MATERIALS ENGINEERING
MT30001
3-0-0

Offered by:

Metallurgical & Materials Engineering Dept.

Instructors:

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Prof. Sujoy Kumar Kar

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Brief CV

2002 - B.E in Metallurgical Engg. from Jadavpur University

2005 – M.Tech from IIT Bombay with DAAD fellowship from Germany, M.Tech project at University of Karlsruhe

2009 – Ph.D. From University of Karlsruhe, Germany on a novel metal/ceramic composite

2011 – Project leader at University of Karlsruhe on a project funded by German Research Foundation

2013 – Head of Materials laboratory at Kennametal Stellite at Koblenz, Germany

2015 – Senior Materials Engineer at BKW Energie AG in Bern, Switzerland

Since July 2018 – Faculty member at MME, IITKGP

Evaluation - second part of the course

- Attendance – 10 marks
  - Less than 70% - 0 marks
  - 70% - 80% - 3 marks
  - 80% - 90% - 6 marks
  - > 90% - 10 marks
  - In case of emergency absence, notification with documentary proof of the reason is mandatory to be exempted from penalty

- End semester examination – 50 marks

Expected behavior during lecture

- Attending classes is highly recommended

- Please do not talk among yourselves during lecture

- Disturbance caused by mobile phones is strictly prohibited

- Instructor can be approached at anytime for queries

Class schedule

September 2018							
N°	S	M	T	W	T	F	S
35							1
36	2	3	4	5	6	7	8
37	9	10	11	12	13	14	15
38	16	17	18	19	20	21	22
39	23	24	25	26	27	28	29
40	30						

October 2018							
N°	S	M	T	W	T	F	S
40		1	2	3	4	5	6
41	7	8	9	10	11	12	13
42	14	15	16	17	18	19	20
43	21	22	23	24	25	26	27
44	28	29	30	31			

November 2018							
N°	S	M	T	W	T	F	S
44					1	2	3
45	4	5	6	7	8	9	10
46	11	12	13	14	15	16	17
47	18	19	20	21	22	23	24
48	25	26	27	28	29	30	

Altogether 22 lectures, each of 1 hour

Topics distribution (tentative)

- Properties of materials - 4 lectures
- Concept of alloying – 1 lecture
- Physical metallurgy of steels - 5 lectures
- Common iron based alloys - 3 lectures
- Non-ferrous alloys – 2 lectures
- Manufacturing technologies - 4 lectures
- Polymers, ceramics & composites – 3 lectures

Important engineering properties of materials and common tests

Properties of materials

Technology advancement calls for development of new materials. However, the main driving force for development of new materials are properties we look for and how different materials fare!!

Steel is heavy, aluminum is light ➔Density

Ceramics break easily, metals are formable ➔Ductility

Heat is conducted much easily through metals than polymers ➔Thermal conductivity

and so on.

Classification of material properties

- Physical properties
- Mechanical properties
- Thermal properties
- Electrical properties
- Magnetic properties
- Optical properties
- Chemical properties...and so on.

Few important material properties will be briefly discussed

Content of this course

Following property classes will be discussed in this course:

- Physical property
- Mechanical property at room and high temperature
- Thermal property
- Electrical property
- Chemical property

Textbooks referred to:

- Materials Science and Engineering an Introduction – W.D.Callister
- Mechanical Behavior of Materials – T.H.Courtney

Majority of the images in this course have been collected from different textbooks and scientific documents available in internet. They are not from my own research and have been used solely here for teaching purpose

Physical property

Density

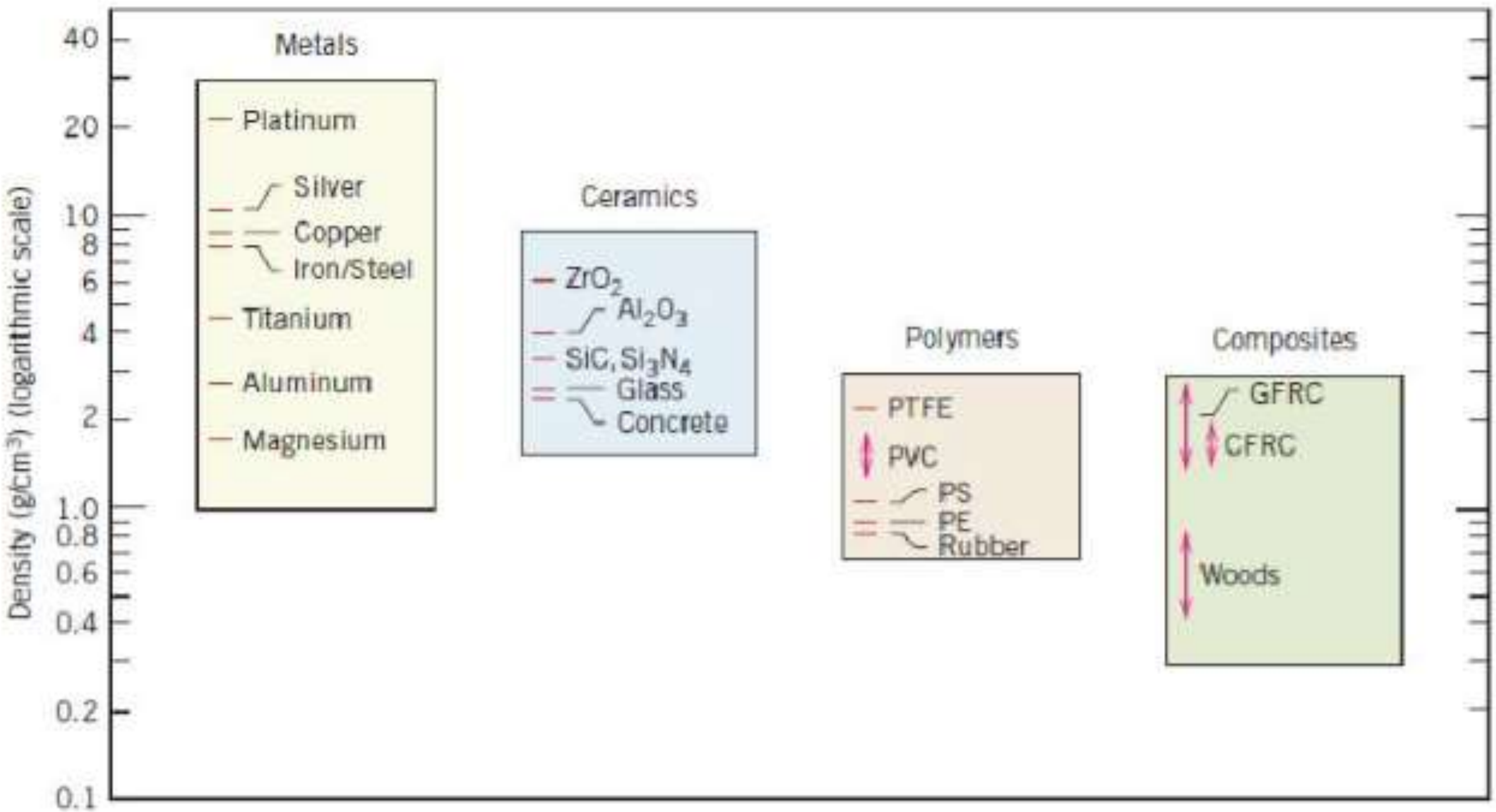
- One of the most fundamental and widely used material properties.

- Defined as (mass/volume) with units $kg.m^{-3}$, $g.cc^{-1}$ etc.

- Ideally measured by Archimedes principle *(refer to any high school book)*

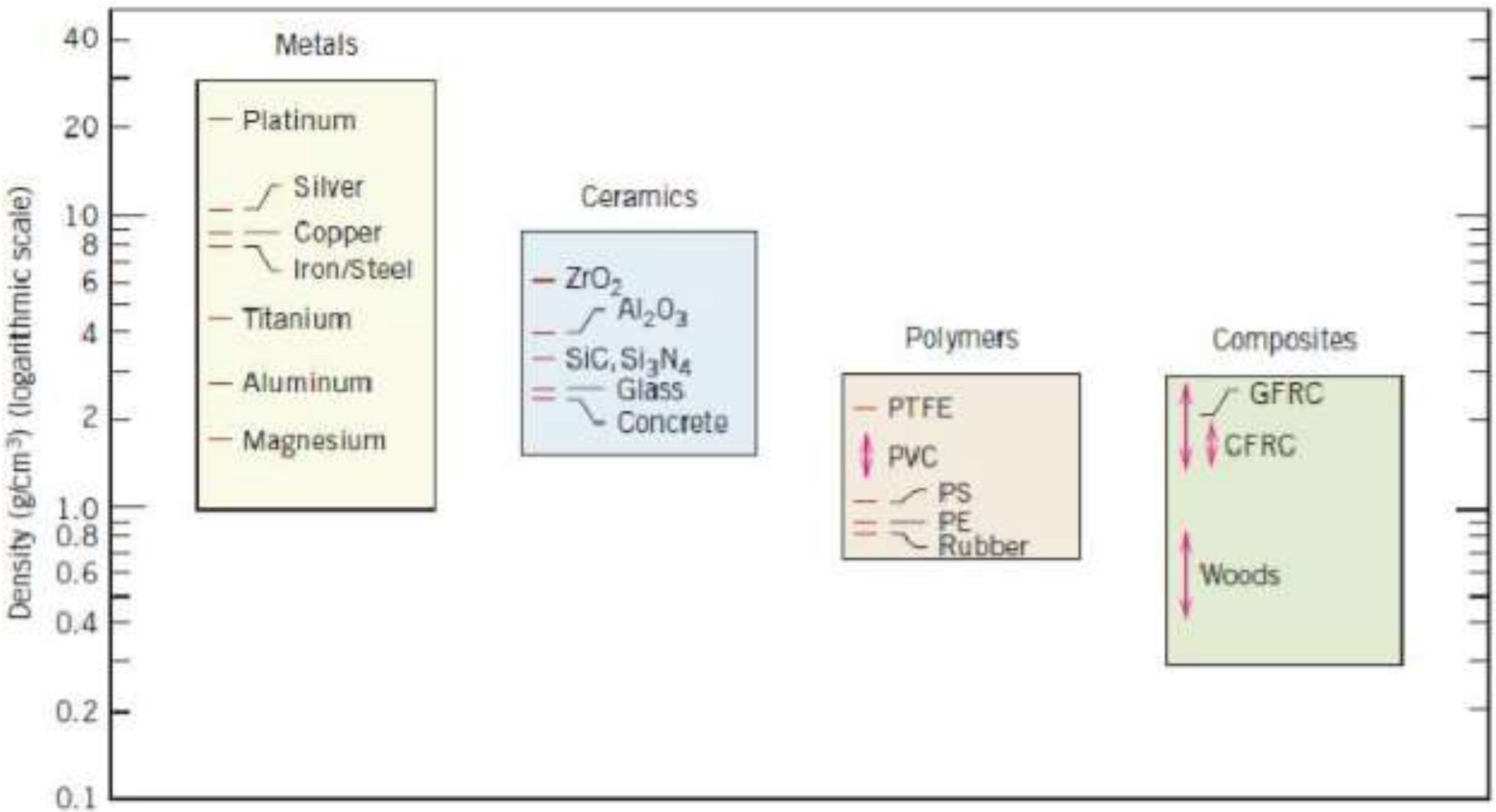
Question: What do we prefer to have, materials having high or low density?

Density



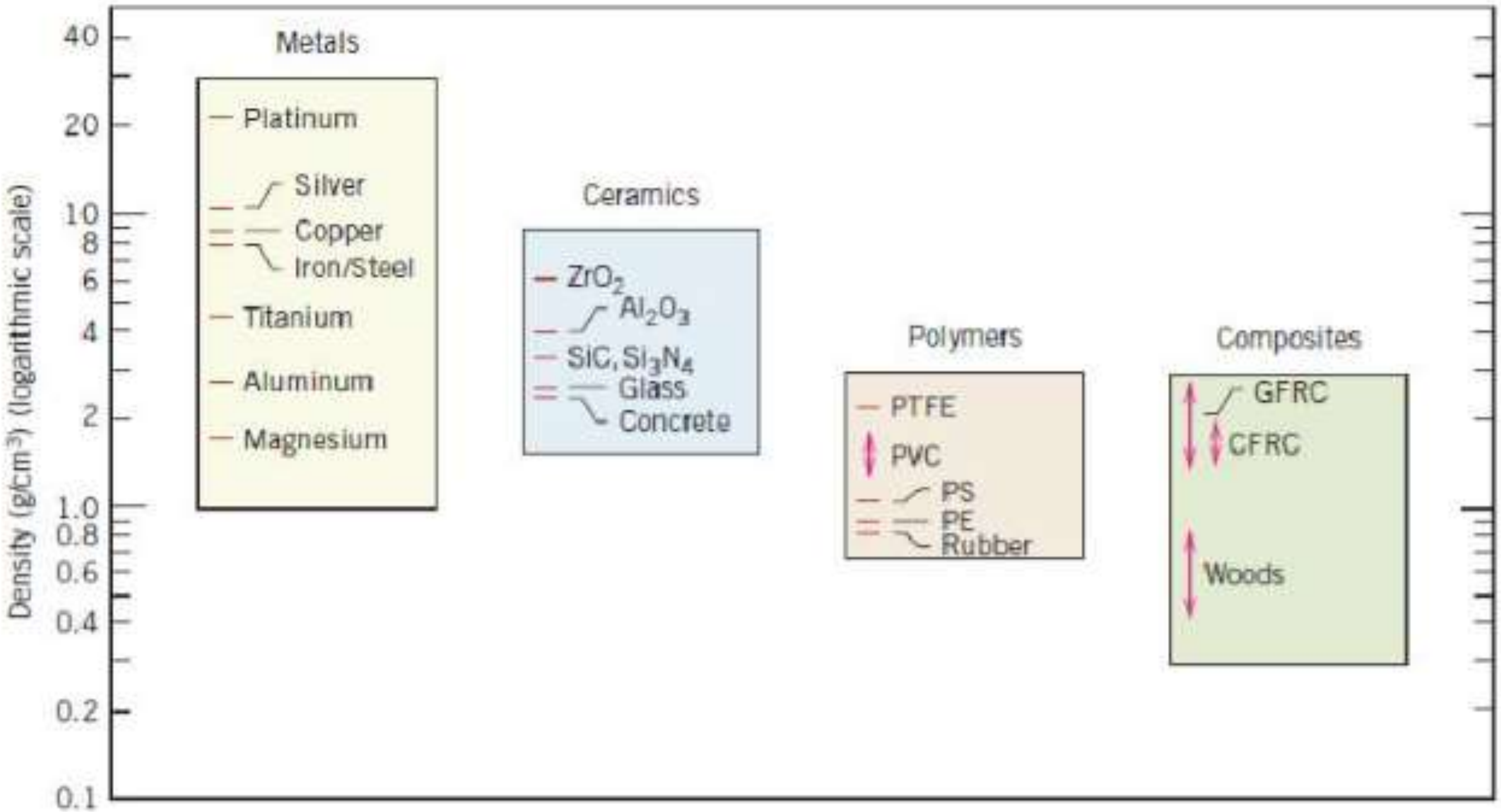
Metals normally have high density ➔
close packed, composed of high atomic weight elements

Density



Polymers have low density ➔
Mostly made of light weight elements like C and H

Density



Density of ceramics are lower than metals ➔
Contain significant amount of light elements O, N and H

Mechanical property

- Reflect to material response (i.e. deformation or failure) under externally applied load.
- Extremely important for structural integrity of any component
- Some key mechanical properties are:
  - Stiffness
  - Yield strength and tensile strength
  - Strain to failure
  - Hardness etc.
- Mechanical properties are dependent upon temperature, loading rate, part geometry, cyclic loading etc.

Concept of stress and strain

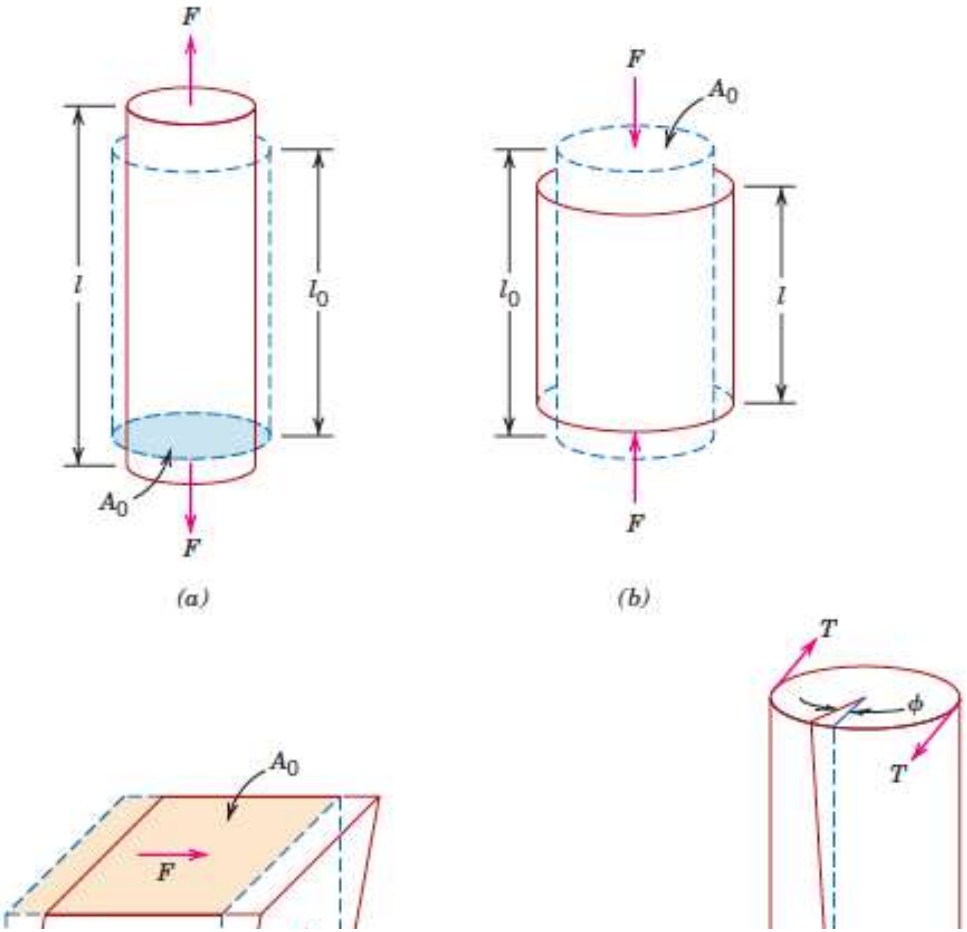
- When external load is applied on a body, it deforms
- The deformation response against applied load is geometry dependent (*high school concept*)
- To normalize this geometry effect, stress (not load) and strain (not deformation) are used
- Stress is defined as (Force/area) with units $N.mm^{-2}$, MPa etc.

$$\sigma = \frac{F}{A}$$

- Strain is defined as (length change/original length) – it is unit less

$$\epsilon = \frac{\Delta l}{l_0}$$

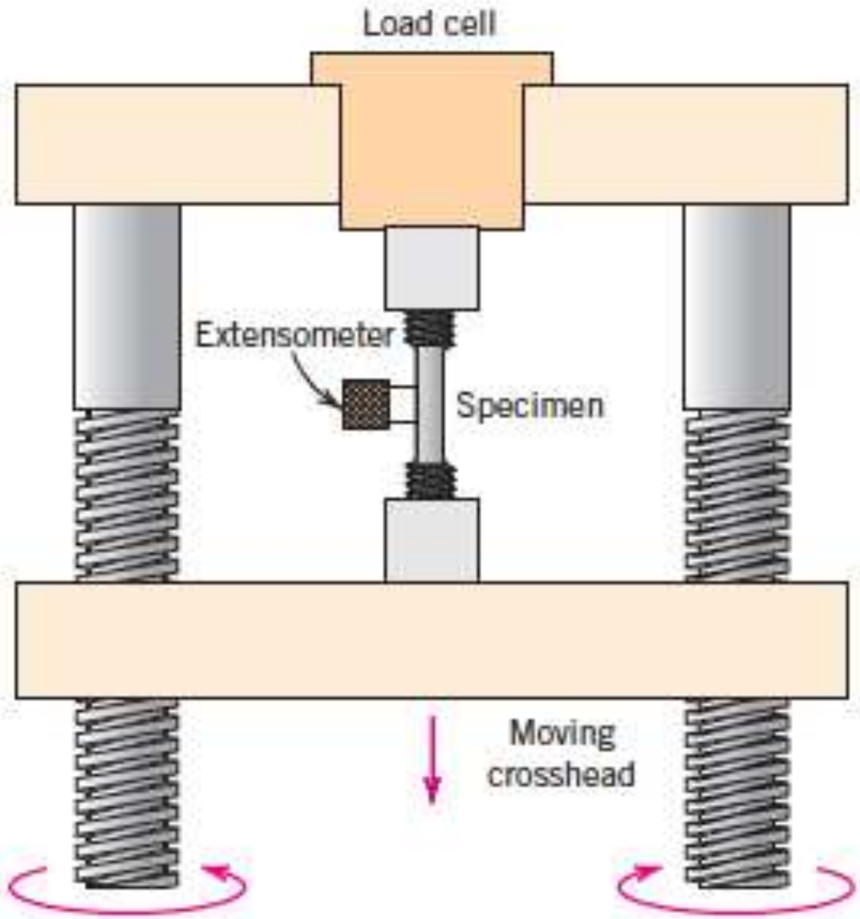
Types of loading



a) Tension
b) Compression
c) Shear
d) Torsion

Uni-axial tension test is one of the most common materials testing processes and this will be primarily studied in this course

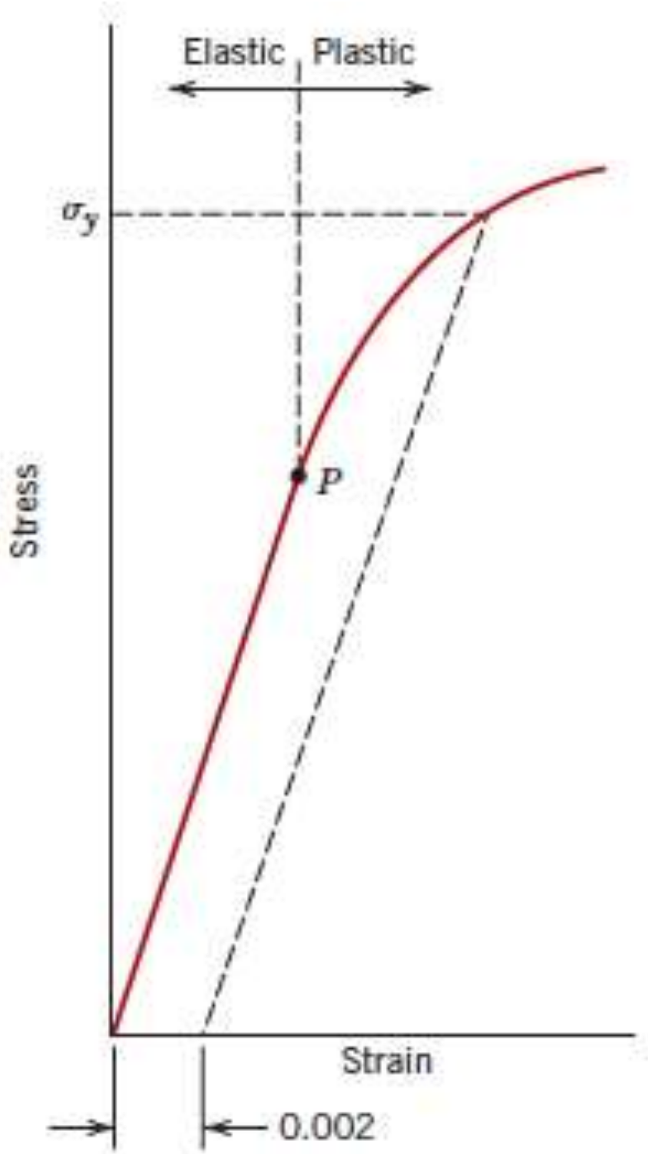
Tensile test procedure



Schematic of tensile testing machine

Typical sample geometries for tensile test

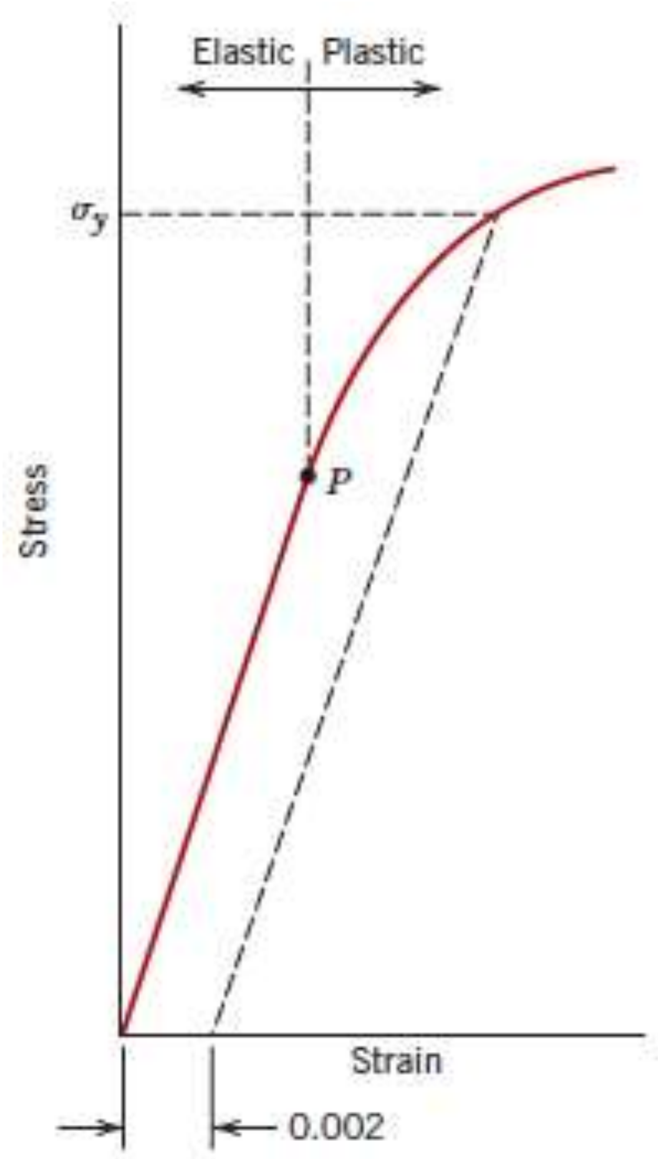
Typical tensile σ–ε behavior of metal



Elastic deformation

- Stress and strain are proportional
- Deformation is nonpermanent – when load is released, material returns to its original shape
- Elastic deformation corresponds to stretching of interatomic bonds.

Typical tensile $\sigma-\varepsilon$ behavior of metal



Plastic deformation

- Stress and strain are no more proportional
- Deformation is permanent – when load is released, material does not return to its original shape
- Plastic deformation corresponds to braking and re-forming of interatomic bonds.

Elastic deformation

Hooke‘s law

$$\sigma = E \cdot \varepsilon$$

Proportional constant E is called Young‘s modulus with unit GPa (10^6 MPa)

In case of shear loading: shear stress and shear strain are also proportional to each other in the elastic region according to the expression:

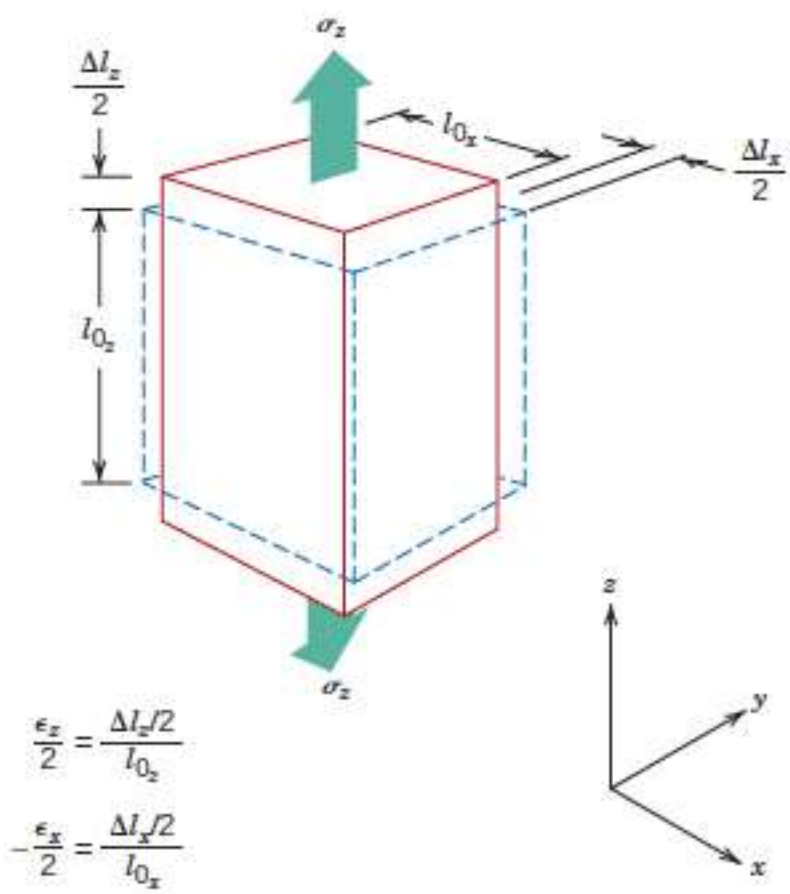
$$\tau = G \cdot \gamma$$

Proportional constant G is called shear modulus; it‘s unit is also GPa (10^6 MPa)

For most isotropic materials $G \approx 0.4E$

Elastic deformation

Poisson‘s ratio



Elastic elongation along z-axis (ε_z) causes thinning along x- and y-axes (ε_x, ε_y).

Definition of Poisson‘s ratio

$$\vartheta = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z}$$

Poisson‘s ratio is unitless and for most metals lie between 0.25 and 0.35

Elastic deformation

Material symmetry and elastic constants

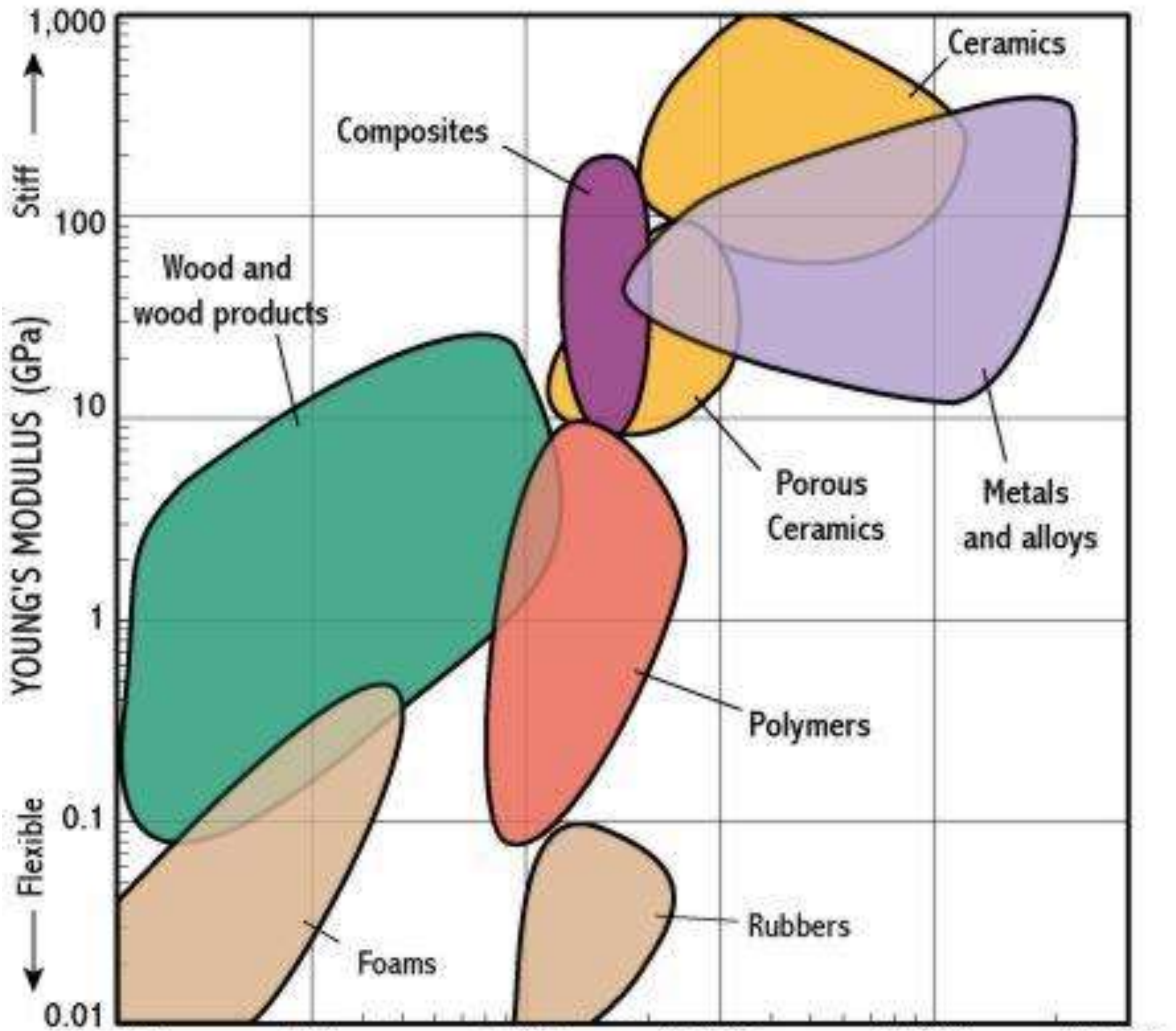
For isotropic materials:

$$E = 2G(1+\nu)$$

i.e. only two elastic constants are needed for complete characterisation. As the material symmetry decreases, more elastic constants are necessary to completely describe the elastic properties of a material.

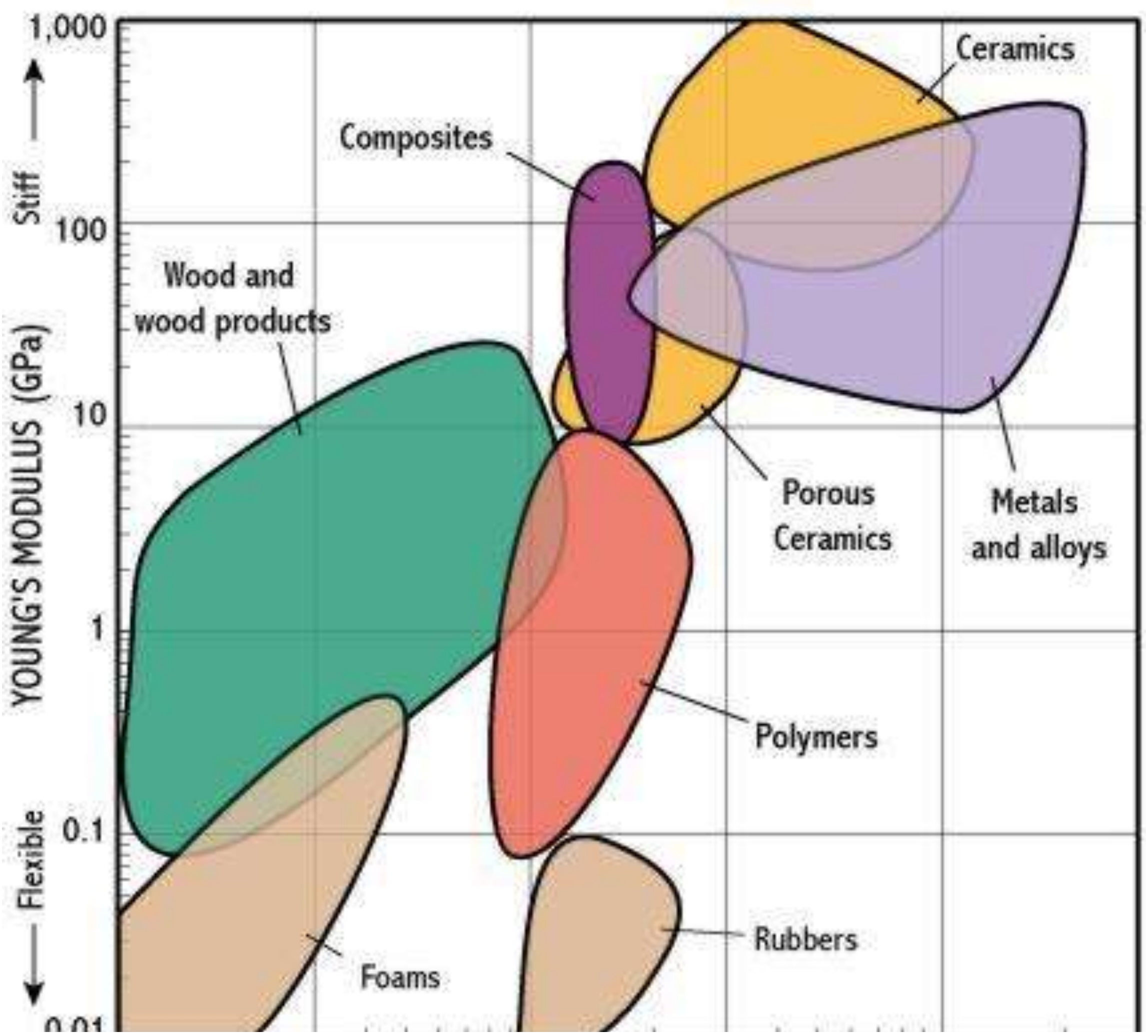
Young's modulus is a material property. It is not affected significantly by alloying or heat treatment. It decreases with increasing temperature

Elastic deformation



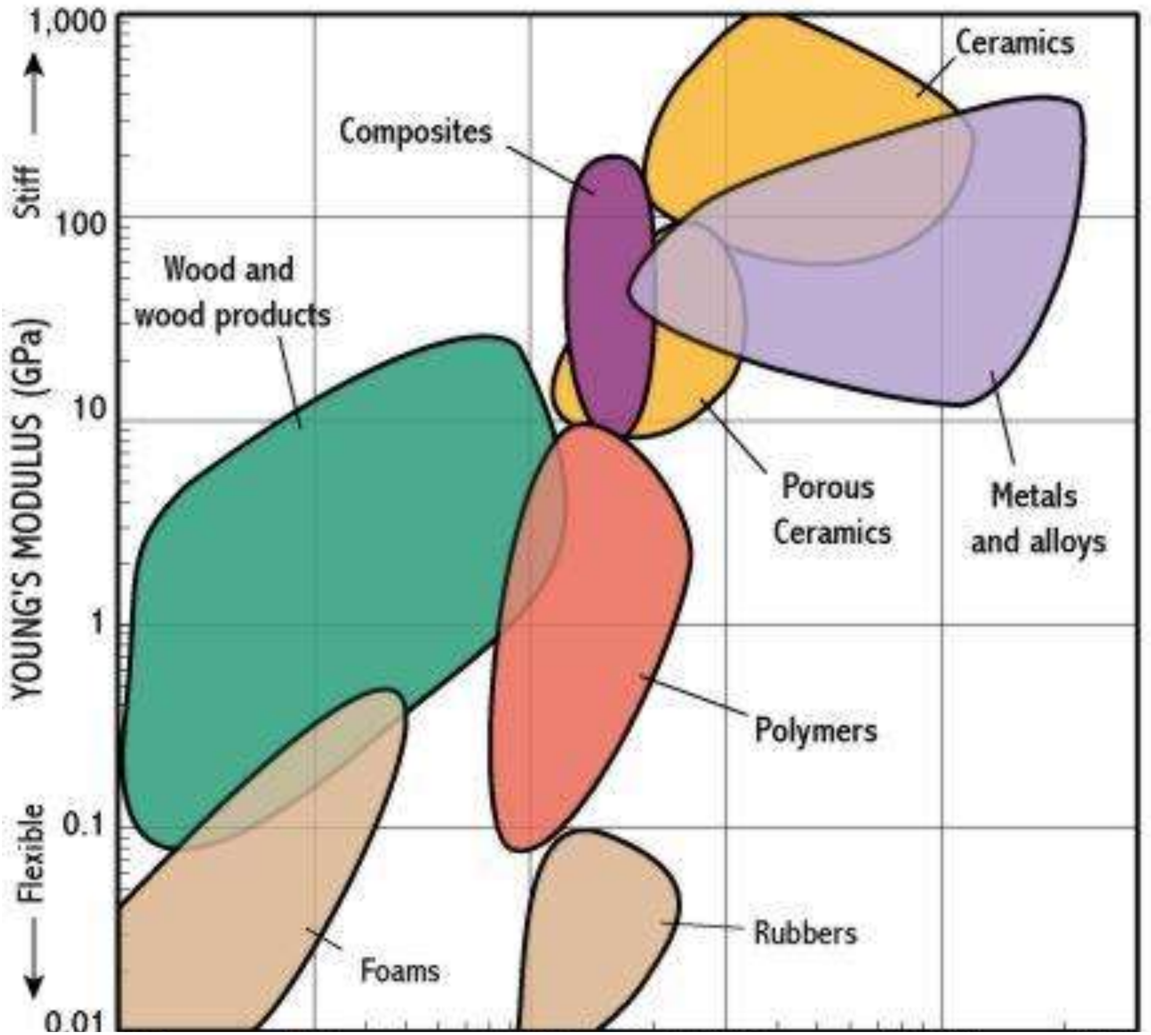
Stiffness of ceramics are highest due to the highest bond strength of covalent and ionic bonds.

Elastic deformation



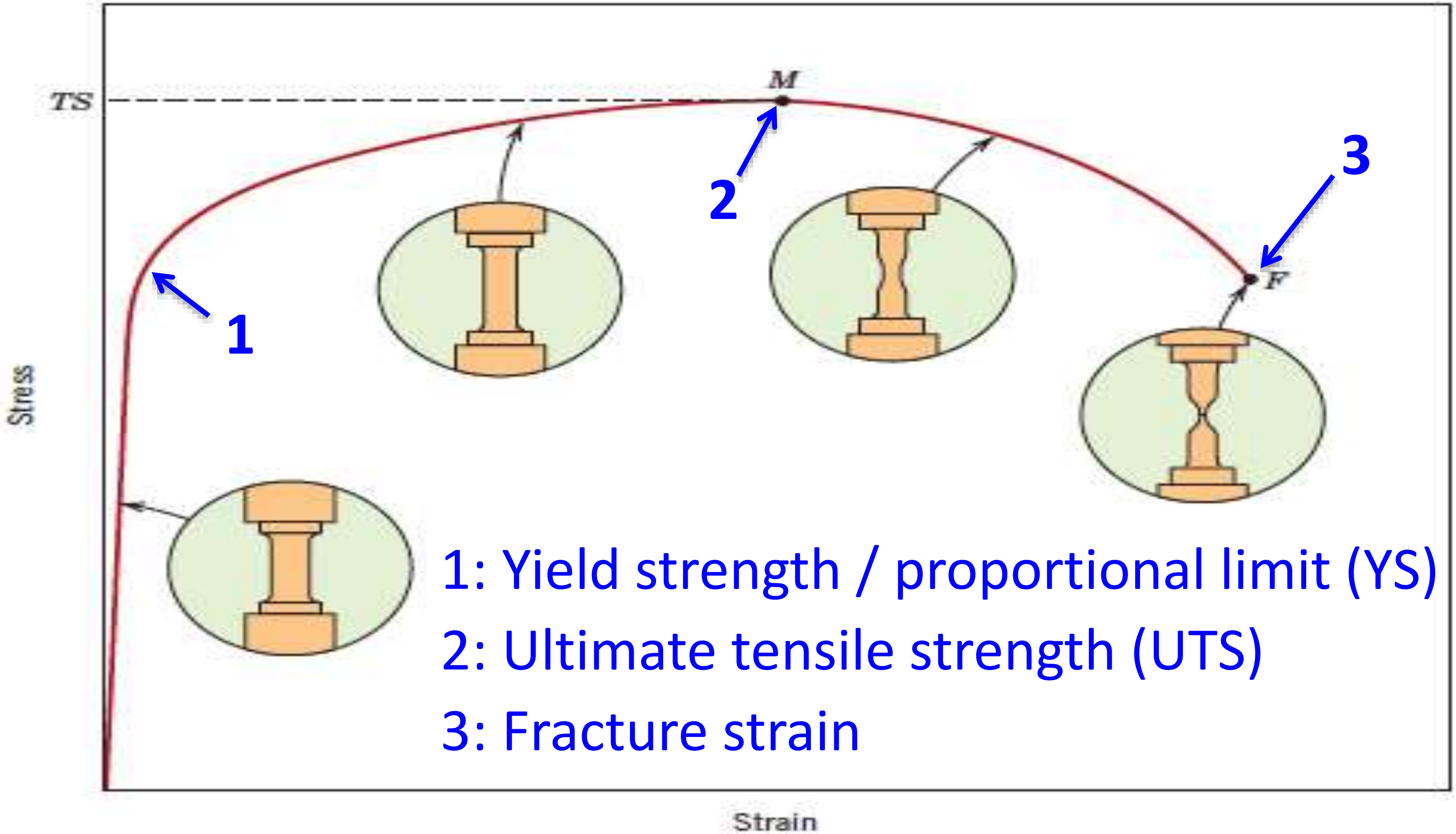
Metallic bond is weaker than covalent bond and hence metals are less stiff than stiffest ceramics

Elastic deformation



Due to the weak interchain Van-der-Waals bonds, stiffness of polymers are very low.

Plastic deformation



1: Yield strength / proportional limit (YS)

2: Ultimate tensile strength (UTS)

3: Fracture strain

Plastic deformation

Yield strength / proportional limit (σ_y)

- With increasing applied stress, the stress value at which the σ-ε plot starts deviating from linearity is defined as proportional limit.
- More conventionally, yield strength (or yield stress) is defined as the point on the σ-ε plot corresponding to a defined permanent deformation of typically 0.002 (also known as 0.2% yield stress)
- Yield strength is the material resistance against any plastic deformation.
- Strong function of alloying, heat treatment, loading rate, mechanical working etc.

Plastic deformation

Ultimate tensile strength (UTS)

- After yielding, with further deformation, the stress necessary increases continuosly – strain hardening
- Highest (engineering) stress sustained by the material in tension test is defined as ultimate tensile strength (UTS).
- The deformation of the sample is uniform throughout the gauge length until UTS.
- At UTS, a neck starts developing at some location of the gauge length and all further deformation is localised in this region
- Ultimate fracture occurs at the neck.

Plastic deformation

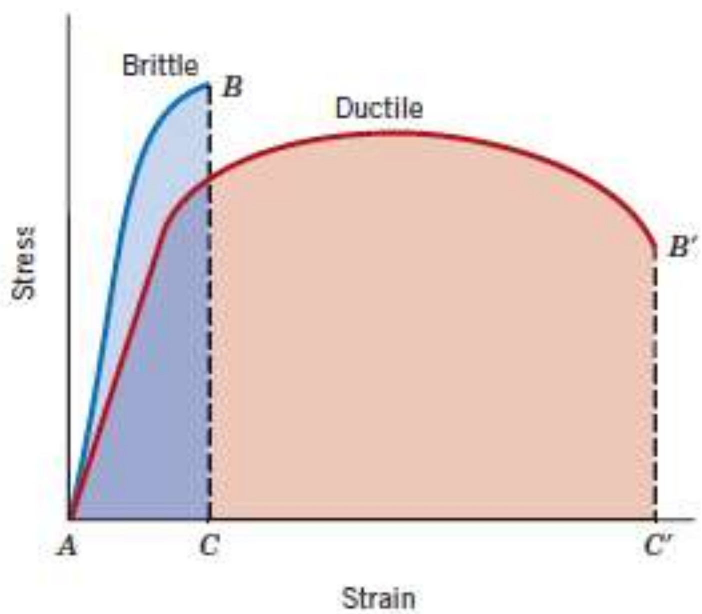
Fracture strain (ε_f)

- Defined as the elongation of the sample until fracture occurs

$$\varepsilon_f = \frac{l_f - l_0}{l_0}$$

l_f = final sample length at fracture

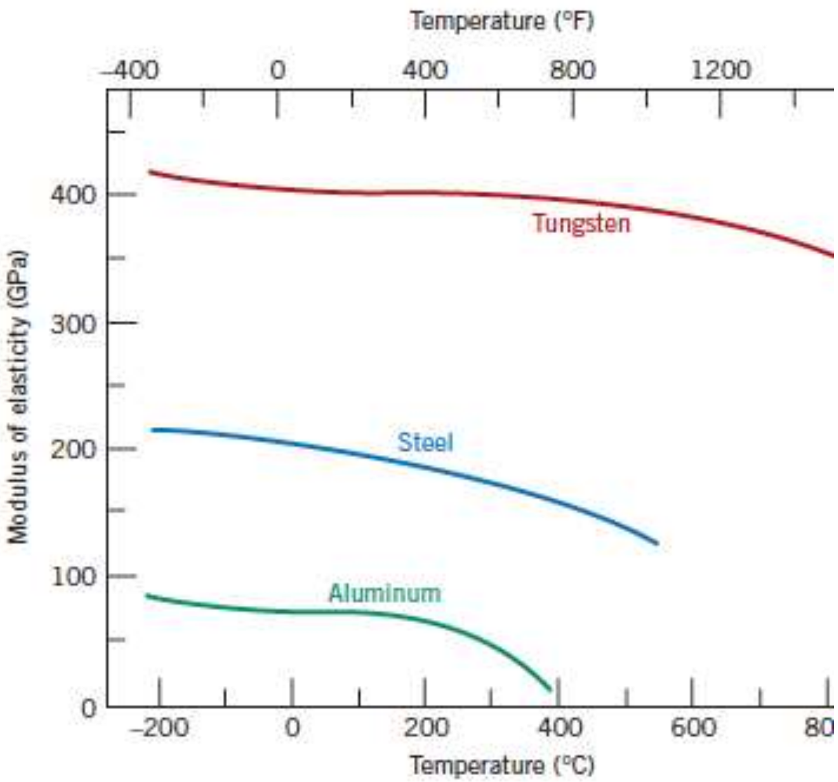
l_o = initial sample length

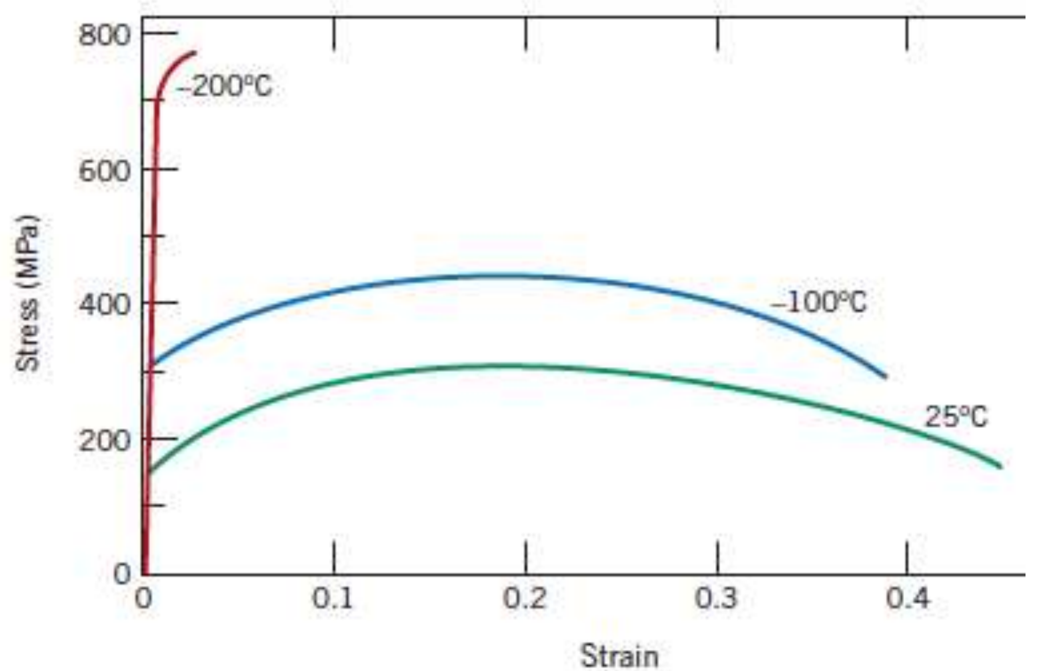


Brittle materials experience limited or less plastic deformation

ε_f is a strong function of alloying, heat treatment, temperature, loading rate etc.

Effect of temperature





As Test temperature increases,

- Young's modulus decreases
- Yield strength decreases
- Ultimate tensile strength decreases
- Strain to failure increases

True stress and true strain

Stress – strain definitions based on original sample cross-section and length are known as engineering stress and strain, respectively.

If however instantaneous area and sample length are considered ➔true stress, true strain

Relation between true and engineering stress and strain

$$\sigma_T = \sigma_E(1 + \varepsilon_E)$$

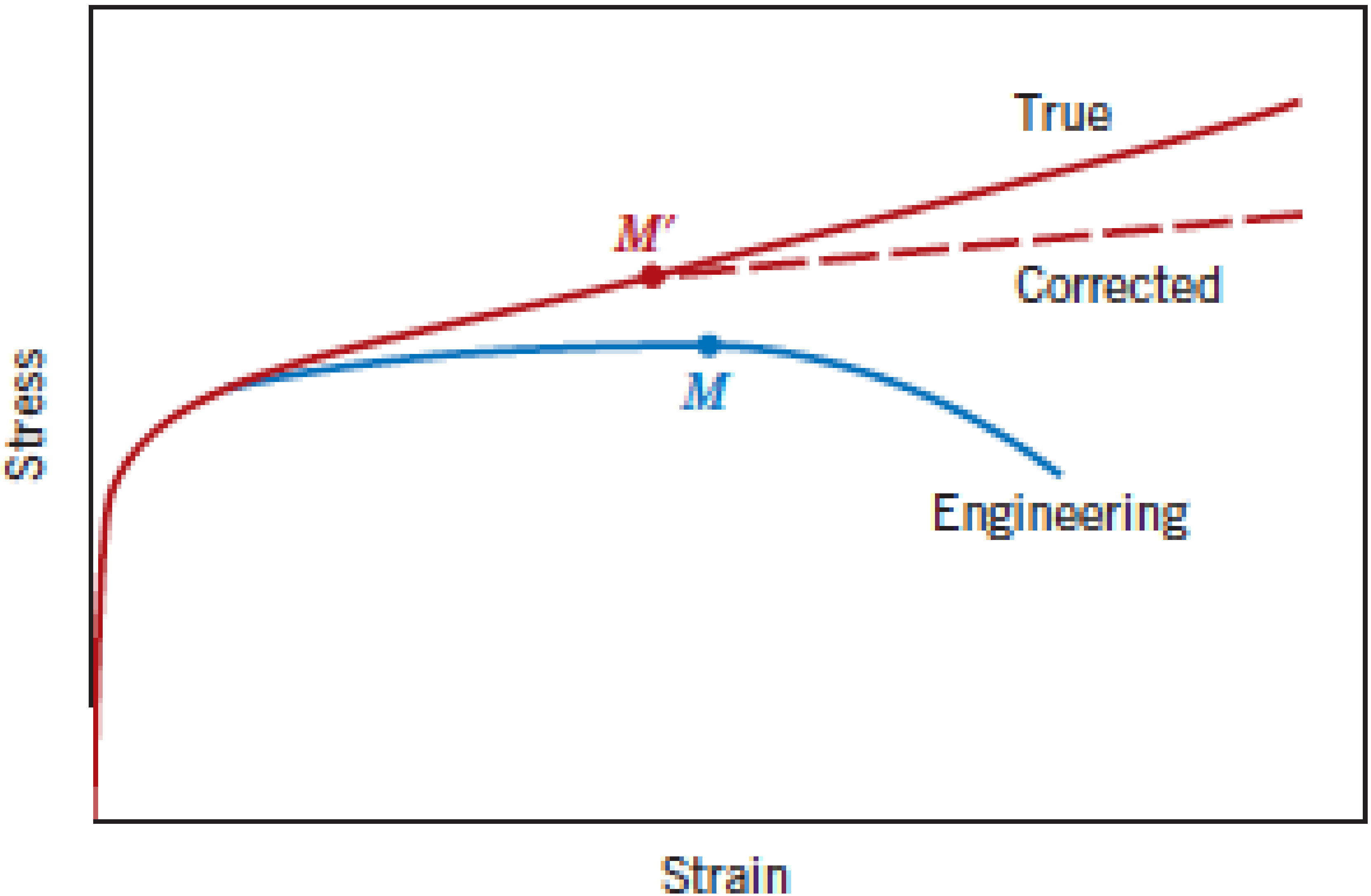
$$\varepsilon_T = ln(1 + \varepsilon_E)$$

σ_T, ε_T: True stress and true strain

σ_E, ε_E: Engineering stress and strain

These relationships are valid only until the onset of necking

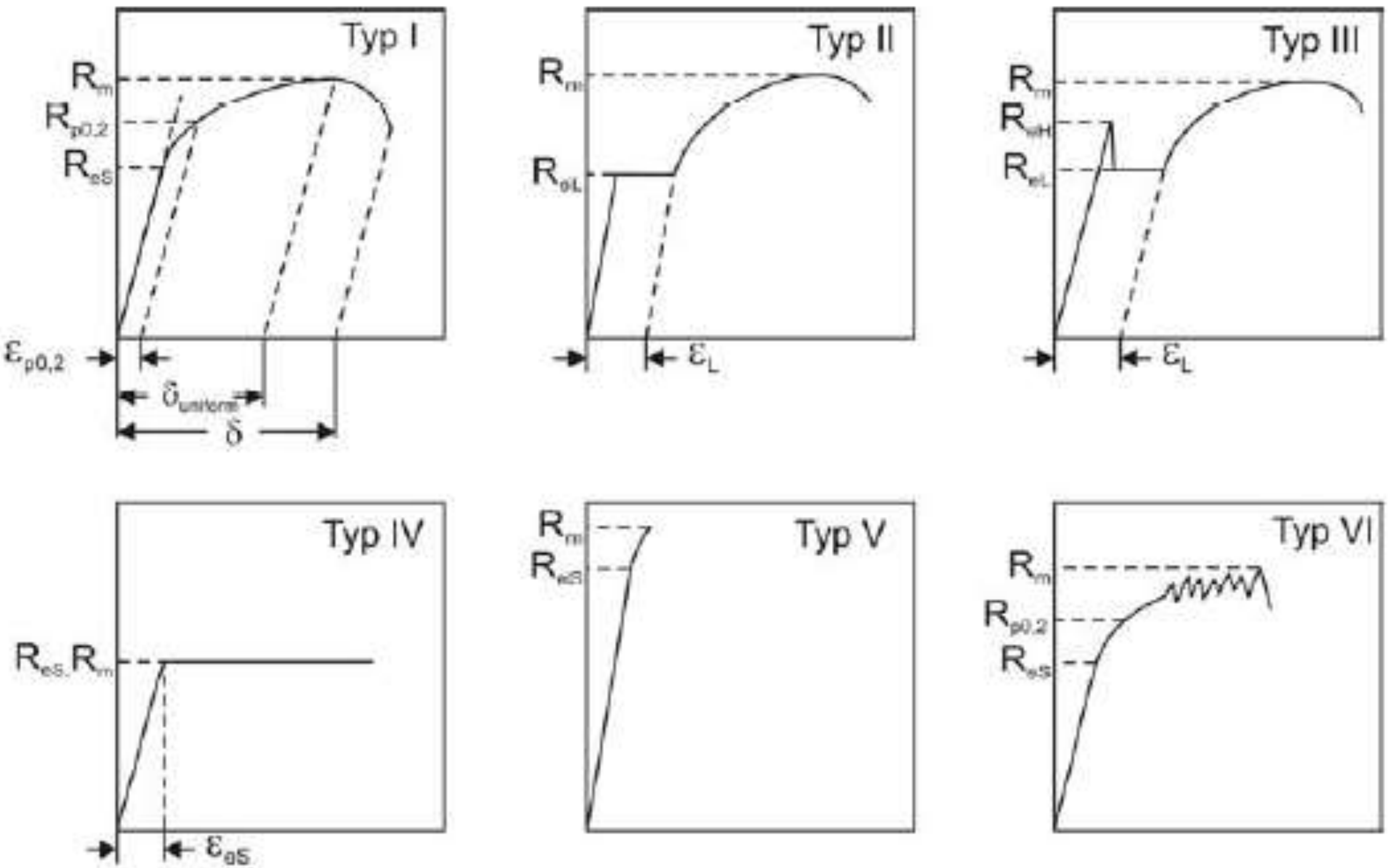
True and engineering σ–ε plots



True and engineering $\sigma-\varepsilon$ plots

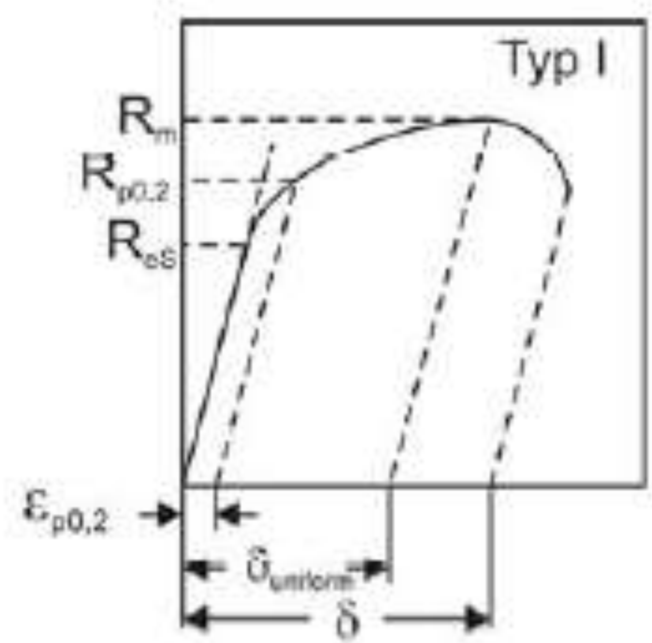
- At necking, local cross-sectional area decreases, hence lesser load is necessary to sustain deformation ➔engineering σ-ε plot drops off
- In reality, the material strain hardens until fracture
- True σ-ε plot, calculated based on instantaneous area and cross-section, increases continuously until material fracture ➔it reflects the real material behavior

Characteristic σ-ε plots for metals



Characteristic σ-ε plots for metals

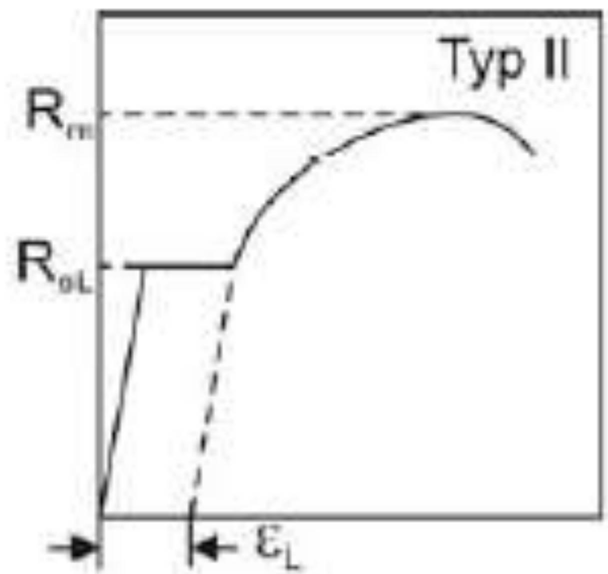
Typ I



Continuous transition from elastic to plastic deformation. Typically observed in fcc metals and their alloys like aluminum, nickel, copper, austenitic stainless steel etc.

Characteristic σ-ε plots for metals

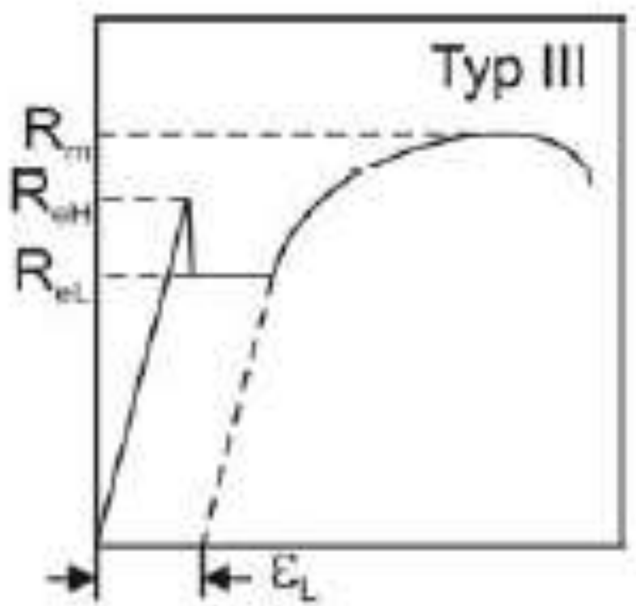
Typ II



Characterized by the presence of lower yield point and an almost horizontal region.
Sporadically observed in some solid solution strengthened Cu- and Al-based alloys

Characteristic σ-ε plots for metals

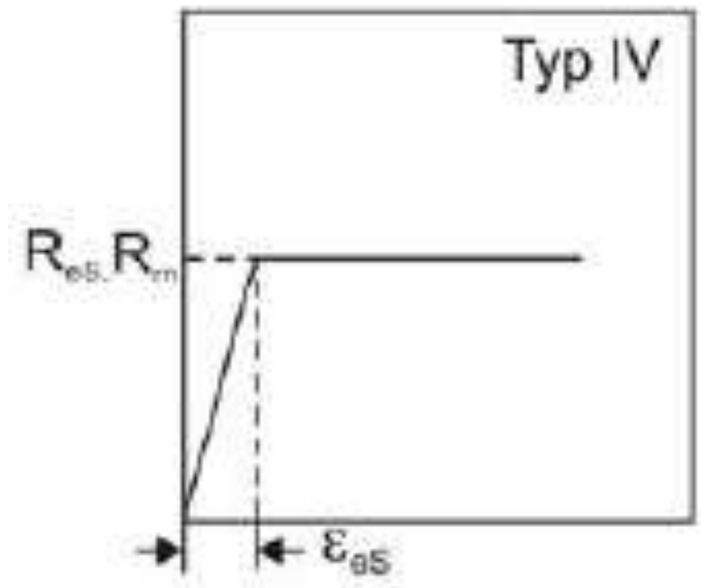
Typ III



Characterized by both upper and lower yield point followed by almost horizontal region.
Typically observed in low carbon steels

Characteristic σ-ε plots for metals

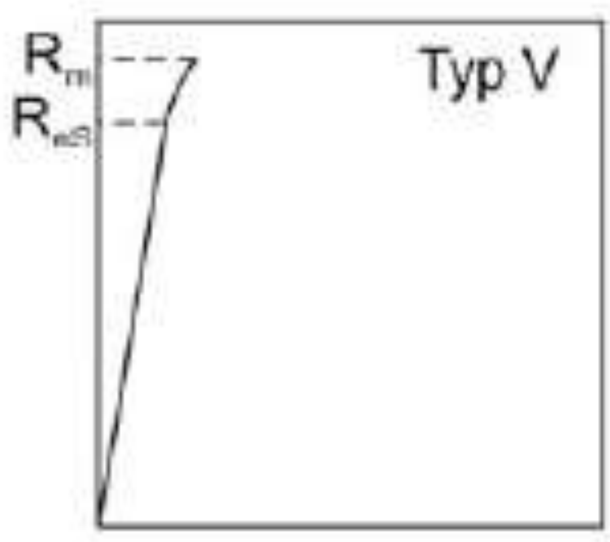
Typ IV



Characterized by elastic, ideal plastic behavior with little or no strain hardening.
Sporadically observed in heavily pre-worked materials and in certain materials deformed at high temperatures.

Characteristic σ-ε plots for metals

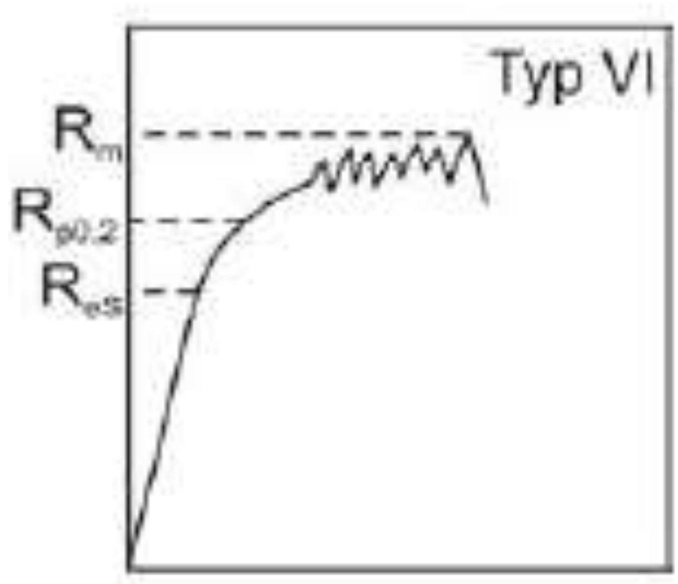
Typ V



Characterized by almost brittle behavior with little plastic strain, no necking.
Observed in alloyed and unalloyed steel in martensitic condition

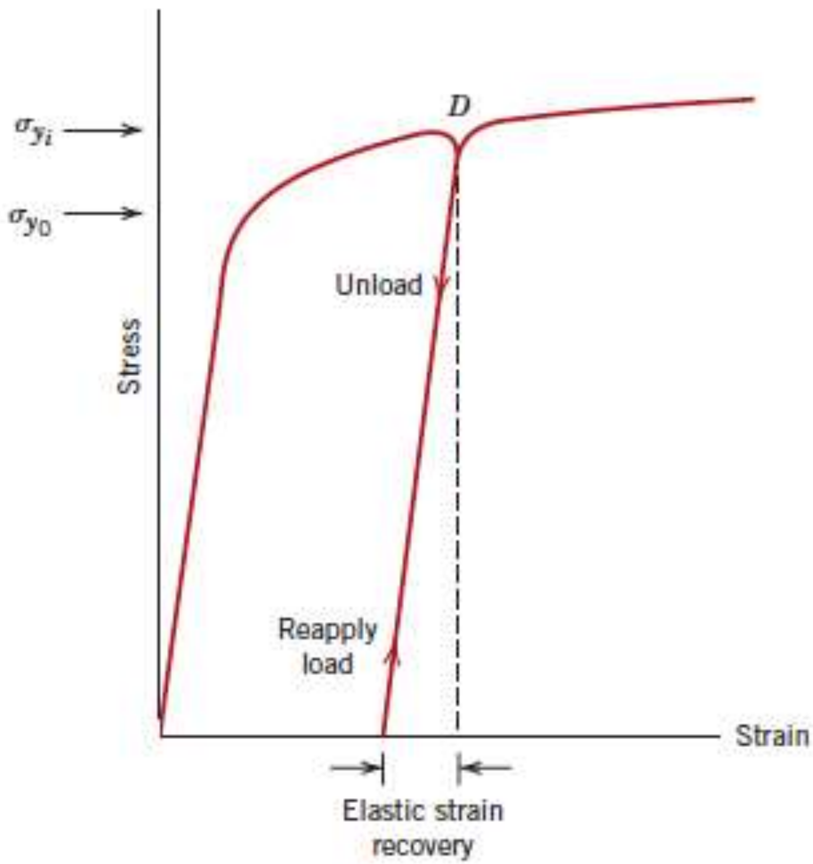
Characteristic σ-ε plots for metals

Typ VI



Characterized by serrated stress-strain curves.
Typically observed plain carbon steels in the temperature range of 250–400 °C

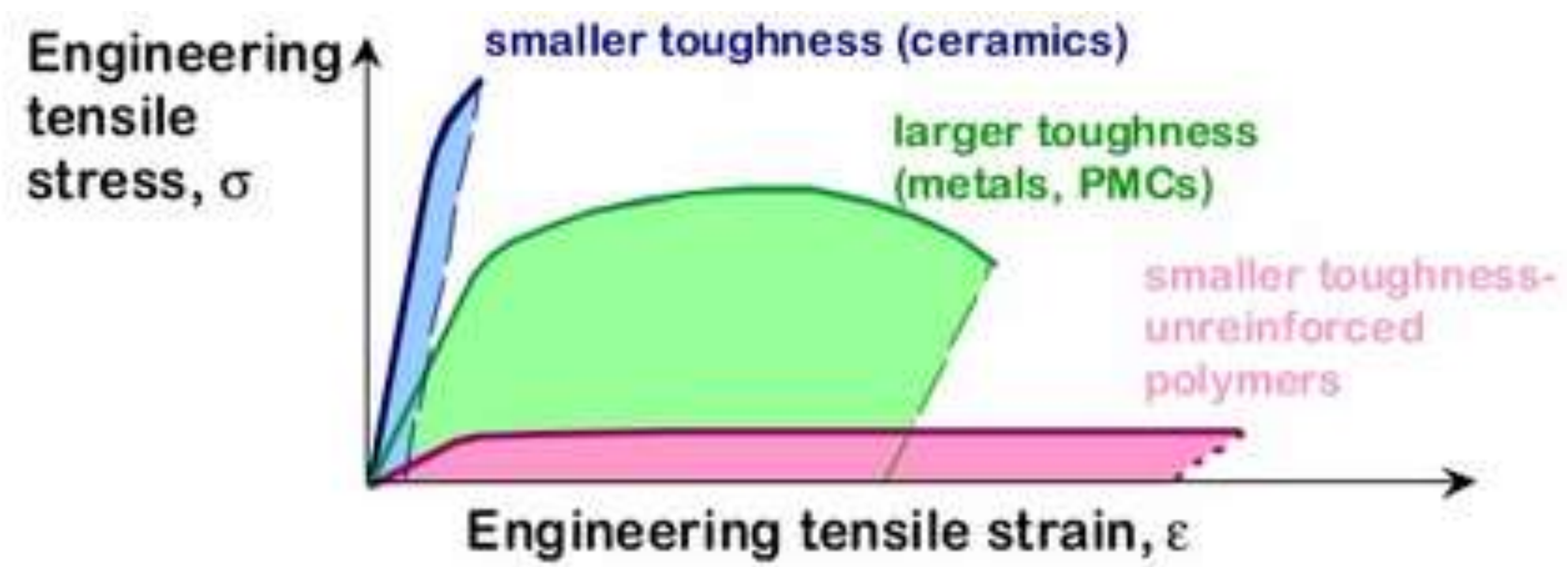
Un- and reloading in plastic region



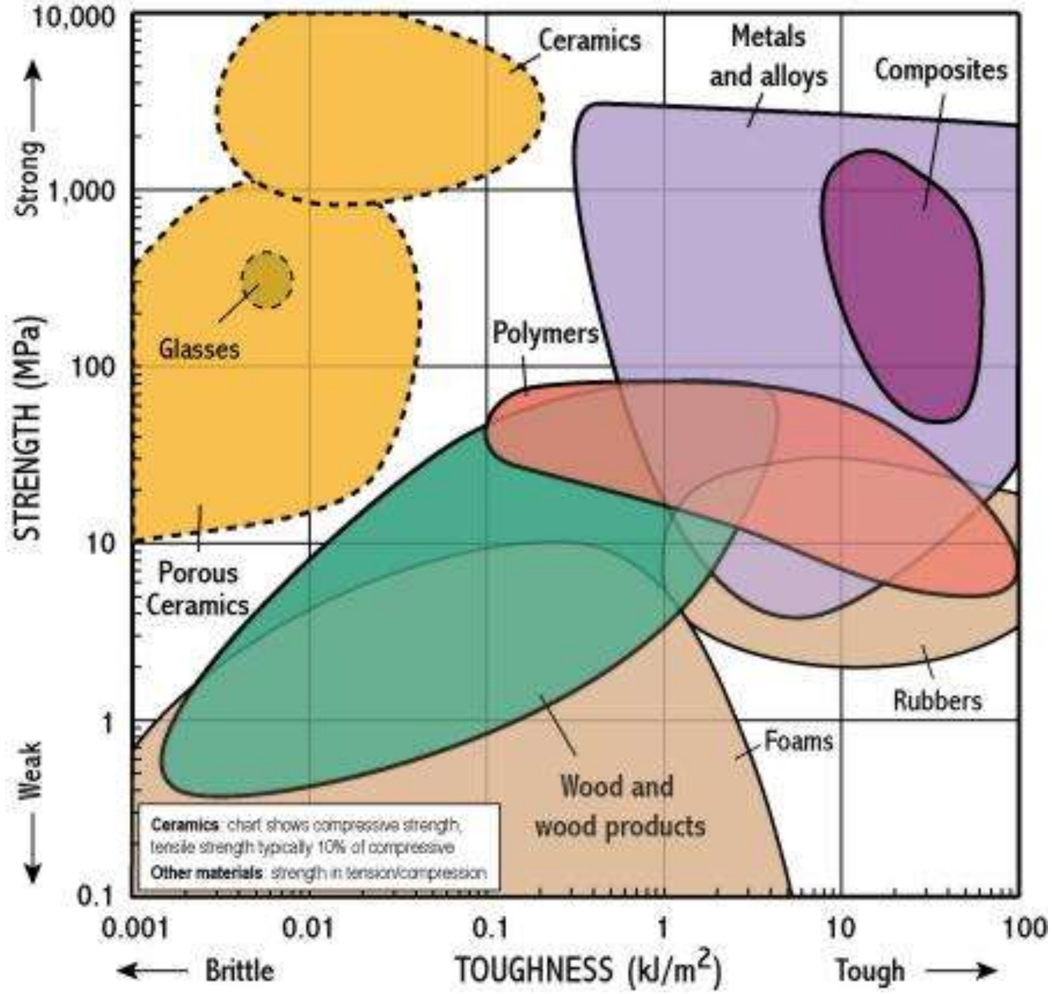
- Unloading in plastic region traces a straight line with slope virtually equal to the loading Young‘s modulus.
- Elastic portion of the total strain is recovered
- Reapplication of load traverses the same path as during unloading
- Yielding at reloading occurs at the initial unloading stress level

Toughness

- Toughness is the ability of a material to absorb energy before fracturing
- It is the area under the σ-ε plot upto the point of fracture



Toughness



Question: Why are metals more popular than ceramics as structural components?

Lecture 2

Hardness testing

Defined as resistance of a material against localized plastic deformation (indentation or scratch).

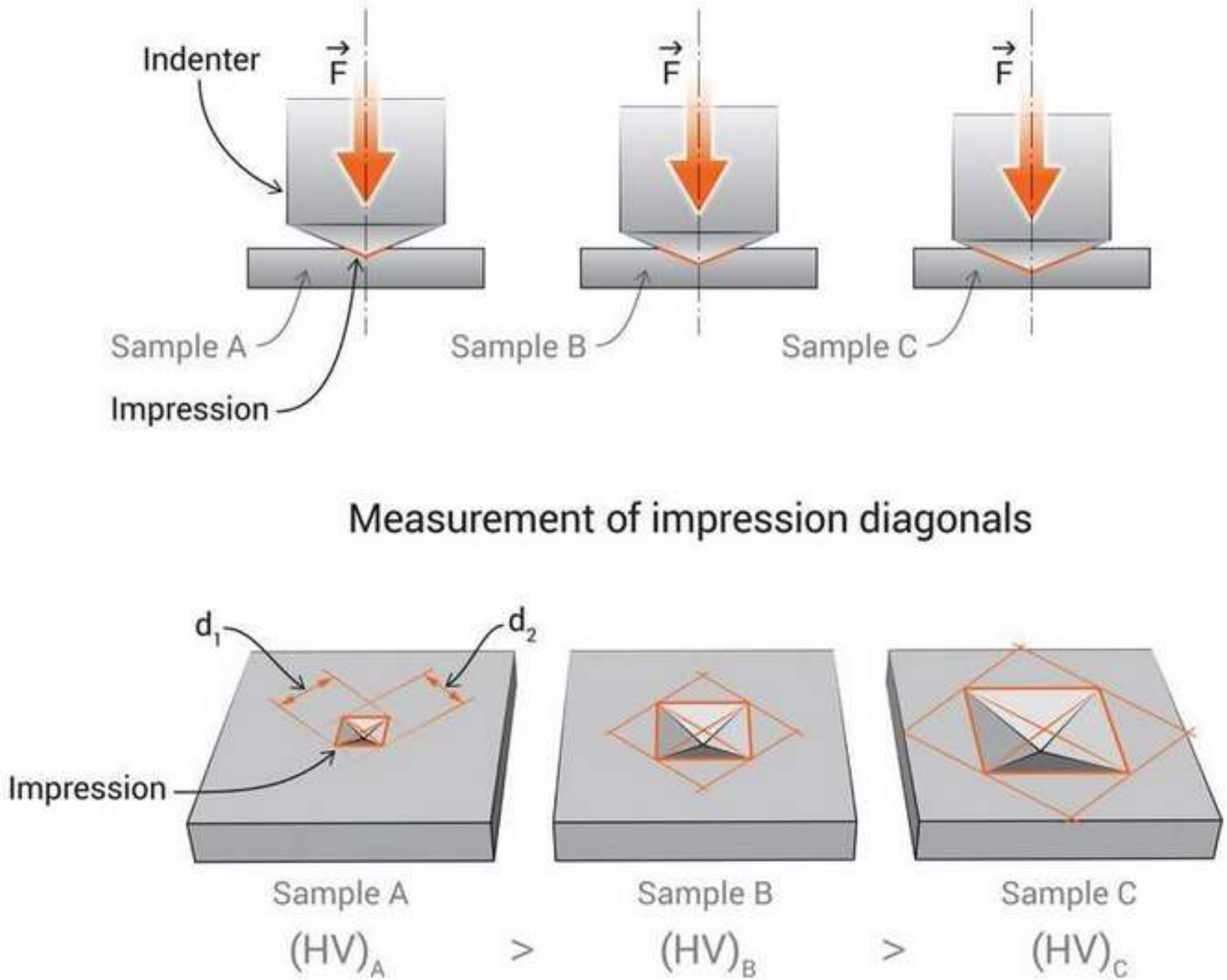
Basic principle

- An indenter is forced into the test surface under controlled loading conditions
- Depth/size of the indentation is measured and hardness is calculated therefrom

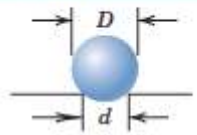
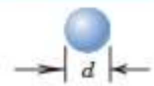
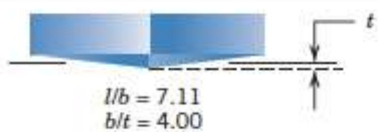
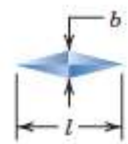
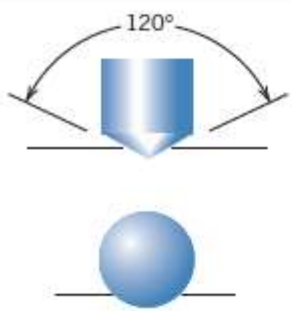
Most used materials analysis technique, because:

- Simple, inexpensive – no special sample preparation
- The procedure is quasi non-destructive
- Can often be easily correlated to other material properties like tensile strength

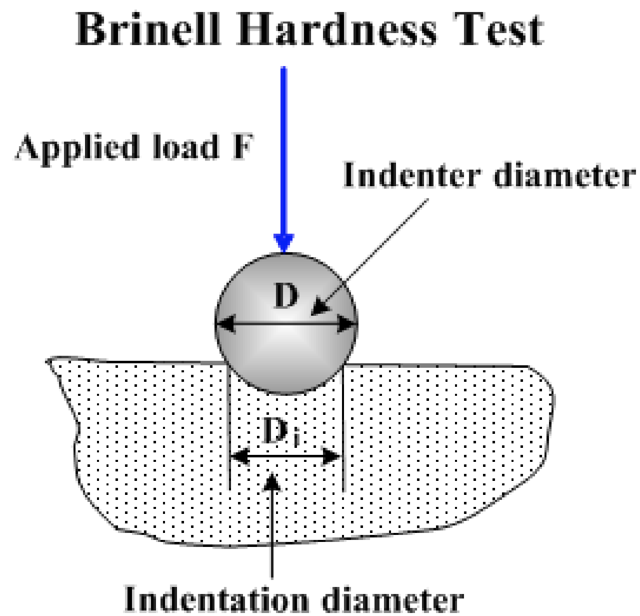
Schematic of typical hardness test



Different hardness test methods

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	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid			P	$HK = 14.2P/l^2$
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	

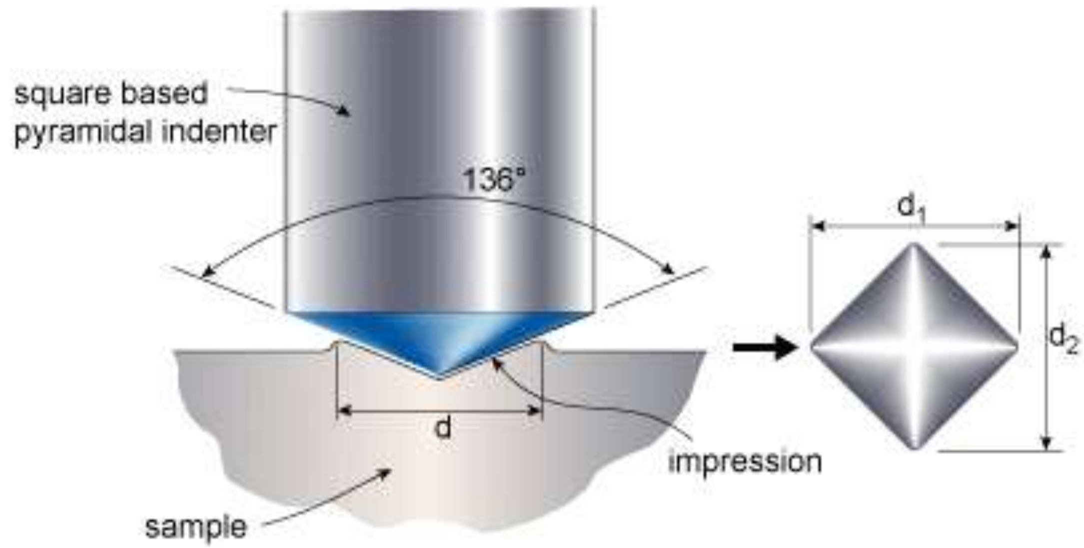
Brinell hardness test



- Hard, spherical indenter made of either hardened steel or tungsten carbide is used
- Standard loads range between 500 and 3000 kg in 500 kg intervals.
- After load application for a specific time, the indentation diameter is measured using low power microscope
- Hardness (denoted as BHN) is calculated using load, indenter and indentation diameter

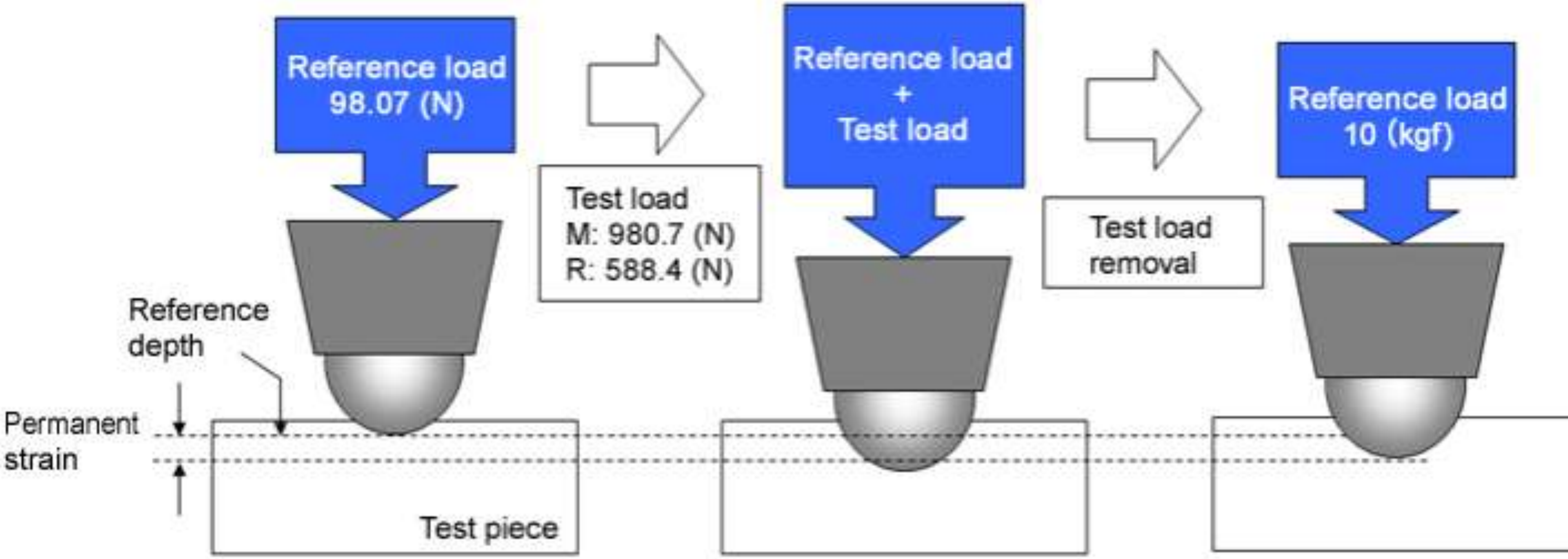
Vickers hardness test

- Indenter is a square based diamond pyramid.
- Careful sample preparation is necessary.



- Applied loads usually vary between 1 kg. And 120 kg.
- Lengths of the two diagonals of the indenter are measured under a microscope
- Vickers hardness (VHN or DPH) is calculated from the applied load and the measured average length of the two indentation diagonals

Rockwell hardness test



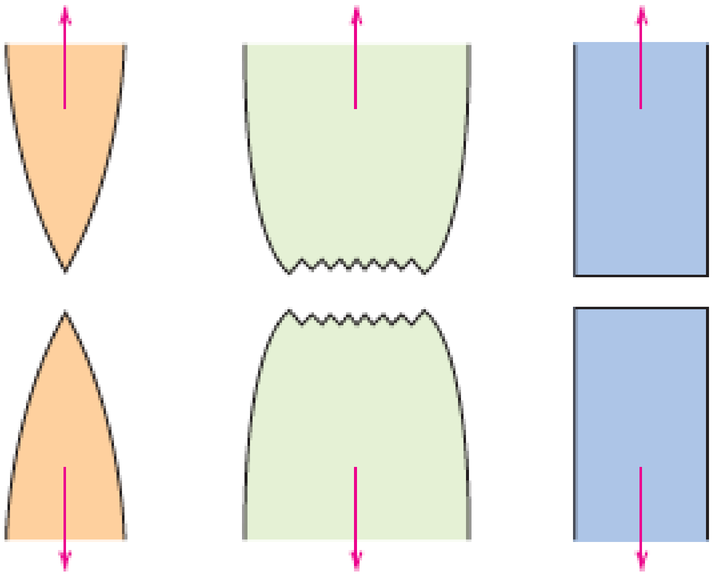
- ➢ Most common method due to ist simplicity
- ➢ Several scales based on indenter type and load are used
- ➢ A unitless hardness number is determined from the difference of depth of penetration resulting from a minor load and subsequent major load

Fracture

Fracture is defined as the separation of a body into two or more parts in response of an external load. Fracture is the ultimate failure of a component and design should avoid it.

Modes of fracture in metals

Ductile fracture: Involves substantial plastic deformation with high energy absorption before fracture



Brittle fracture: Involves little or no plastic deformation with very little energy absorption.

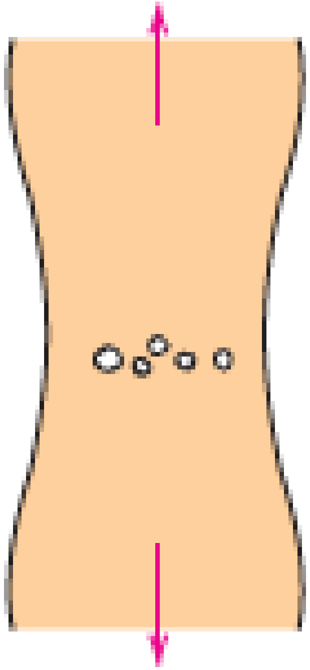
Ductile fracture

The most common feature of ductile fracture is the appearance of a moderate to significant amount of necking

Stages of ductile fracture

Stage I

After the initiation of necking, small cavities or microvoids form at local inhomogeneities at the neck region.



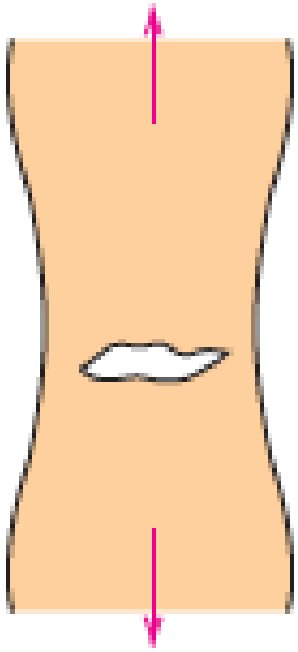
Ductile fracture

The most common feature of ductile fracture is the appearance of a moderate to significant amount of necking

Stages of ductile fracture

Stage II

With continuing deformation the microvoids grow and coalesce to form elliptical crack with long axis normal to loading direction.



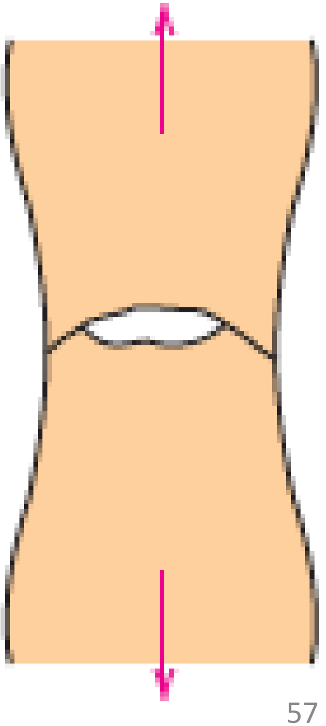
Ductile fracture

The most common feature of ductile fracture is the appearance of a moderate to significant amount of necking

Stages of ductile fracture

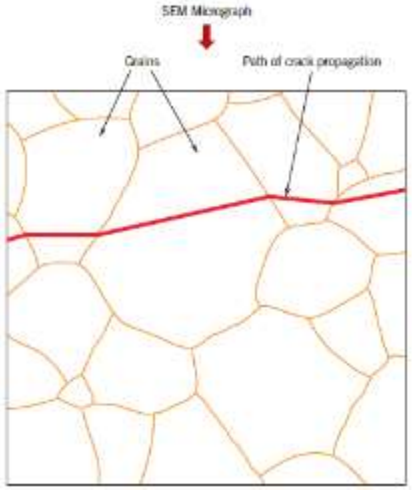
Stage III

Final fracture occurs by rapid propagation of the crack around the outer periphery of the neck by shear deformation at an angle of 45° with the tensile axis.



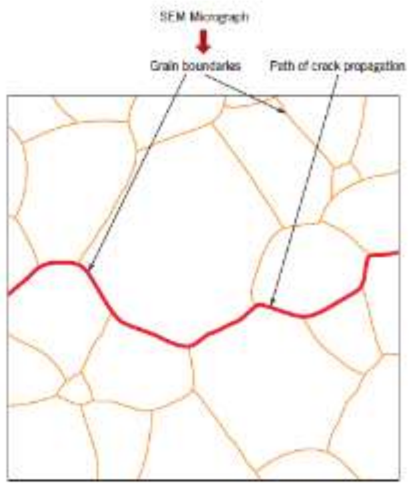
Brittle fracture

The direction of crack propagation is nearly perpendicular to the direction of applied stress. Fracture surfaces are macroscopically flat and shiny.



Broad classes of brittle fracture

Transgranular fracture: The cracks pass through grains with little or no change of direction



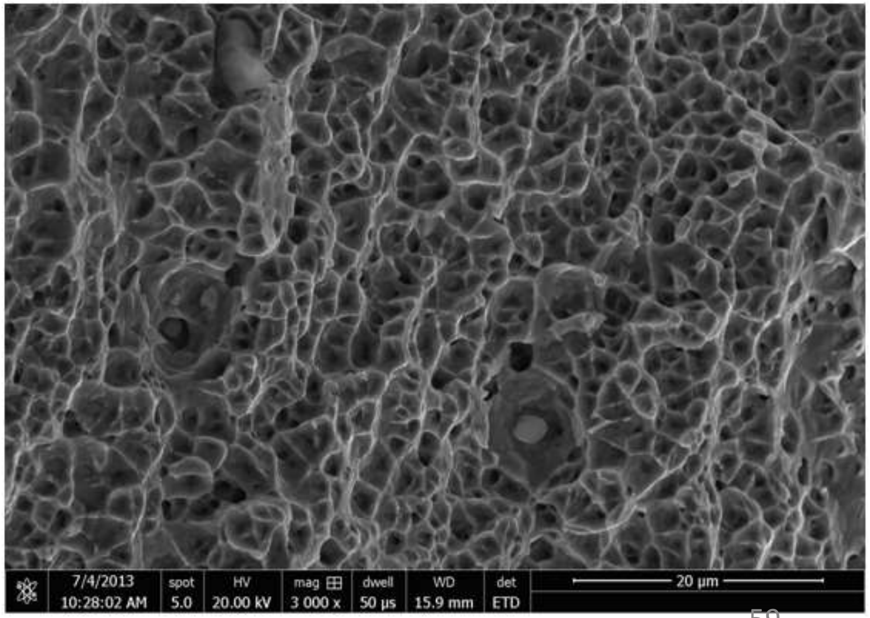
Intergranular fracture: Crack propagation occurs mostly along the grain boundaries

Fractography

Detailed study of the microscopic features of the fracture process, normally using scanning electron microscope (SEM). SEM is used due to its higher resolution and depth of field.

Fractographic appearance of ductile fracture

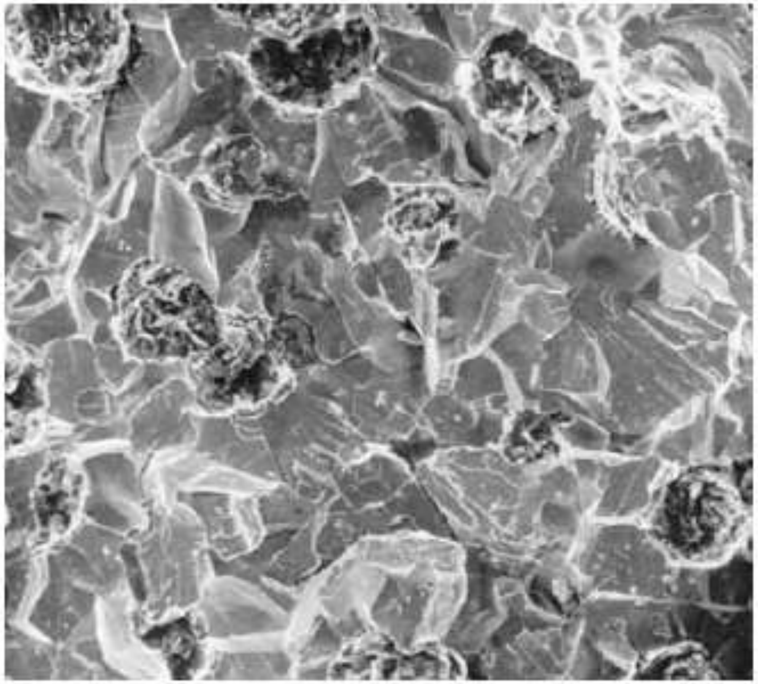
- Fracture surface consists of numerous spherical dimples
- Each dimple correspond to one half of a microvoid formed before crack nucleation



Fractography

Detailed study of the microscopic features of the fracture process, normally using scanning electron microscope (SEM). SEM is used due to its higher resolution and depth of field.

Fractographic appearance of brittle transgranular fracture



Fractography

Detailed study of the microscopic features of the fracture process, normally using scanning electron microscope (SEM). SEM is used due to its higher resolution and depth of field.

Fractographic appearance of brittle intergranular fracture

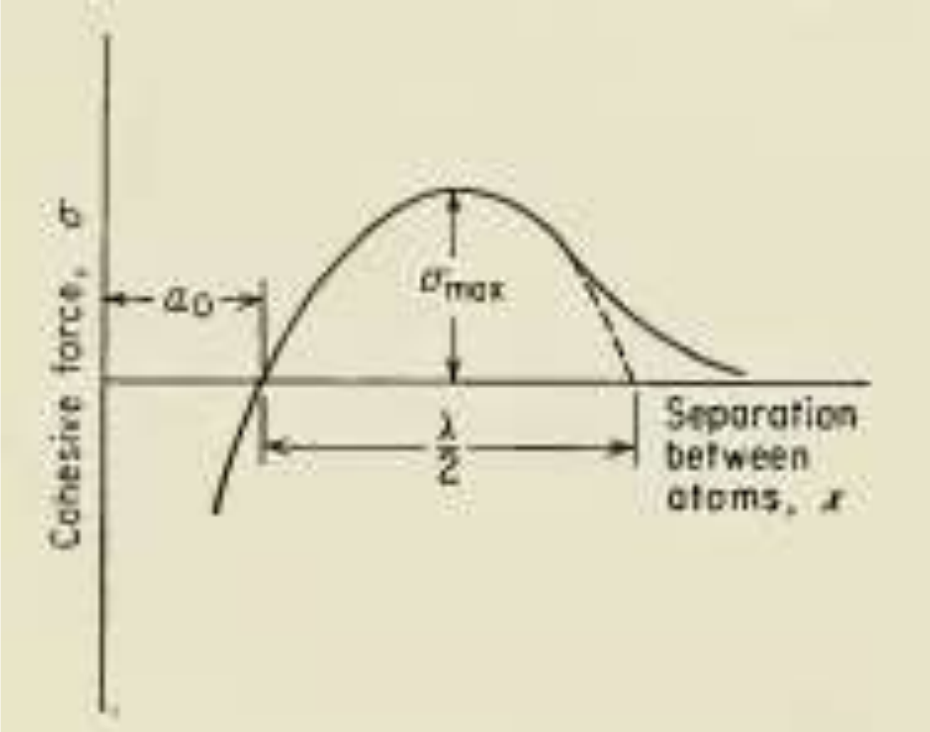
Real world examples of fracture

Real world examples of fracture

Real world examples of fracture

Real world examples of fracture

Theoretical fracture strength



- Curve showing the variation of cohesive force as a function of interatomic spacing
- Maximum of the curve → theoretical fracture strength

Approximately (E/10)

Theoretical strength & actual strength

Material	Theoretical strength (GPa)	Actual tensile strength (MPa)	Ratio of theoretical to actual strength
Au	7.8	130 – 220	35 - 60
Cu	12.1	210 – 400	30 – 60
Ni	22.5	345 – 1000	22.5 – 60
Al	6.9	100 – 200	35 – 70
Fe	21	540	40

Theoretical fracture strength of materials is approx. 35 – 70 times higher than the real strength of materials

Concept of fracture mechanics

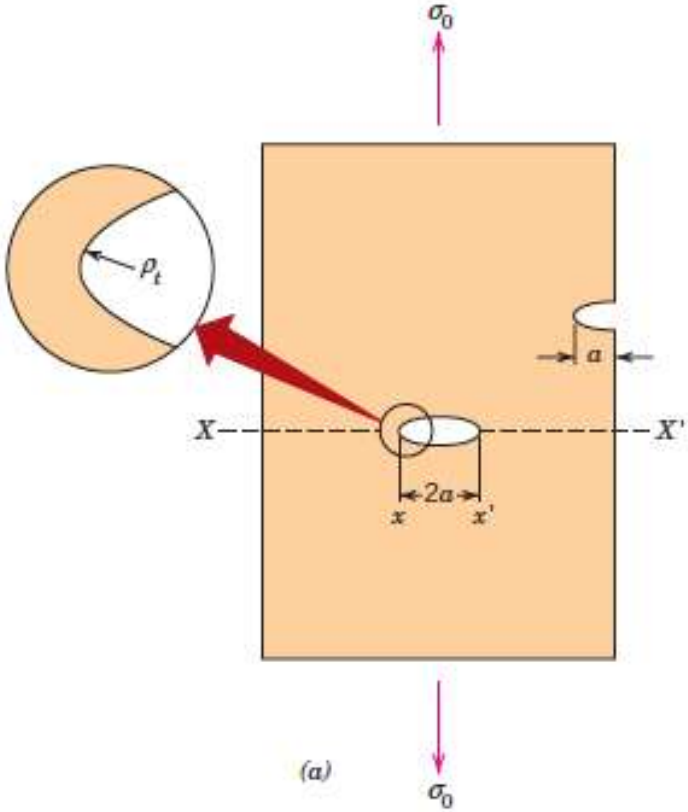
The actually observed lower fracture strength of materials can be attributed to defects like

- Preexisting surface/interior cracks
- Flaws introduced by microscopic or macroscopic plastic deformation
- Macroscopic discontinuities like voids, inclusions, notches, sharp corners, scratches etc.

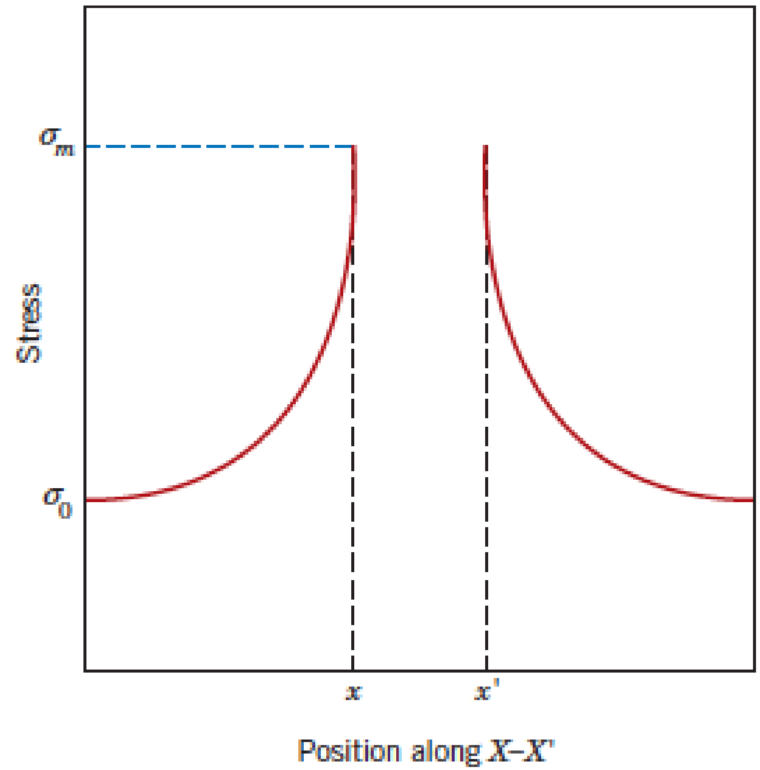
The defects cause stress concentration in their vicinity, thereby significantly raising the local stress values to much higher values ➔fracture occurs at lower applied stress

Due to this stress raising effect, these flaws are also called stress raisers

Stress concentration at crack tip



(a)



For an elliptical internal *crack of length 2a*, *tip radius of curvature ρ_t*, oriented normal to the *applied stress σ_0*

$$\sigma_m = 2\sigma_0 \left(\frac{a}{\rho}\right)^{1/2}$$

σ_m = Maximum stress at the crack tip

Stress concentration at crack tip

$$K_t = \frac{\sigma_m}{\sigma_0} = 2\left(\frac{a}{\rho}\right)^{1/2}$$

- The quantity K_t is known as – stress concentration factor
- Stress concentration factor increases with increasing crack length and decresing crack tip radius
- The maximum stress at the crack tip for an internal crack with length 2a is identical to that of a surface crack of length a

  ➔Surface cracks are more deleterious than internal cracks

Fracture of a brittle material

Griffith theory of brittle fracture

Under tensile stress a crack propagates to cause brittle fracture when the decrease in elastic strain energy is at least equal to the energy increase necessary to create the new crack surface.

For thin plates, the fracture stress in a brittle solid is denoted as:

$$\sigma_F = \left(\frac{2\gamma E}{\pi c}\right)^{1/2}$$

E = Young's modulus

c = Half length of an internal crack

γ is defined as the surface energy per unit area and for completely brittle solids,

Material toughness, $\zeta_c = 2\gamma$

Fracture involving plastic deformation

- Any plastic deformation corresponds to additional work expended for crack propagation ➔ crack extension is hindered and higher fracture stress than that predicted for truly brittle solids is necessary.
- Stress intensity at the crack tip causes local yielding at the crack tip and the plastic zone extends a distance above and below the fracture plane.
- The toughness in Griffitth equation becomes:

$$\zeta_c = 2(\gamma + \gamma_p)$$

- γ_p is a function of material yield strength and also temperature.

Fracture involving plastic deformation