Ceramics - II

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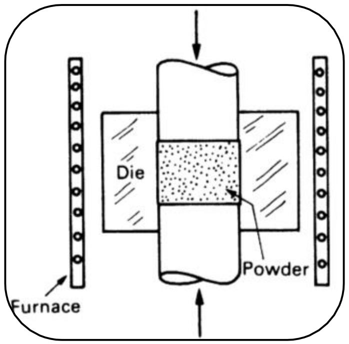
Content

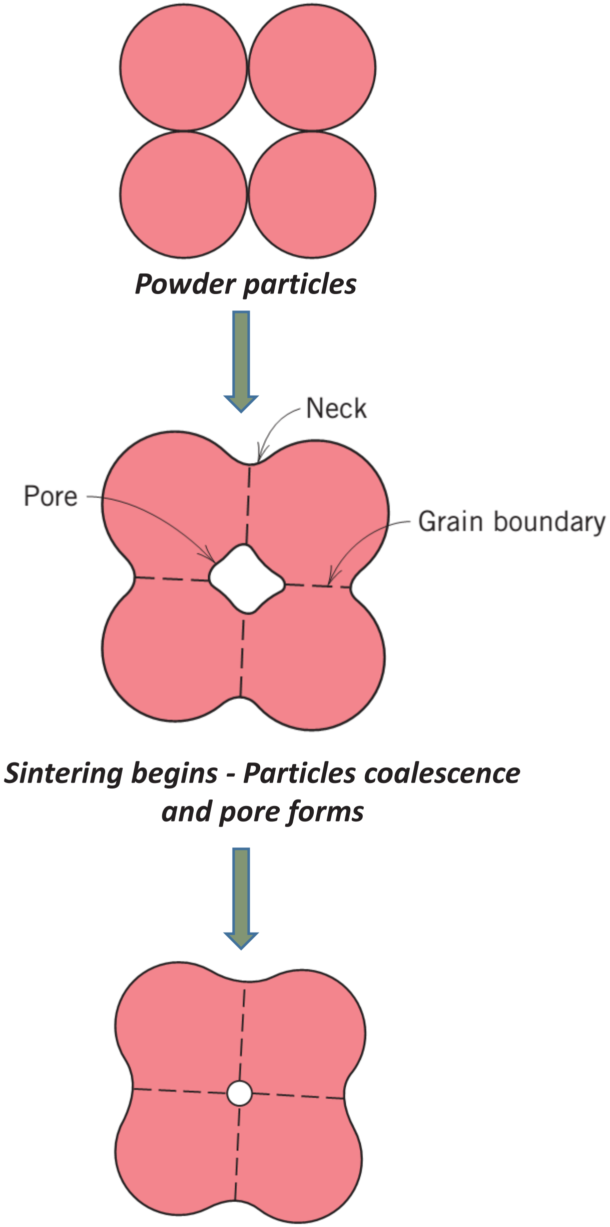
- ✓ Processing of ceramics
- ✓ Ceramic elastic modulus
- ✓ Weibull modulus
- ✓ Hardness
- ✓ Fracture toughness
- ✓ Failure in ceramics

Processing of Ceramics

- Unlike **metals and glasses**, which can be **cast** from the **melt** and subsequently rolled, drawn, or pressed into shape, **ceramics** are made from **powders**.
- **Ceramics powder** is consolidated and densified by **sintering**.
- **Sintering** is a process whereby **particles bond** and merge under the influence of **pressure & heat**, leading to shrinkage and reduction in porosity.
- Expensive fabrication technique due to **high cost** of mould & die.
- A similar process in **metal manufacturing** is referred to as **powder metallurgy**.



Sintering



Powder particles

Sintering begins - Particles coalescence and pore forms

Sintering terminates - pores change size and shape

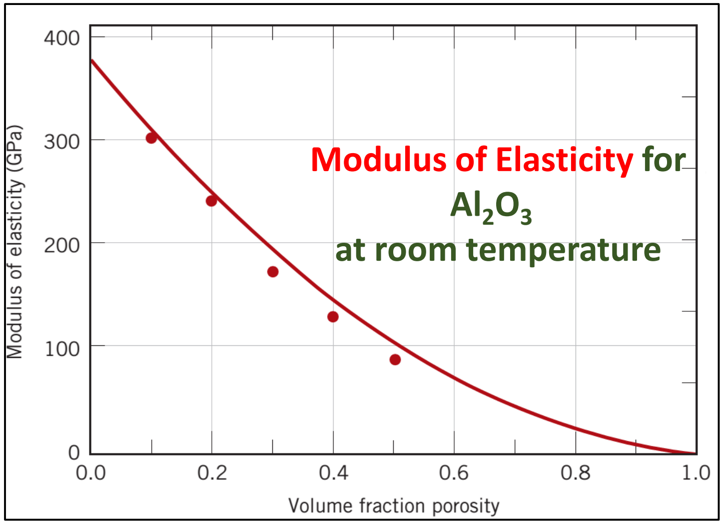
Reference: Engineering Materials 2: Ashby & Jones, 4th Ed.

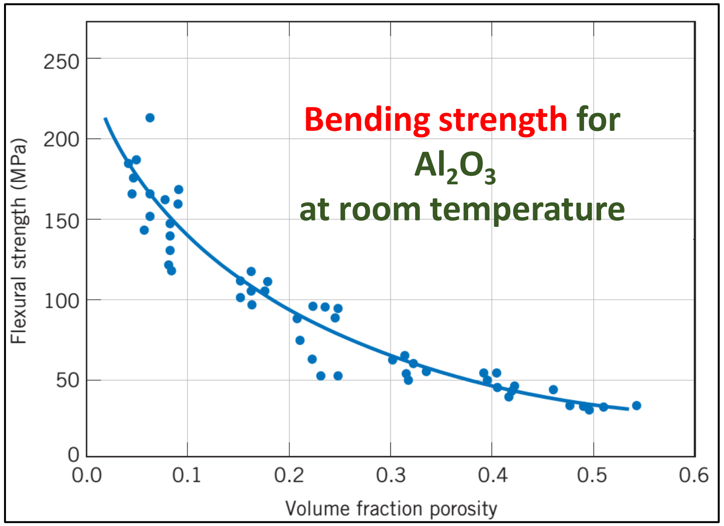
Reference: W.D Callister, 7 Ed.

Influence of Porosity

- There always occur some pores or void spaces between the powder particles even after sintering and subsequent heat treatment.
- Residual porosity has a negative influence on both the elastic properties and strength.
- Porosity also leads to :-
  - ✓ Reduction in effective load carrying area.
  - ✓ Acts as stress concentrators.

$$Volume\ fraction\ porosity = \frac{Volume\ of\ pores}{Volume\ of\ specimen}$$





Reference: W.D Callister, 7 Ed.

How to measure Ceramic Elastic modulus?

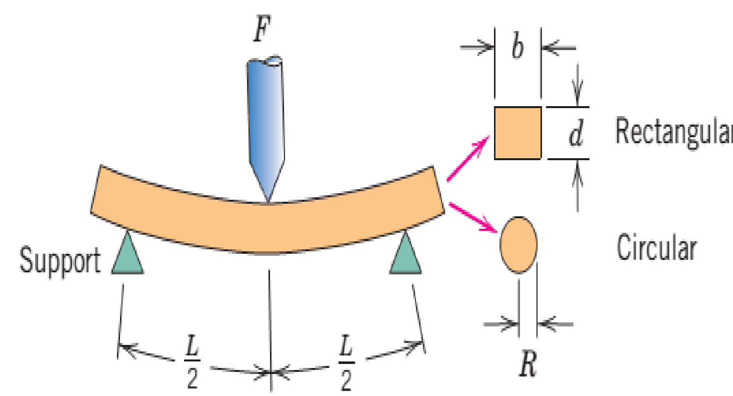
Ceramics are not subjected to Tensile testing due to 3 important reasons:

- ✓ Difficult to prepare test specimen as required for tensile testing.
- ✓ Difficult to grip brittle materials without fracturing.
- ✓ Ceramics fail at very low strain (≈0.1%), which requires very precise alignment on machine to avoid bending stress.

Hence, three-point bending test is used.

Three-point bending test

- At the point of loading
  - ✓ Specimen top surface in compression
  - ✓ Bottom surface in tension
- Stress is computed from the specimen thickness, B.M, and the M.I of the cross section.
- Maximum tensile stress at the bottom surface directly below the loading point.
- Fracture occurs on the tensile specimen face.
- Tensile strengths of ceramics are about one-tenth of their compressive strengths.



$$\sigma = \text{stress} = \frac{Mc}{I}$$

where M = maximum bending moment

c = distance from center of specimen to outer fibers

I = moment of inertia of cross section

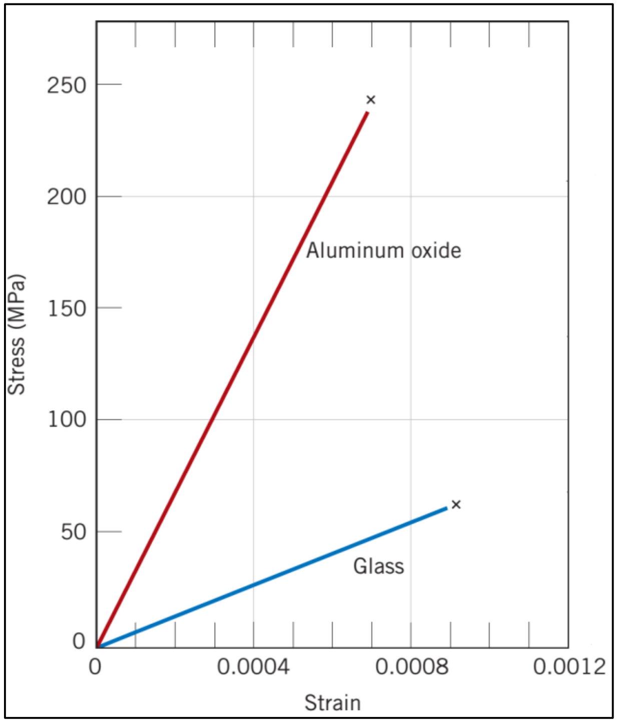
F = applied load

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

Reference: W.D Callister, 7 Ed.

Modulus of Elasticity

- The slope in the elastic region is the modulus of elasticity.
- Range of moduli of elasticity for ceramic materials is between about 40 and 1000 GPa (Diamond).
- Ceramics have compressive strength 10-15 times of their tensile strength.
- Under compression failure occur either by crushing or buckling.

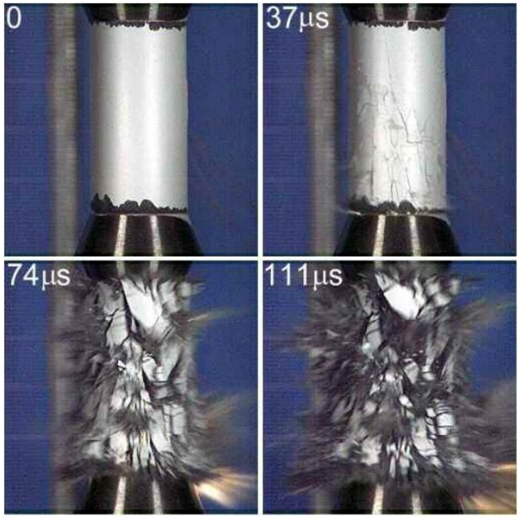


Reference: W.D Callister, 7 Ed.

Specific Moduli: Ceramics Compared to Metals

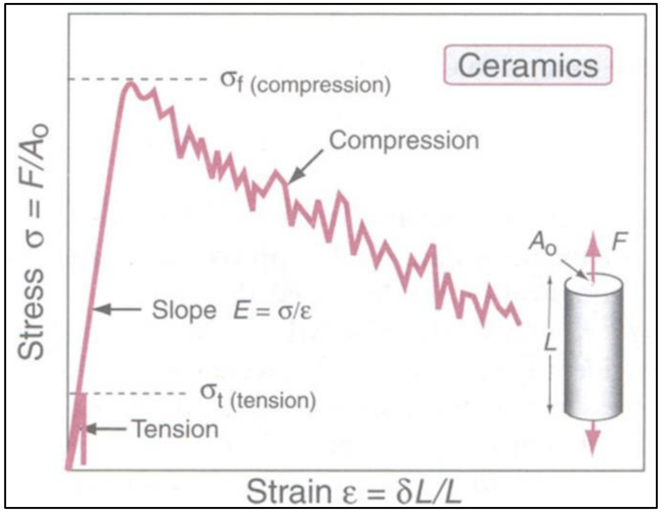
Material	Modulus *E* (GN m^{-2})	Density ρ (Mg m^{-3})	Specific Modulus E/ρ
Steels	210	7.8	27
Al alloys	70	2.7	26
Alumina, Al_2O_3	390	3.9	100
Silica, SiO_2	69	2.6	27
Cement	45	2.4	19

Reference: Engineering Materials 2: Ashby & Jones, 4th Ed.



Silicon carbide under compression

Reference: www.csm.mech.utah.edu



Comparison under Tension & Compression

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Weibull Modulus

- For ceramics and other brittle materials, the **maximum stress** before failure may **vary** from specimen to specimen, even under identical testing conditions.
- Occurs due to the **distribution of physical flaws** present in the surface or volume of the brittle specimen.
- Weibull modulus maps the **probability of failure** of a component at **varying stresses**.
- **Probability of failure** for components can be **calculated** without knowing defect density.

Probability of Survival & Failure :

$$P_S = exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right]$$

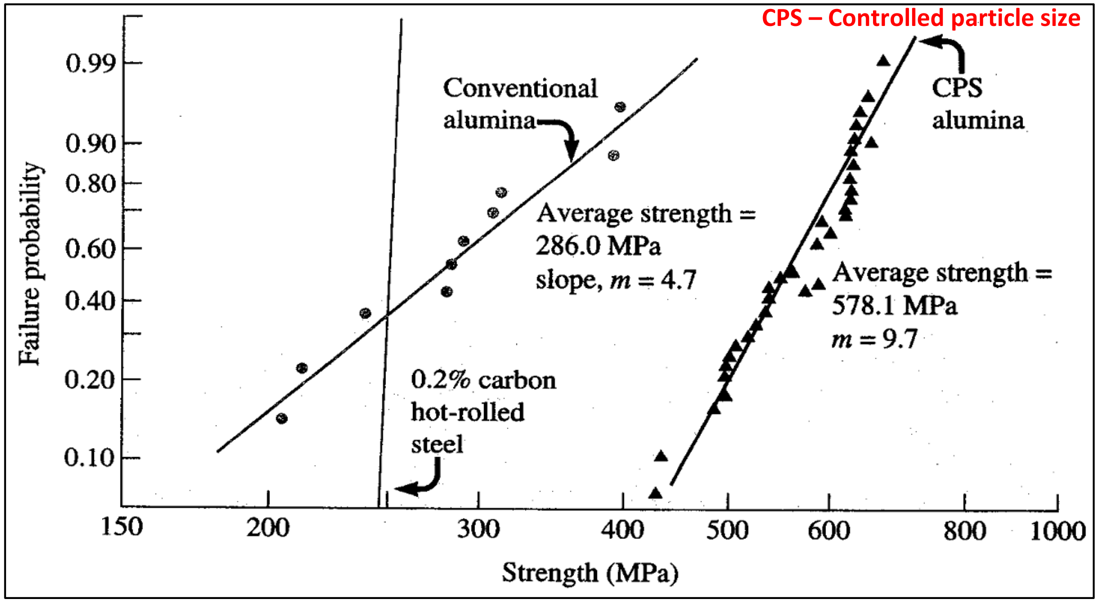
$$P_f = 1 - P_S = 1 - exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right]$$

$$P_f = \frac{n_x}{N+1}$$

Where,

n_x : No. of samples failed at particular stress x
N : Total no. of samples
σ : Applied stress
σ_0 : Average strength (or stress level for which survival probability is 37%)
m : Weibull modulus (slope of straight line)

CPS – Controlled particle size



If $\sigma = \sigma_0$, then $P_S = \frac{1}{e} \approx 0.37$

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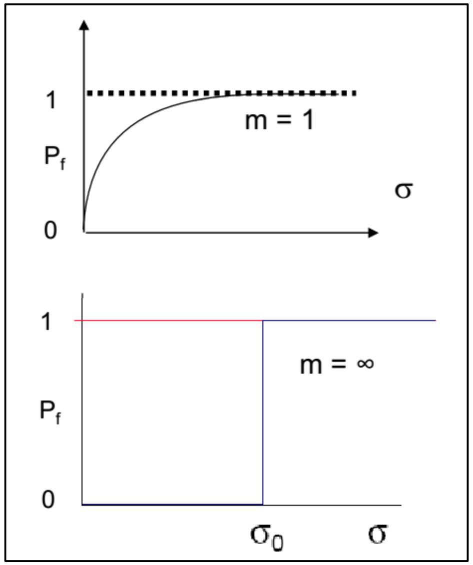
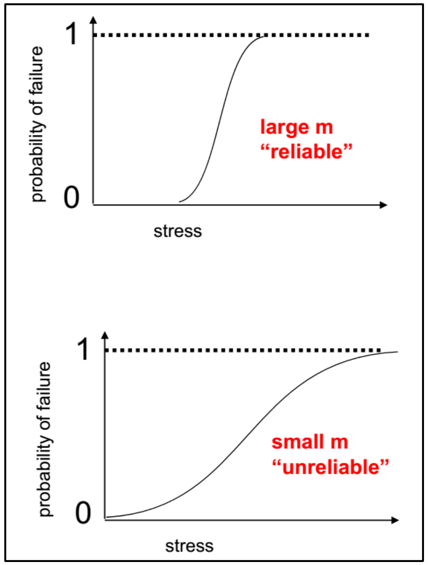
Ref: http://www.ecs.umass.edu/mie/faculty/nair/mie302/Lab%20Handouts/weibull%20handout.pdf

σ_0 : Characteristic/Average strength (or stress level for which survival probability is 37% or failure probability is 63%).





Ref: http://www.nonmet.mat.ethz.ch/

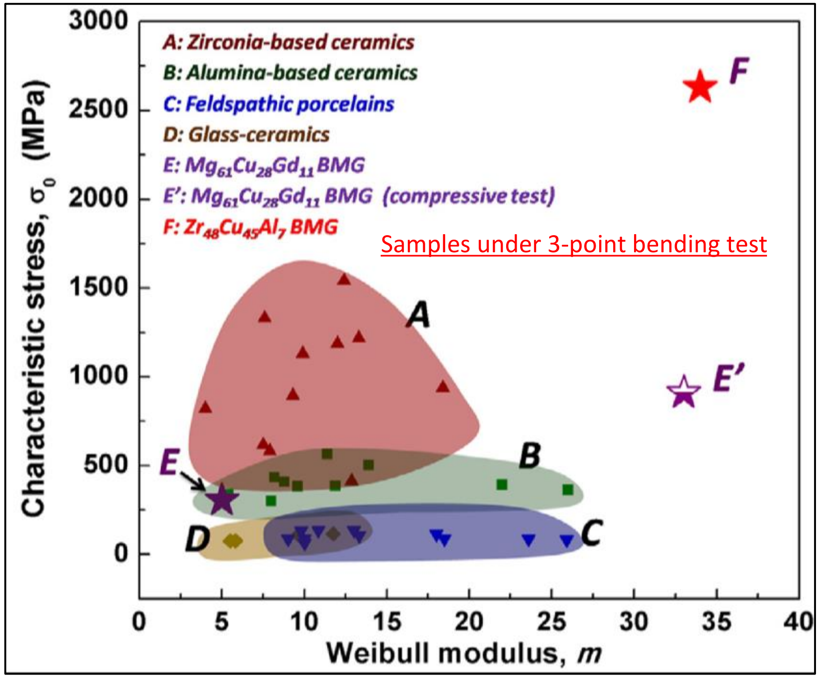
Weibull modulus (m)

- m = 0 : P_f is independent of applied stress
- m = 1 : P_f is exponential asymptotic curve
- m = ∞ : P_f is "step curve"
  - ✓ $P_f = 0$, if $\sigma < \sigma_0$
  - ✓ $P_f = 1$, if $\sigma > \sigma_0$
- Large m : Narrow distribution; small spread in fracture strength
- Small m : Wide distribution, large spread in fracture strength

For Zirconia based BMG, m = 35 (under bending)
m = 73.4 (under compression)

Sample	Weibull modulus, *m*	Dimension	Stress condition
$Mg_{71}Zn_{25}Ca_4$	41	Φ1.9 mm × 4 mm	Compression
$Mg_{66}Zn_{30}Ca_4$	26	Φ1.9 mm × 4 mm	Compression
$Mg_{61}Cu_{28}Gd_{11}$	33	Φ1.9 mm × 4 mm	Compression
$Mg_{61}Cu_{28}Gd_{11}$	5	3 mm ×4 mm × 40 mm	Bending
$(Zr_{48}Cu_{45}Al_7)_{98}Y_2$	25.5	Φ1.5 mm × 3 mm	Compression
$Zr_{48}Cu_{45}Al_7$	73.4	Φ1.5 mm × 3 mm	Compression
$Zr_{48}Cu_{45}Al_7$	36.5	4 mm × 1 mm × 0.7 mm	Tensile
$Zr_{48}Cu_{45}Al_7$	34	3 mm × 4 mm × 40 mm	Bending
$Cu_{45}Hf_{46}Al_9$	53	Φ1.5 mm × 3 mm	Compression
$Cu_{49}Hf_{42}Al_9$	40	Φ1.5 mm × 3 mm	Compression
$Zr_{55}Ti_2Co_{28}Al_{15}$	107.9	Φ4 mm × 8 mm	Compression
$Zr_{55}Ti_2Co_{28}Al_{15}$	36.2	Φ6 mm × 12 mm	Compression
$Zr_{55}Ti_2Co_{28}Al_{15}$	3.8	Φ3 mm × 15 mm	Tensile

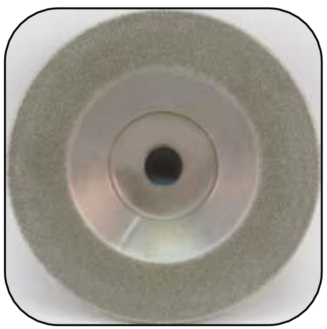
Weibull modulus for several Bulk metallic glass



Ref: *J. Zhang*, et al., JMST(2016)

Hardness

- Ceramics are hard and brittle due to the presence of **ionic & covalent bonds** that hold the atoms together.
- This property is utilized when an **abrasive or grinding action** is required.
- Ceramics having **Knoop hardness** of about 1000 or greater are utilized for their abrasive characteristics.



Tungsten carbide wheel

Diamond abrasive

Knoop hardness value (100gm load)

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
Glass	550

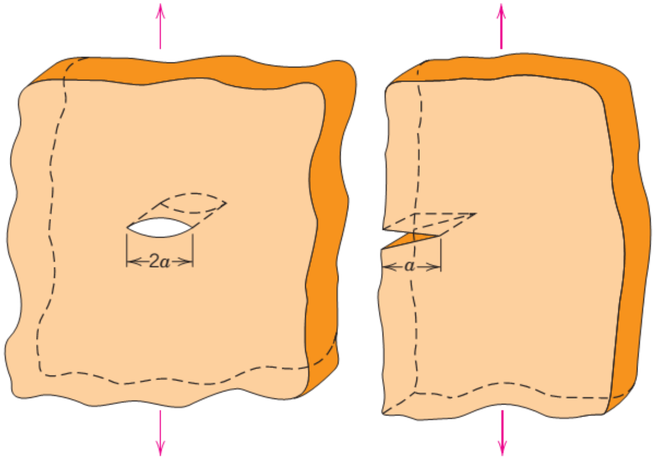
Reference: W.D Callister, 7 Ed.

Fracture toughness of Ceramics

- ✓ **Ceramics** – highly brittle in nature, thus ***low fracture toughness.***
- ✓ Fracture toughness – a material property
  - Ability to resist crack propagation.
  - Measurement of the energy required to grow a thin crack
  - Unit = MPa $\sqrt{m}$
- ✓ Low Fracture toughness = Brittle failure
- ✓ High fracture toughness = Ductile failure

$$Fracture\ toughness, K_c = Y\sigma_c\sqrt{\pi a}$$

Where,
Y = dimensionless parameter
σ_c = critical stress for crack propagation
a = crack length



Interior Crack ***Edge Crack***

Reference: W.D Callister, 7 Ed.

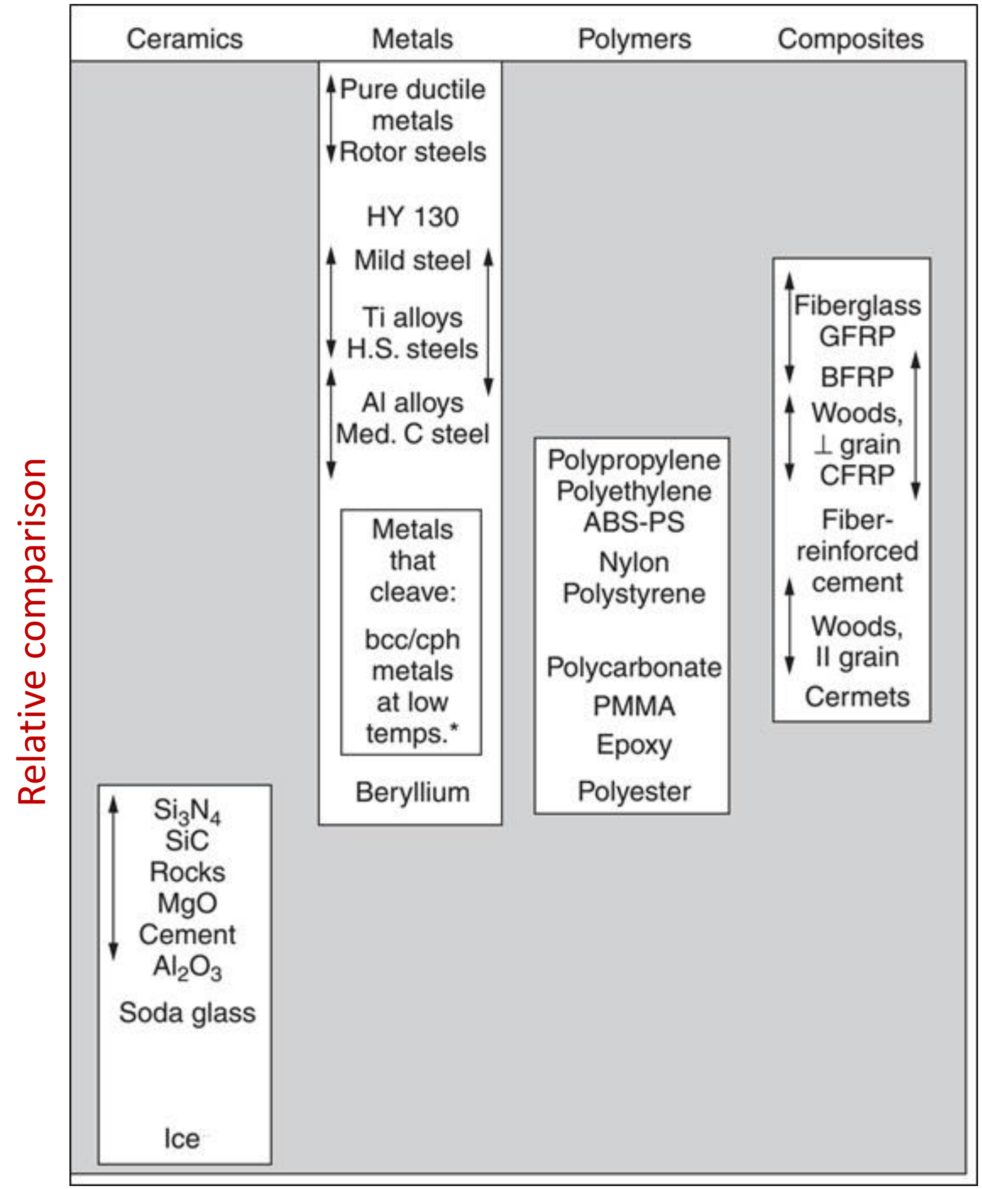
Fracture toughness comparison

Room temperature values

Material	Yield Strength MPa	Fracture toughness $MPa\sqrt{m}$
Metals		
Aluminum Alloy[a] (7075-T651)	495	24
Aluminum Alloy[a] (2024-T3)	345	44
Titanium Alloy[a] (Ti-6Al-4V)	910	55
Alloy Steel[a] (4340 tempered @ 260°C)	1640	50.0
Alloy Steel[a] (4340 tempered @ 425°C)	1420	87.4
Ceramics		
Concrete	—	0.2–1.4
Soda-Lime Glass	—	0.7–0.8
Aluminum Oxide	—	2.7–5.0

Reference: W.D Callister, 7 Ed.

Thus, cracks propagates **slowly** in **metals** as compared to ceramics or **metals absorb more energy** before fracture occurs.

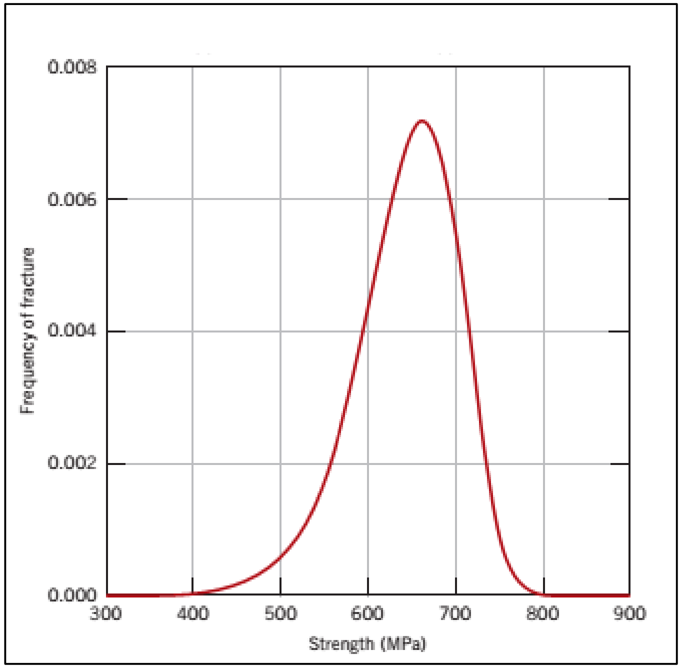


Reference: Engineering Materials 2: Ashby & Jones, 4th Ed.

Failures in Ceramics

- Ceramics have **negligible plastic deformation** before fracture (no warning).
- The brittle fracture of ceramics limits its applications.
- Occurs due to the **unavoidable** presence of **microscopic flaws** (micro-cracks, internal pores, and atmospheric contaminants) that result during fabrication.
- The **inherent flaws** leads to crack formation and propagation.
- Ceramics are good structural materials under compression as difficult for crack to propagate.
- The **flaws cannot** be closely **controlled** in **manufacturing**; this leads to a **large variability** (scatter) in the **fracture strength** of ceramic materials.

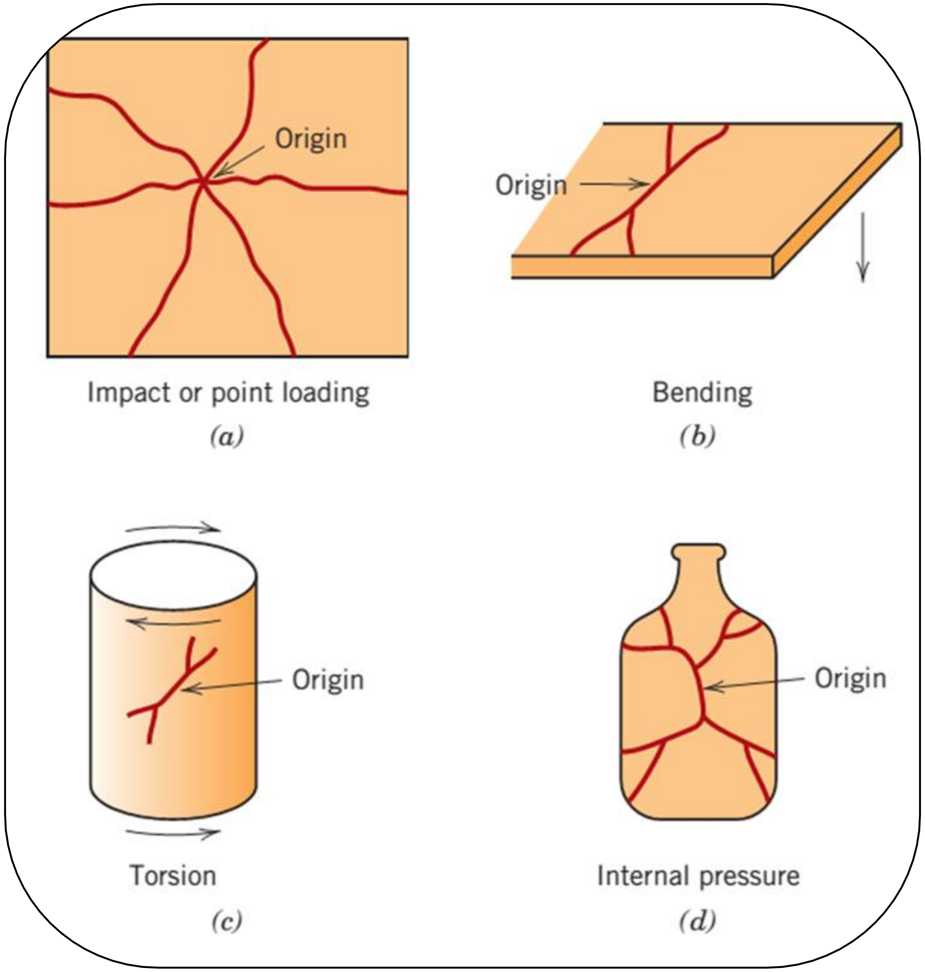
Brittle failure



Variability in fracture strength for Silicon nitride

Reference: W.D Callister, 7 Ed.

Brittle fracture of Ceramics

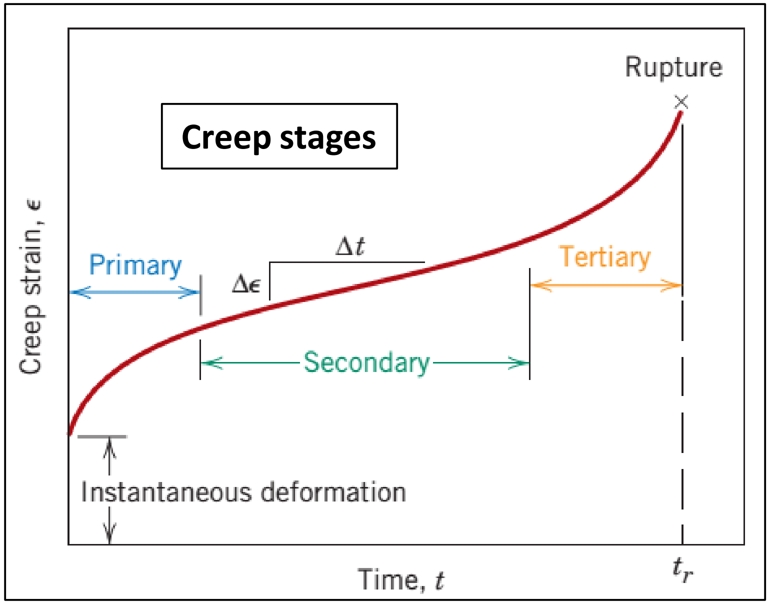


Typical crack configurations for common loadings

Reference: W.D Callister, 7 Ed.

Creep

- Ceramic materials experience creep deformation under stress (usually compressive) at elevated temperatures.
- Time–deformation creep behavior of ceramics is similar to that of metals but at relatively higher temperatures



Creep behavior

Reference: W.D Callister, 7 Ed.

How to make Ceramics Conductive?

Two ways to make ceramics electrically conductive.

- ✓ At sufficiently high temperatures point defects such as oxygen vacancies can arise, leading to ionic conductivity.
  Example : Zirconia

- ✓ Introduction of certain **transition-metal** elements (such as iron, copper, manganese, or cobalt), **lanthanide elements** (such as cerium), or **actinide elements** (such as uranium) can produce special electronic states in which mobile electrons or electron holes arise.
  Example: Copper-based superconductors are a good example of conductive transition-metal oxide ceramics—in this case, conductivity arising at extremely low temperatures.

In the **next lecture**, we will learn:

✓ Introduction on Polymers

✓ Classification

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