by brittle fracture
- It fails without the formation of necking or any plastic deformation
- The process of brittle fracture consist of the formation and propagation of cracks through the cross section of material in a direction perpendicular to the applied load
- Crack growth through grains, specific crystallographic planes and planes of high density

Factors affecting the mechanical properties of ceramics



Factors affecting strength of ceramics

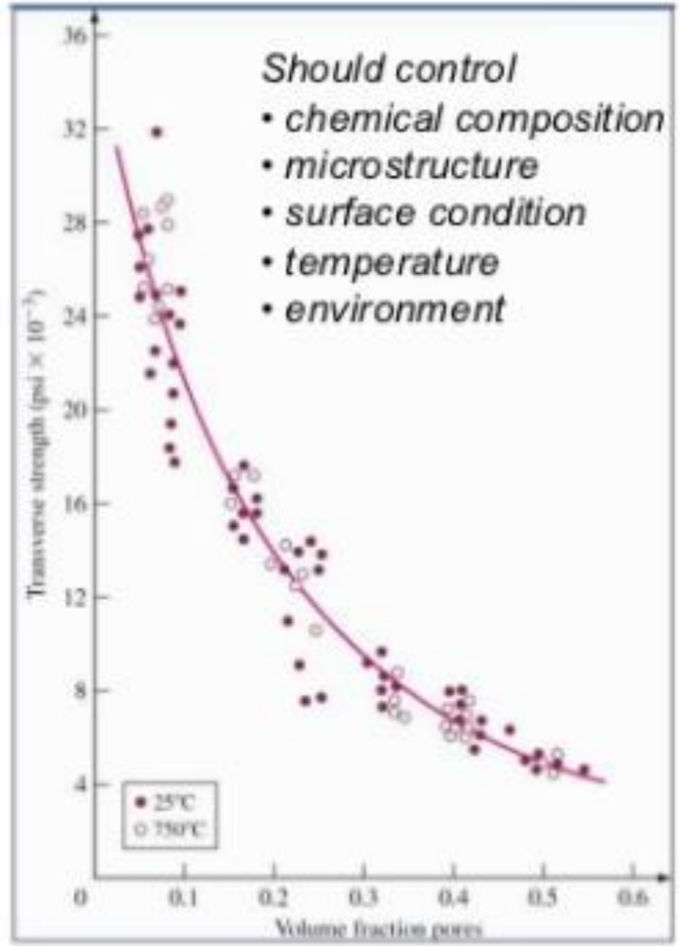
Depending on amount of defects
→ giving stress concentration

- ***Surface cracks***
- ***Porosity***
- ***Inclusions***
- ***Excessive grain sizes***

} Fabrication

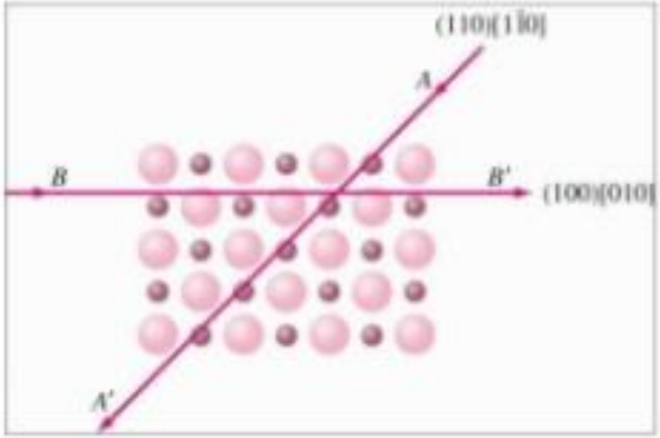
Note:

No plastic deformation during crack propagation from defects → very brittle.



Deformation mechanisms

- Lack of plasticity due to ionic and covalent bonding (directional).
- Stressing of covalent crystal → ***separation of electron-pair bonds without subsequent reformation*** → brittle
- Deforming of ionic single crystal (***MgO or NaCl***) shows considering amount of plastic deformation under compressive force. However ionic polycrystals are brittle due to crack formation at grain boundaries.



NaCl structure showing slip on the (110) plane [110] direction or AA' and on the (100) plane [010] direction BB'

- *Brittle*
- *High strength (varying from 0.7 – 7000 MPa)*
- *Better compressive strength than tensile (5-10 times)*

Level of strength (MPa)	Materials
> 1000	polycrystalline long ceramic fibres (Al_2O_3, SiC): 1-2 GPa, single crystal short ceramic fibres (Al_2O_3, SiC whiskers): 5-20 GPa,
600-1000	Hot Pressed structural ceramics such as silicon nitride, silicon carbide, alumina; sintered tetragonal zirconia and sialon; cemented carbides
200-600	sintered pure alumina and SiC; tempered glass
100-200	impure and/or porous alumina; mullite; high-alumina porcelains; reaction bonded silicon nitride and carbide; glass ceramics
50-100	porcelains; steatite, cordierite; magnesia, polished glasses;
<50	refractory; porous ceramics; glasses

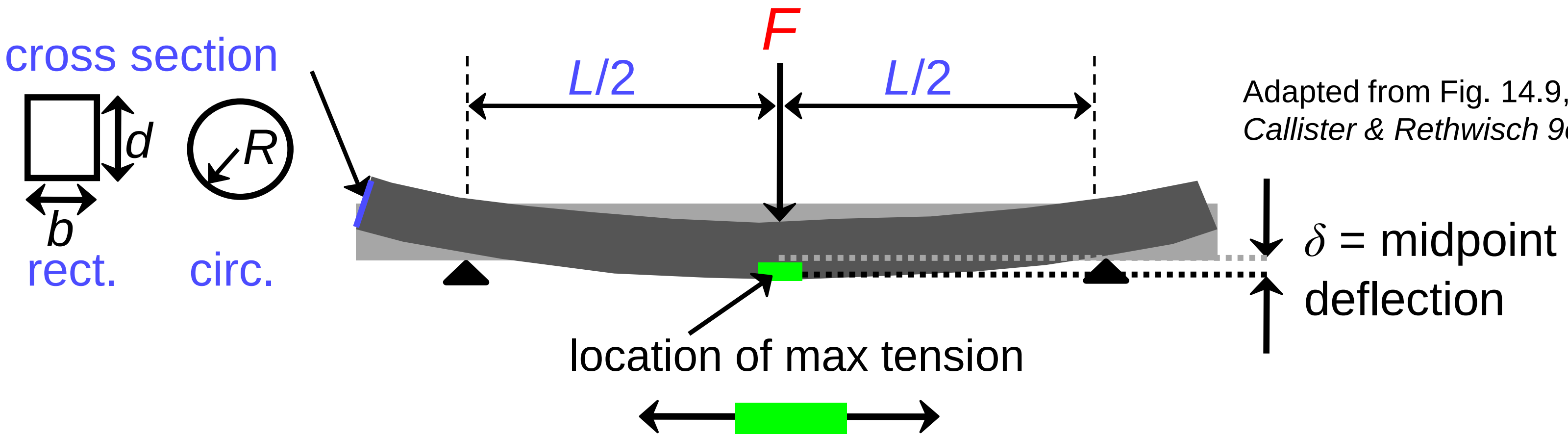
What are the differences between ductile fracture & brittle fracture?

Ductile fracture	Brittle fracture
•Plastic deformation	•Small/ no plastic deformation
•High energy absorption before fracture	•Low energy absorption before fracture
•Characterized by slow crack propagation	•Characterized by rapid crack propagation
•Detectable failure	•Unexpected failure
•Eg: Metals, polymers	•Eg: Ceramics, polymers

Flexural Tests – Measurement of Flexural Strength

- ❑Room T behavior is usually elastic, with brittle failure
- ❑Cannot use typical tensile test as metals.
- ❑3-Point Bend Testing often used.

- 3-point bend test to measure room-T flexural strength.



Adapted from Fig. 14.9, *Callister & Rethwisch 9e.*

- Flexural strength:

$$\sigma_{fs} = \frac{3F_f L}{2bd^2} \quad \text{(rect. cross section)}$$

$$\sigma_{fs} = \frac{F_f L}{\pi R^3} \quad \text{(circ. cross section)}$$

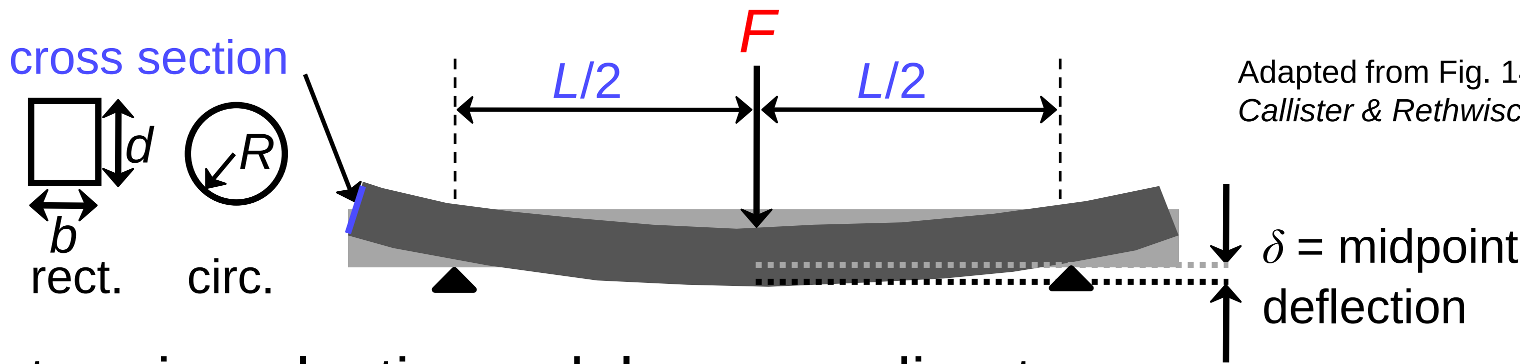
- Typical values:

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 14.1, *Callister & Rethwisch 9e.*

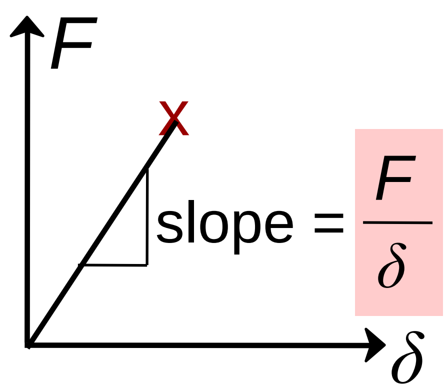
Flexural Tests – Measurement of Elastic Modulus

- Room *T* behavior is usually elastic, with brittle failure.
- 3-Point Bend Testing often used.
  -- tensile tests are difficult for brittle materials.



Adapted from Fig. 14.9, *Callister & Rethwisch 9e.*

- Determine elastic modulus according to:



linear-elastic behavior

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

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

CLASS ASSIGNMENT

A three-point bending test was performed on an aluminum oxide specimen having a circular cross section of radius 3.8 mm; the specimen fractured at a load of 445 N when the distance between the support points was 50.8 mm.

(a) Compute the flexural strength.

(b) The point of maximum deflection Δy occurs at the center of the specimen where modulus of elasticity 393 GPa.Compute Δy.

A three-point bending test is performed on a glass specimen having a rectangular cross section of height d = 6 mm and width b = 12 mm the distance between support points is 45 mm.

(a) Compute the flexural strength if the load at fracture is 290 N.

(b) The point of maximum deflection Δy occurs at the center of the specimen and is described by

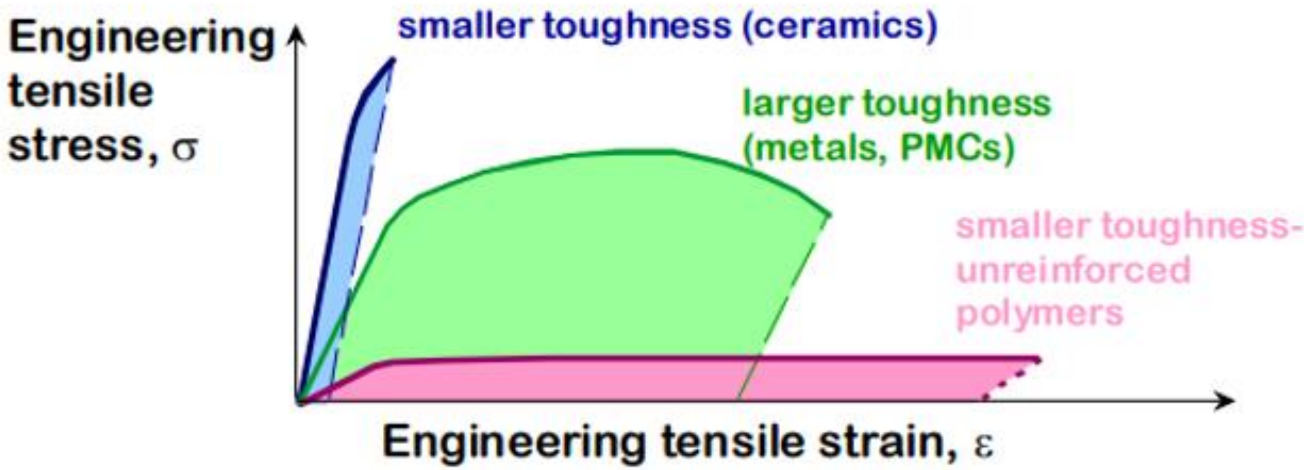
$$\Delta y = \frac{FL^3}{48EI}$$

where E is the modulus of elasticity and I is the cross-sectional moment of inertia. Compute Δy at a load of 266 N.

* Modulus elastic (E) of glass is 69 GPa

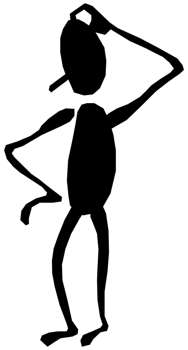
TOUGHNESS

- Material's resistance to fracture when crack.
- Ability of a material to absorb energy and plastically deform before fracturing.
- Energy to break a unit volume of material.
- Approximate by the area under the stress-strain curve.
- For a metal to be tough it must display both strength and ductility

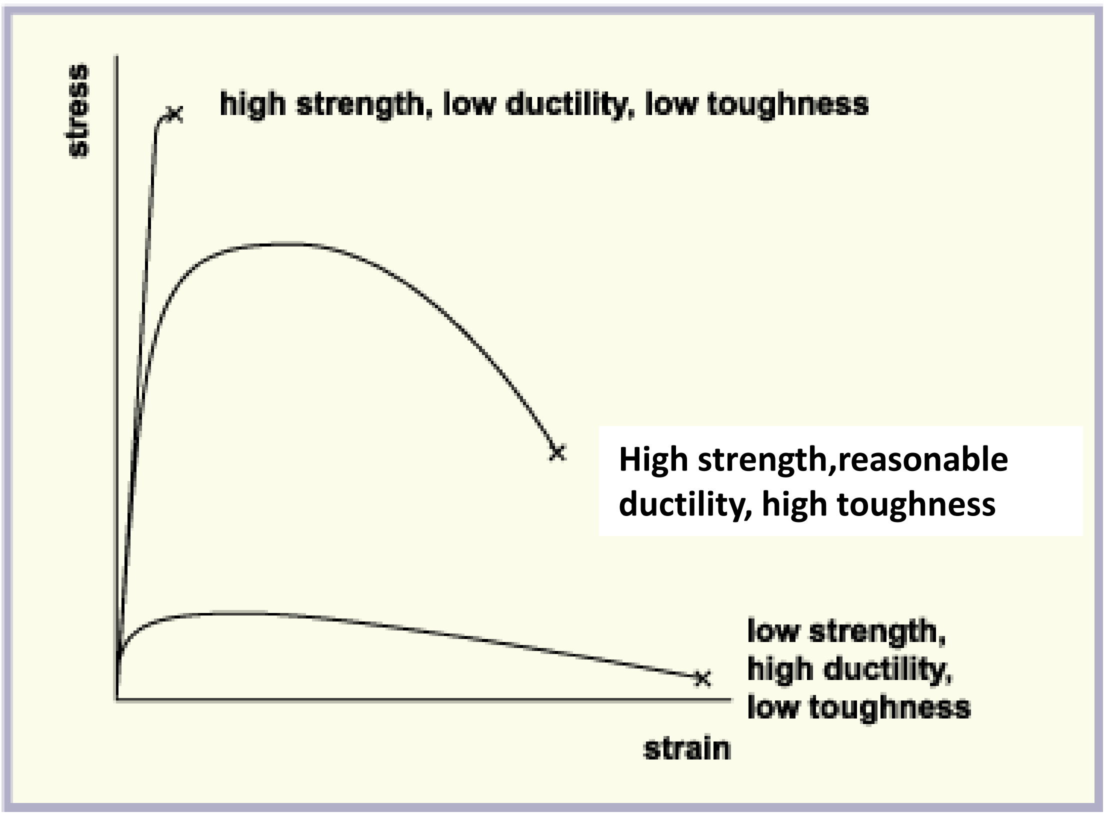


Brittle fracture: elastic energy

Ductile fracture: elastic + plastic energy



Look at the graph below and discuss.



Fracture toughness

Ability of material to resist fracture when a crack is present

The general factors, affecting the fracture toughness of a material are:

1) Temperature
2) strain rate
3) presence of structure defects
4) presence of stress concentration (**notch**) on the specimen surface.

Stress-intensity Factor (K)

Quantitative parameter of fracture toughness determining a maximum value of stress which may be applied to a specimen containing a crack (notch) of a certain length.

Depending on the direction of the specimen loading and the specimen thickness, four types of stress-intensity factors are used: $\mathbf{K_C}$, $\mathbf{K_{IC}}$, $\mathbf{K_{IIC}}$, $\mathbf{K_{IIIC}}$:

1) $\mathbf{K_C}$– stress-intensity factor of a specimen, thickness $<$ critical value.

2) $\mathbf{K_C}$ depends on the specimen thickness -**plane stress**.

3) $\mathbf{K_{IC}}$,$\mathbf{K_{IIC}}$, $\mathbf{K_{IIIC}}$– stress-intensity factors, relating to the specimens, thickness $>$ critical value therefore the values of $\mathbf{K_{IC}}$, $\mathbf{K_{IIC}}$, $\mathbf{K_{IIIC}}$ do not depend on the specimen thickness - **plane strain**.

4) $\mathbf{K_{IIC}}$ and $\mathbf{K_{IIIC}}$ – stress-intensity factors relating to the fracture modes in which the loading direction is parallel to the crack plane. These factors are rarely used for metallic materials and are not used for ceramics;

5) $\mathbf{K_{IC}}$ – plane strain stress-intensity factor relating to the fracture modes in which the loading direction is normal to the crack plane. This factor is widely used for both metallic and ceramic materials.

K_{IC} is used for estimation critical stress applied to a specimen with a given crack length:

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

K_{IC} – stress-intensity factor, measured in MPa*m½;
σ_C– the critical stress applied to the specimen;
a – the crack length for edge crack or half crack length for internal crack;
Y – geometry factor.

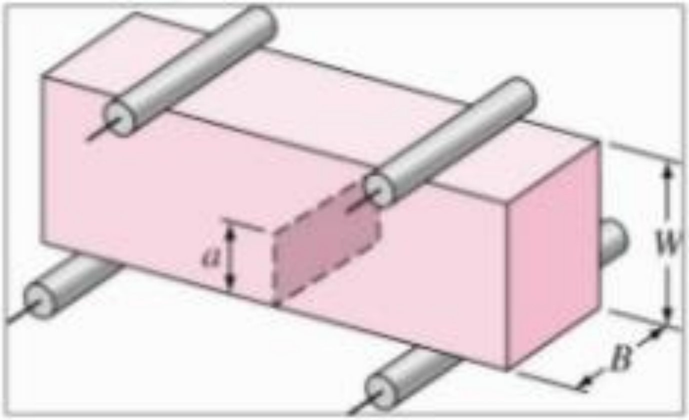
Two test methods are used for measuring fracture toughness parameter (stress-intensity factor) of ceramic materials:

1) Flexure Test
2) Indentation Fracture Test

Toughness of ceramics

Example

A reaction-bonded silicon nitride has a strength of 300 MPa and a fracture toughness of 3.6 MPa.m[1/2], What is the largest-size internal crack that this material can support without fracturing? Given Y = 1



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

$$a = \frac{K_{IC}^2}{\pi\sigma_f^2} = \frac{\left(3.6MPa.\sqrt{m}\right)^2}{\pi(300MPa)^2}$$

$$a = 4.58\times10^{-5}\,m = 45.8\,\mu m$$

Therefore the largest internal crack $2a = 91.6\ \mu m$

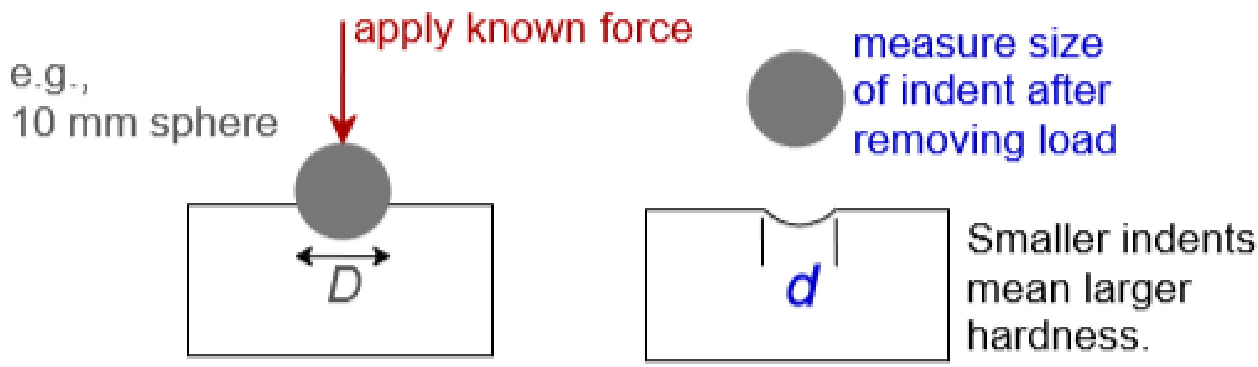
Toughness of ceramics

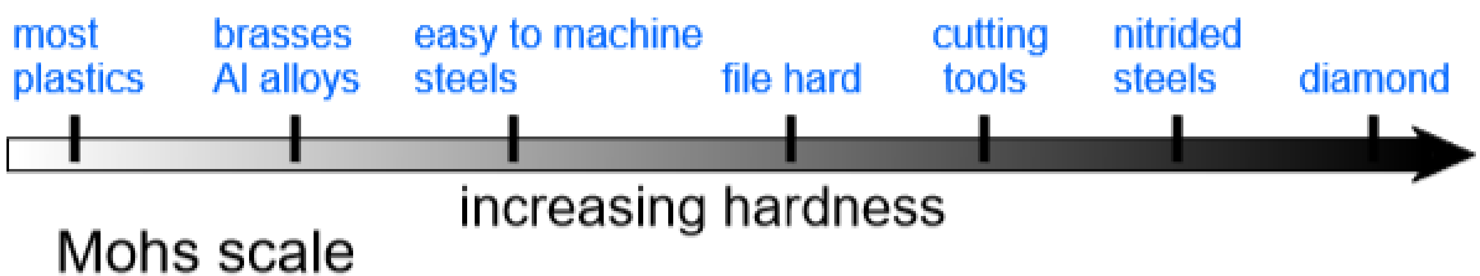
- Low toughness due to covalent-ionic bonding.
- Using hot pressing, reaction bonding to improve toughness.
- Fibre-reinforced ceramic matrix composites.

Material	Density (g/cm^3)	Compressive strength		Tensile strength		Flexural strength		Fracture toughness	
		MPa	ksi	MPa	ksi	MPa	ksi	MPa$\sqrt{m}$	ksi$\sqrt{in}$
Al_2O_3 (99%)	3.85	2585	375	207	30	345	50	4	3.63
Si_3N_4 (hot-pressed)	3.19	3450	500	···	···	690	100	6.6	5.99
Si_3N_4 (reaction-bonded)	2.8	770	112	···	···	255	37	3.6	3.27
SiC (sintered)	3.1	3860	560	170	25	550	80	4	3.63
ZrO_2, 9% MgO (partially stabilized)	5.5	1860	270	···	···	690	100	8+	7.26+

Hardness

- A measure of material's resistance to localized plastic deformation.
- Resistance to permanently indenting the surface.
- Large hardness means:
  -- resistance to plastic deformation or cracking in compression.
  -- better wear properties.





Hardness test

Hardness - resistance of material to Plastic deformation caused by indentation.

Sometimes hardness refers to resistance of material to scratching or abrasion.

Hardness may be measured from a small sample of material without destroying it.

There are hardness methods, allowing to measure hardness onsite.

Principle of any hardness test method

forcing an indenter into the sample surface followed by measuring dimensions of the indentation (depth or actual surface area of the indentation).

Hardness is not fundamental property and its value depends on the combination of yield strength, tensile test and modulus of elasticity.

Hardness: Measurement

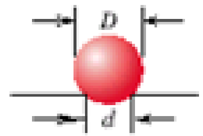
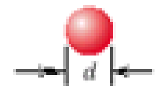
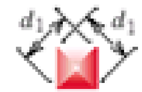
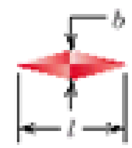
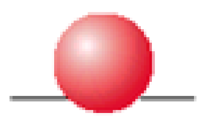
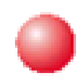
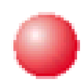
- Rockwell
  - Indenters – spherical and hardened steel balls
  - No major sample damage
  - Each scale runs to 130 but only useful in range 20-100.
  - Initial minor load   10 kg
  - Followed by major load   60 (A), 100 (B) & 150 (C) kg
    - A = diamond, B = 1/16 in. ball, C = diamond

- HB = Brinell Hardness
  - *Similar to Rockwell but load is maintained constant for a specified time (10-30 sec)*

- Correlation between hardness and tensile strength
  - TS (MPa) = 3.45 X HB

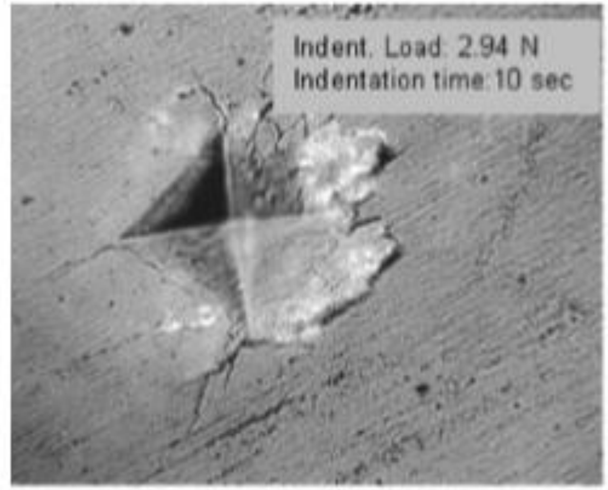
Hardness: Measurement

Table 8.5 **Hardness Testing Techniques**

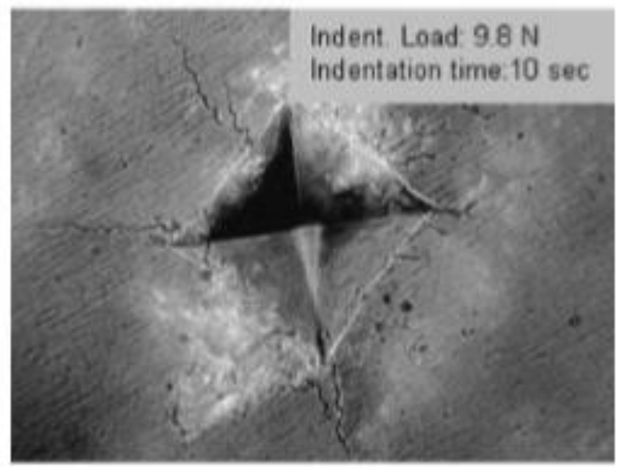
Test	*Indenter*	*Shape of Indentation* — *Side View*	*Shape of Indentation* — *Top View*	*Load*	*Formula for Hardness Number*[a]
Brinell	10-mm sphere of steel or tungsten carbide			P	$\text{HB} = \dfrac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$\text{HV} = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid			P	$\text{HK} = 14.2P/l^2$
Rockwell and Superficial Rockwell	Diamond cone; $\frac{1}{16}, \frac{1}{8}, \frac{1}{4}, \frac{1}{2}$ in. diameter steel spheres	 	 	60 kg, 100 kg, 150 kg (Rockwell); 15 kg, 30 kg, 45 kg (Superficial Rockwell)	

[a] For the hardness formulas given, P (the applied load) is in kg, while D, d, d_1, and l are all in mm.

Source: Adapted from H. W. Hayden, W. G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*. Copyright © 1965 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.


Indent. Load: 2.94 N
Indentation time:10 sec

(a)


Indent. Load: 9.8 N
Indentation time:10 sec

(b)