MATERIAL SCIENCE (MEE102B)

Module-2

Properties of metals & non-metals

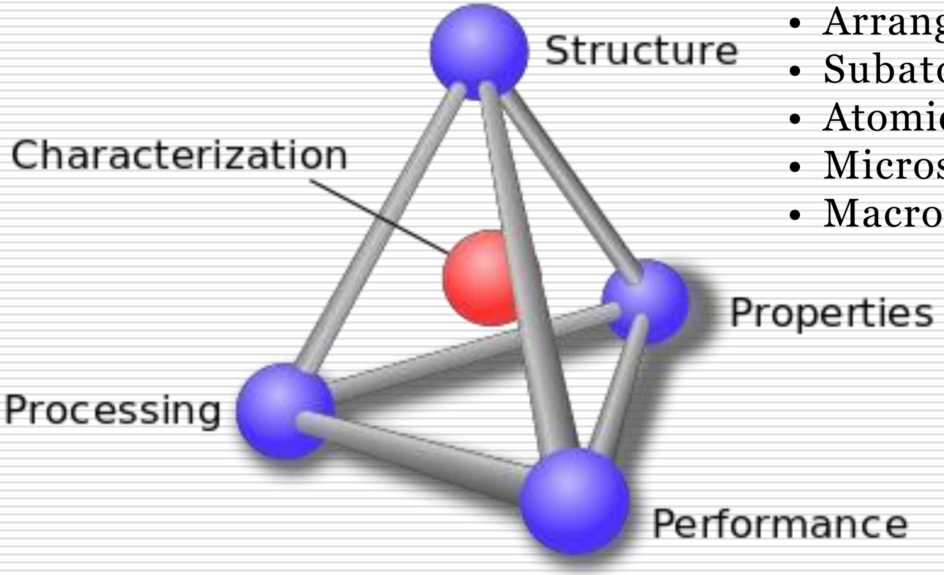
Learning Objectives

1. To learn the different properties of metals and nonmetals.
2. Understand the stress-strain behavior for both ductile and brittle materials.
3. To learn different magnetic materials and its properties.

Introduction

- Material selection is based on properties. The designer must decide the properties of a material for a part or a component under design and then weight the properties of candidate material.
- To properly choose a material for given application, it is necessary to understand what these properties mean, how they are measured, and how they should be compared in the selection test.
- The standards organization like American Society for Testing and Materials (ASTM), International Organization for Standardization (ISO), American National Standards Institute (ANSI), Bureau of Indian Standards (BIS) etc.

The Materials Tetrahedron



- Arrangement of internal components
- Subatomic
- Atomic
- Microscopic
- Macroscopic (bulk)

- Material characteristic
- Response to external stimulus
- Mechanical, electrical, thermal, magnetic, optical, deteriorative

- Behavior in a particular application

Mechanical Properties

- The mechanical properties of material include those characteristics of material that describe its behavior under the action of external forces.
- Mechanical properties are the characteristics of a material that are displayed when a force is applied to the material.
- They usually relate to the elastic and plastics behavior of materials.
- Strength, Ductility, brittleness, malleability etc. mechanical properties are of foremost importance.
- Each material has many properties. It is incorrect, for example to describe a material as just “strong” or “weak” as for example concrete is strong in compression but weak in tension.

Mechanical Properties

Strength: The capacity of a material to withstand or support a load is called its strength.

The strength of a material may be defined as the ability of the material to sustain loads without undue distortion or failure.

The strength may also be classified as :

i. Tensile Strength – the ability to withstand pulling forces or Tension forces

ii. Compressive Strength – the ability to withstand ‘squeezing’ forces or Compression forces

iii. Torsional Strength – the ability to withstand ‘twisting’ forces or Torsion forces

Mechanical Properties

Brittleness: The property of a material by virtue of which it will fracture without appreciable deformation is called its brittleness.

- It is opposite to ductility.
- The brittle behavior of material may be due to brittleness of grain boundaries or crystals themselves,

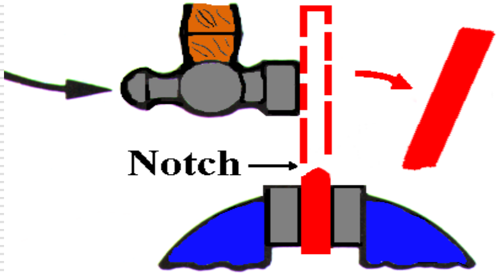


Fig.3 The same as the toughness test however those materials that fracture easily are said to be brittle.

Example:- cast iron, glass ceramics , concrete etc

Mechanical Properties

Malleability: The capacity of a material to withstand deformation under compression without rapture is called malleability

- It is the property of a material of being rolled or hammered to thin sheets. Gold is most malleable and lead is malleable next to gold.
- Malleability differs from ductility because ductility is considered tensile property while malleability is considered compressive property.

Fig. A material that can be rolled or hammered into shape without rupture.

Mechanical Properties

Ductility: The property of a material to undergo deformation under tension without fracture is called ductility.

- In this material can be measured by percentage elongation and the percentage reduction of area before rapture of a test piece.

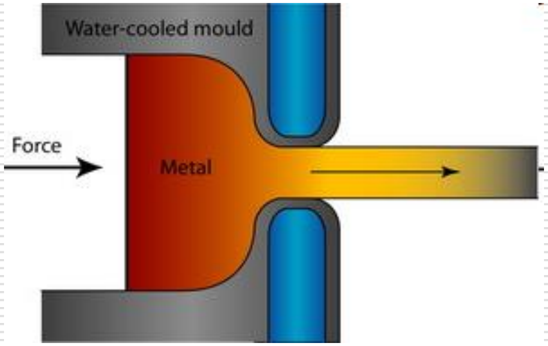


Fig.5 A material that can be pulled or stretched into a thin wire or thread**.**

Mechanical Properties

Ductility (Cont.): The ability of a material to be drawn from a large section to a small section is known as its ductile

Percentage Elongation :- the percentage increase in the original length of a road of a material under tensile load up to its fracture is known as percentage elongation of that material.

Percentage Elongation = Max.Change in length / original length*100

Mechanical Properties

Percentage Reduction of area :- the percentage decrease in the cross-sectional area of a bar of a material when pulled axially in a testing machine up to its fracture.

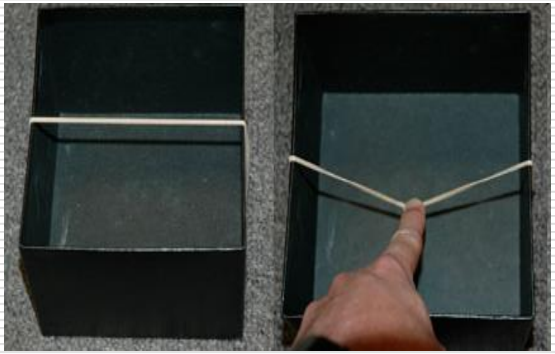
Percentage Reduction of area =Decrease of area / original area *100

A material with more percentage reduction of area can be drawn into thinner wire.

Mechanical Properties

Elasticity:

The ability of a material to return to its original shape after deformation.



The ability of a materiel to regain its original shape and size after the removal of load is known as elasticity

No material are known which are perfectly elastic through that entire range.

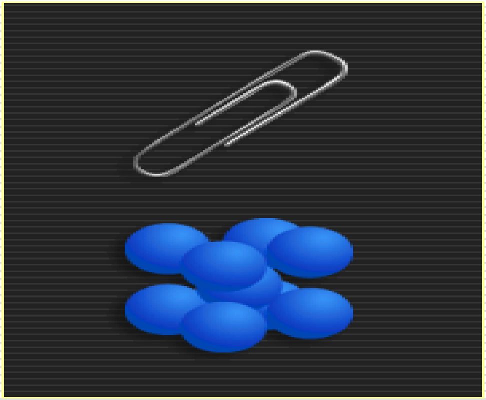
Mechanical Properties

Plasticity:

- The ability of a material to be permanently deformed without fracture.

That property of a material by virtue of which it retains the shape given to it under the action of a force, even after the removal of the force, is known as plasticity.

All metals posses plastically to little or more extent. More of that show more plastically when hot then when cold.



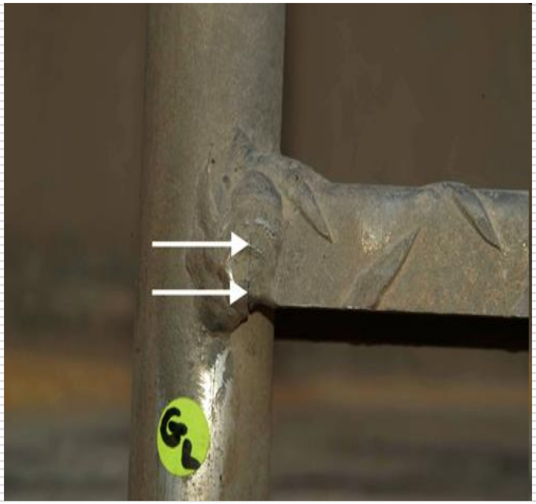
Mechanical Properties

Fatigue:

- Occurs when materials have become overworked and fracture or fail.

the failure of a material caused under repeated loads or stresses is known as fatigue failure.

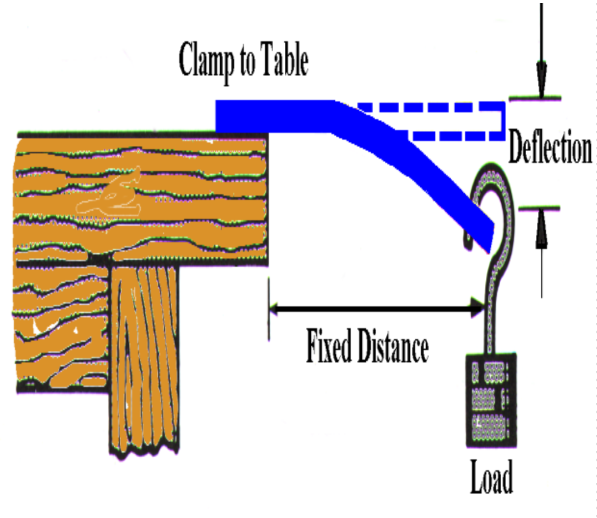
the property of a material to withstand repeated application of stress is known as endurance.



Mechanical Properties

Stiffness:

- The ability of a material to resist bending deformation.
- The property of material which enables it to resist deformation or deflection is called stiffness.
- It is also made use in graduating spring balances and spring controlled measuring devices.

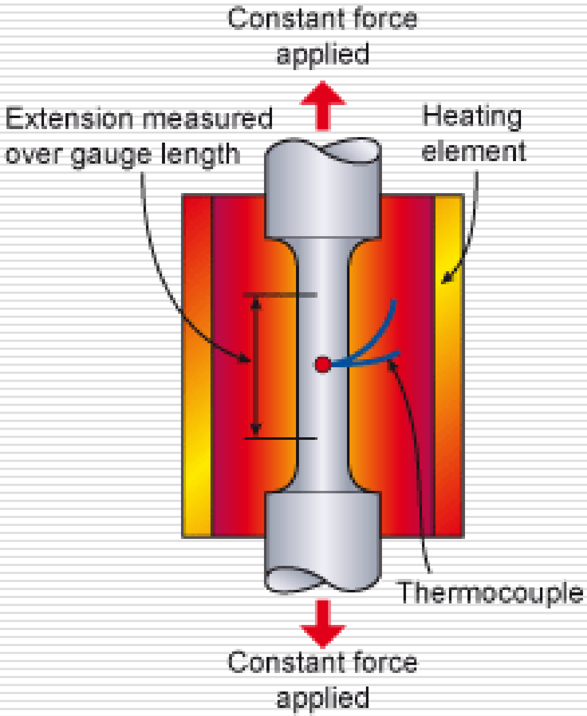


Mechanical Properties

Creep :

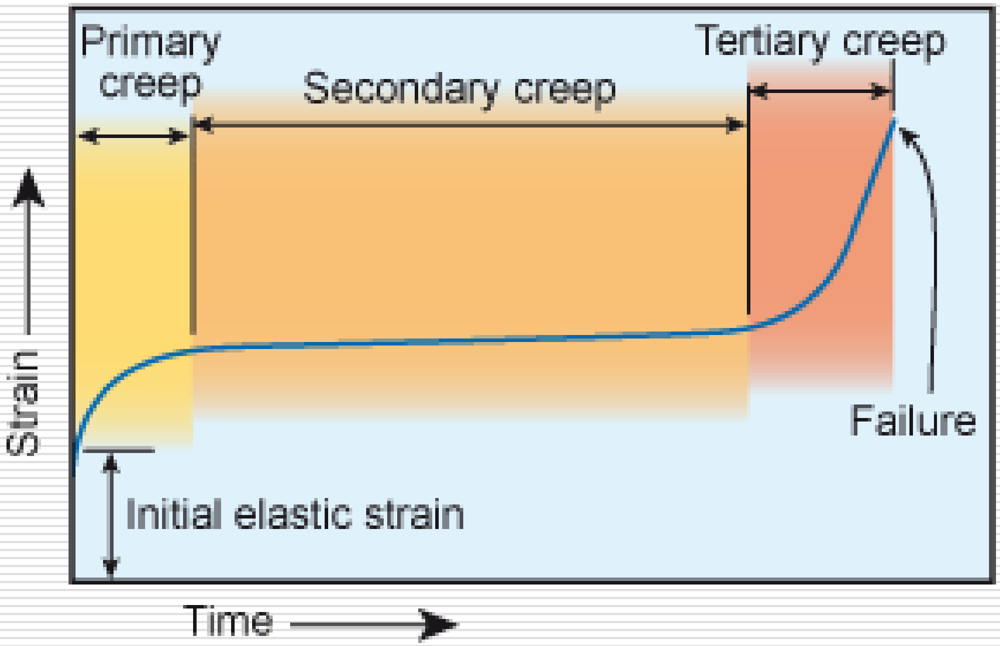
The slow and continuous deformation of a material under steady load is known as creep. This property is given due consideration while designing I.C. engine, boiler and turbine components which are subjected to raised temperatures for long periods in their working conditions.

Mechanical Properties



Schematic of a creep test

Mechanical Properties



Typical creep curve for steel

Mechanical Properties

Toughness:

The ability of a material to withstand blows or sudden impact OR

The ability to absorb energy up to fracture = The total area under the strain-stress curve up to fracture

Units: the energy per unit volume, e.g. J/m^3

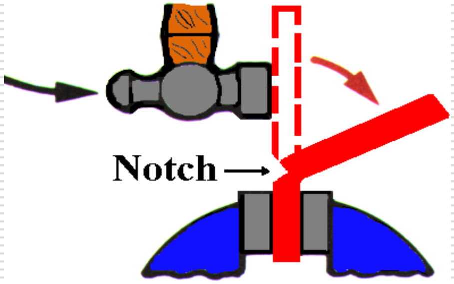
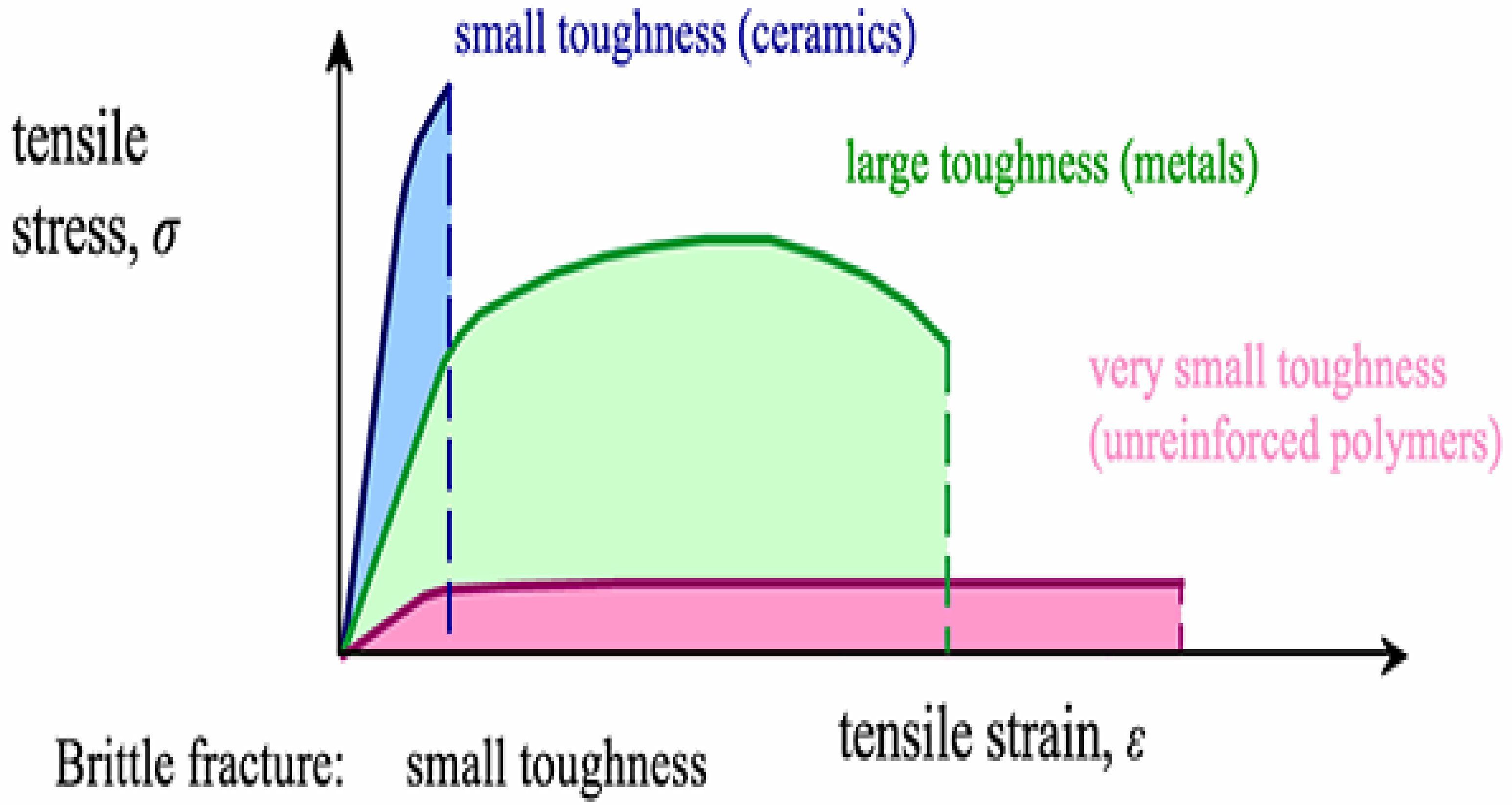


Fig. Toughness

Mechanical Properties



Brittle fracture: small toughness

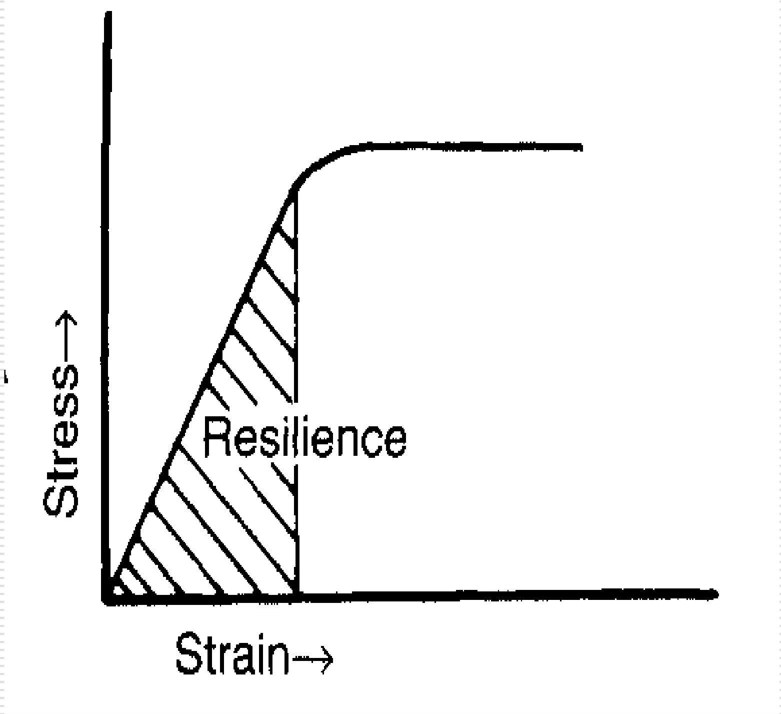
Ductile fracture: large toughness

Mechanical Properties

Energy terms

Resilience

- It indicates the amount of energy necessary to deform the material to the proportional limit.
- Energy absorb by material up to proportional limit.



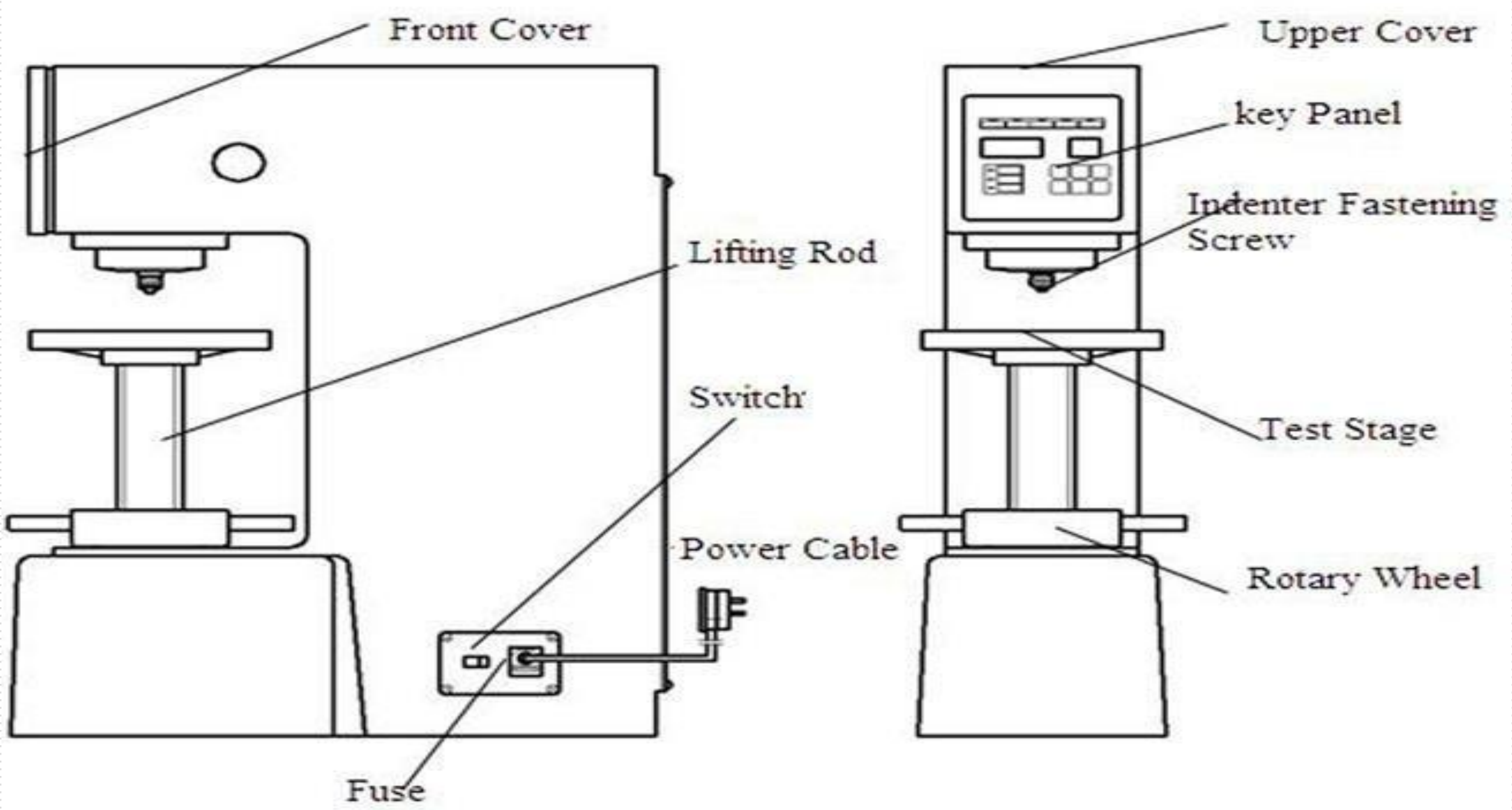
Mechanical Properties

Hardness:

The ability of a material to withstand scratching, wear & abrasion or indentation by harder bodies is known as hardness.

It is mostly measured by determining the resistance to penetration by different methods such as brinell, Rockwell

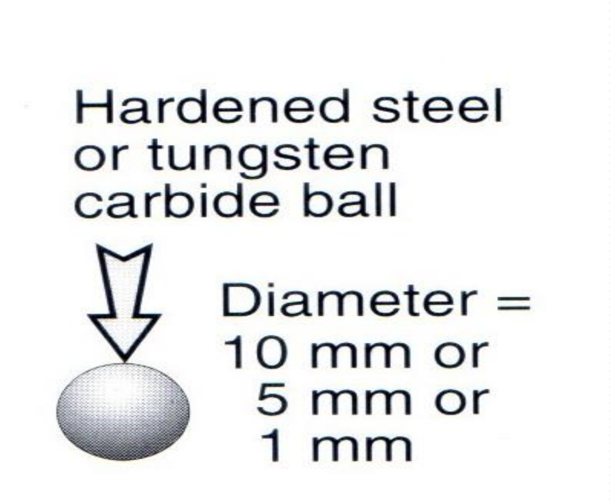
Brinell hardness test



Brinell hardness tester

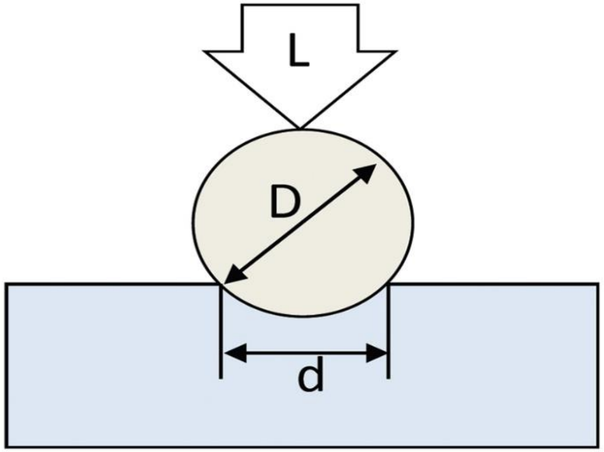
Brinell hardness test

- Uses ball shaped indenter.
- Cannot be used for thin materials.
- Ball may deform on very hard materials
- Surface area of indentation is measured.



Brinell hardness test

- A load of 3000 kg (500 kg for softer materials) is applied for 10 – 30 s.
- Dia of the indentation is measured to obtain the hardness (Brinell Hardness No.) from the relationship
- Brinell method determines the indentation hardness of metal materials and is typically used for materials with a coarse surface or a surface too rough to be tested through other methods.



$$BHN = \frac{2P}{\pi D\left(D - \sqrt{D^2 - d^2}\right)}$$

BHN – Brinell Hardness Number in kg/mm^2

P – load in kgf

D – steel ball diameter in mm

d – depression diameter in mm

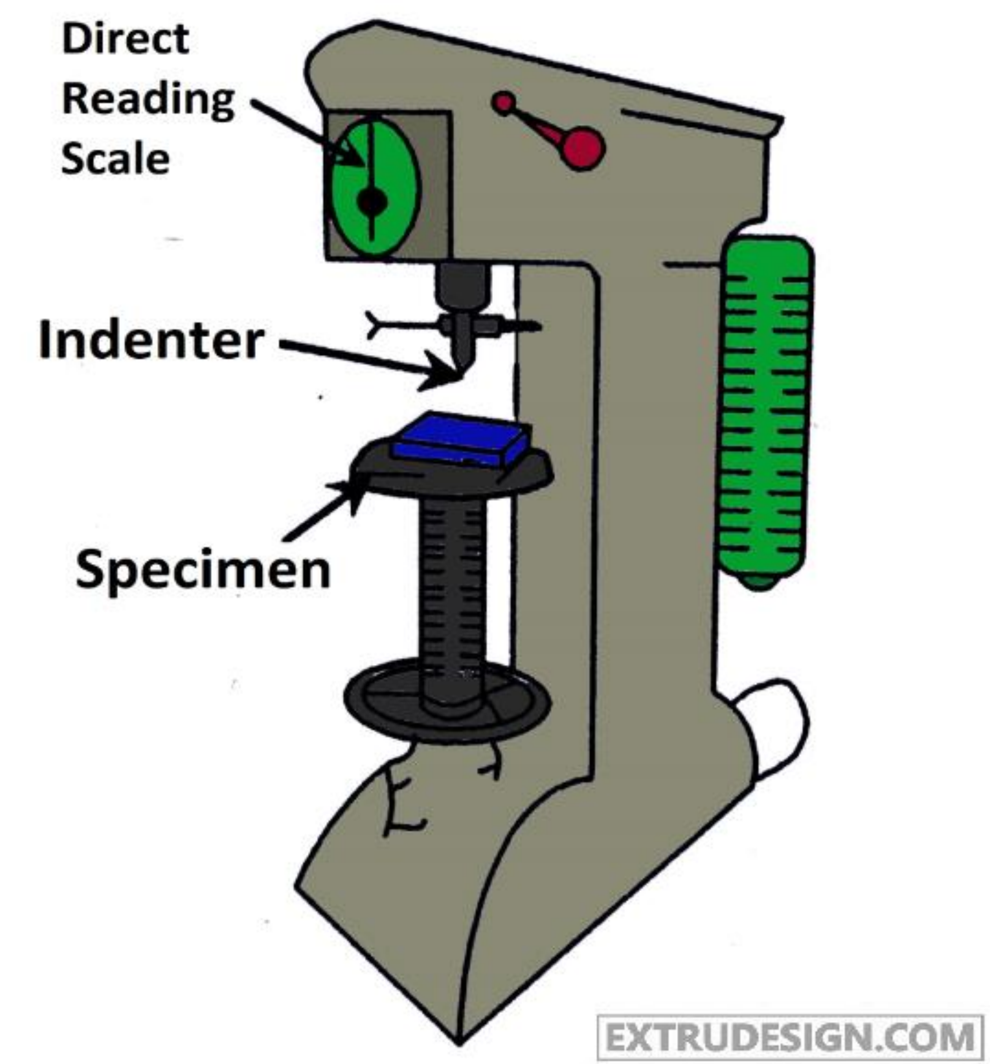
Rockwell hardness tests

- ☐ Gives direct reading.
- ☐ Rockwell B (ball) used for soft materials.
- ☐ Rockwell C (cone) uses diamond cone for hard materials.
- ☐ Flexible, quick and easy to use.

Two most common indenters are
Ball – B and
Cone – C

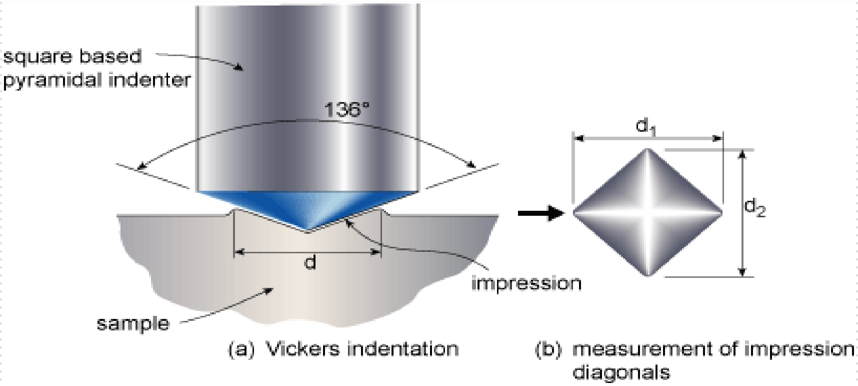
Rockwell hardness tests

Two most common indenters are
Ball – B and
Cone – C



Vickers hardness test

- Uses square shaped pyramid indenter.
- Accurate results.
- Measures length of diagonal on indentation.
- Usually used on very hard materials



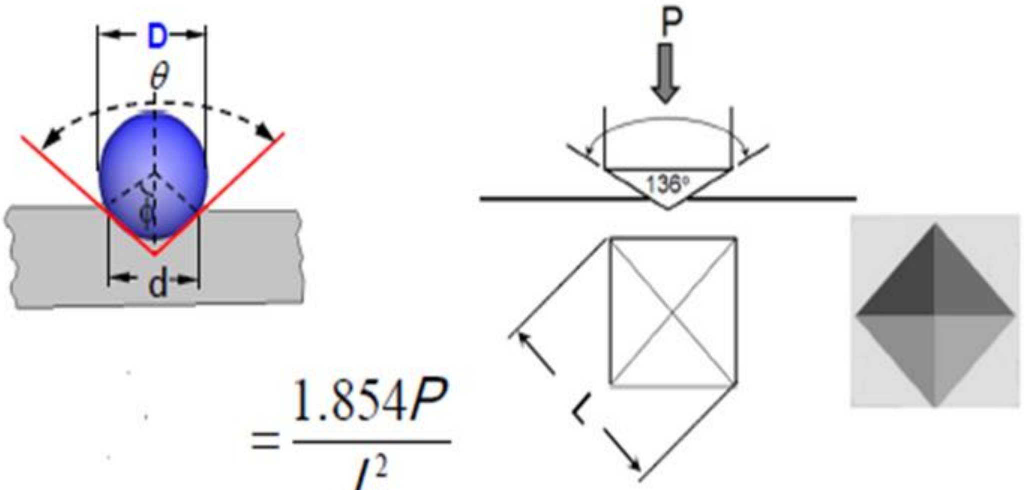
(a) Vickers indentation

(b) measurement of impression diagonals

Vickers hardness test

Vickers hardness tester

Vickers hardness test



$$VHN = \qquad = \frac{1.854P}{L^2}$$

Stress and Strain

In order to compare materials, we must have measures.

- **Stress : load per unit Area**

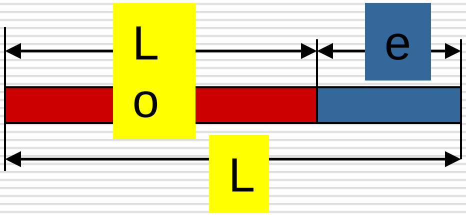
$$\boxed{\sigma = \frac{F}{A}}$$

F : load applied in N
A : cross sectional area in M^2
σ : stress in MPa

Stress and Strain

- **Strain:**
  - Ratio of elongation of a material to the original length
  - unit deformation

$$\boxed{\varepsilon = \frac{e}{L_o}}$$



e : elongation (mm)

Lo : unloaded(original) length of a material (mm)

ε : strain (mm/mm)

Elongation:

$$\boxed{e = L - L_o}$$

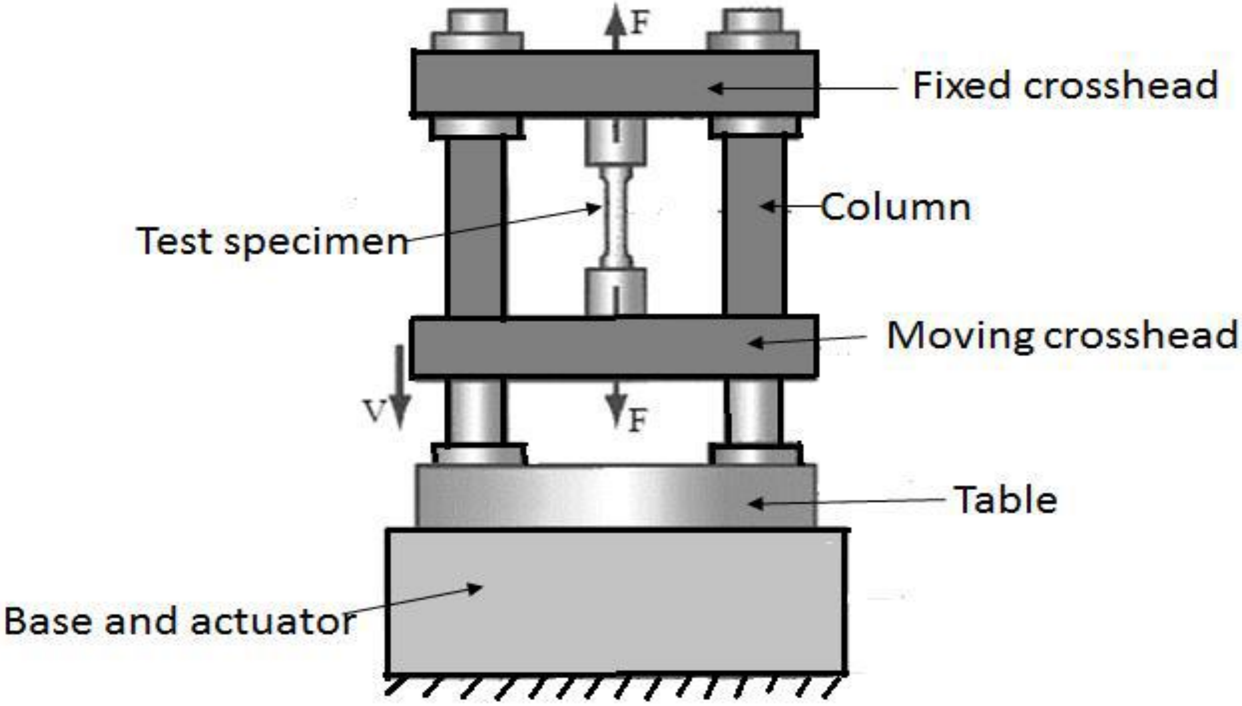
L : loaded length of a material mm

UTM Machine

Hydraulic Machine for Tension & Compression test

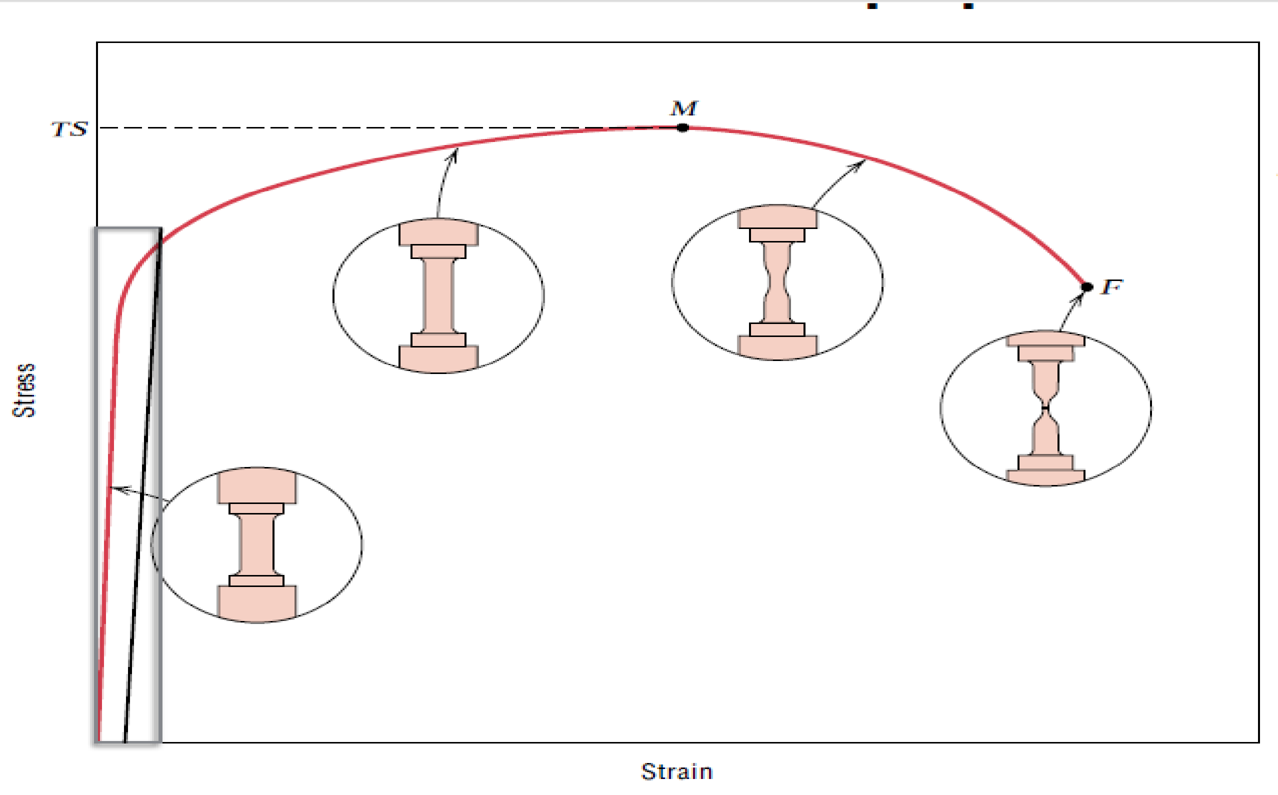
UTM Machine

UTM Machine

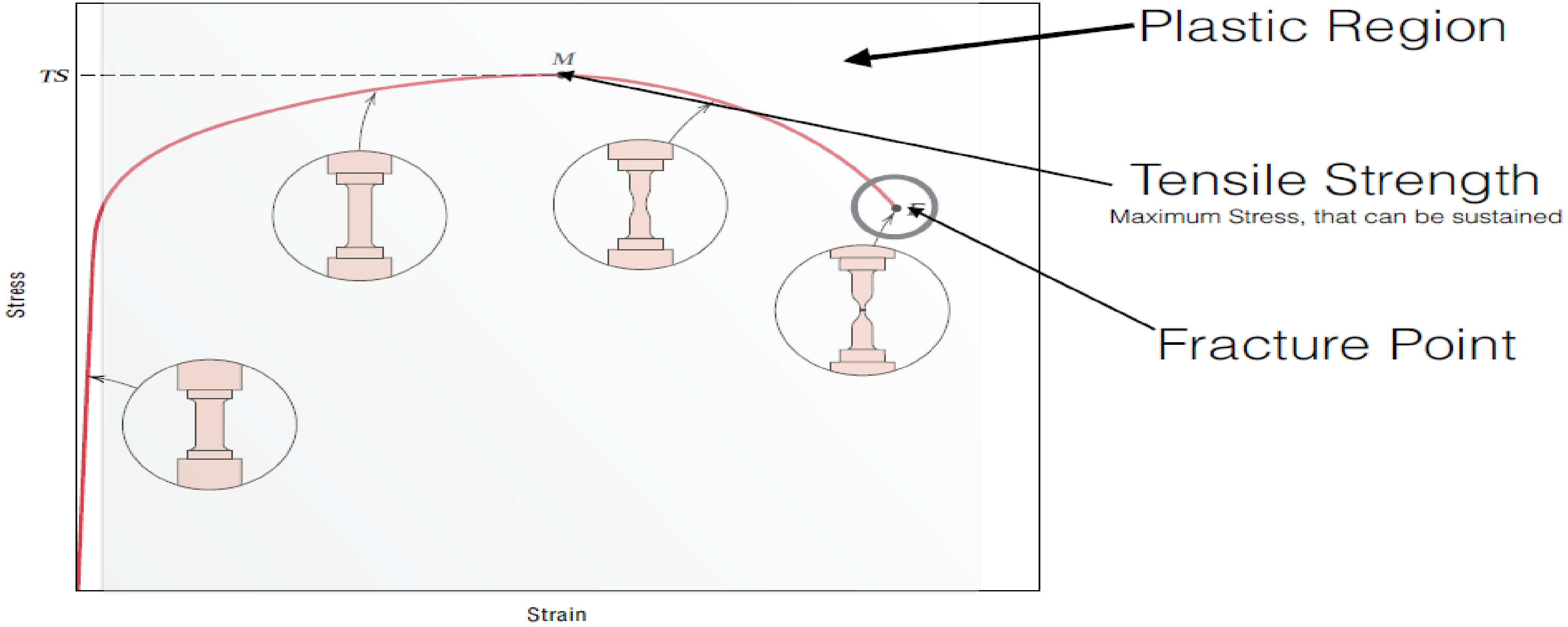


UTM Machine

Stress-Strain Diagram



Stress-Strain Diagram



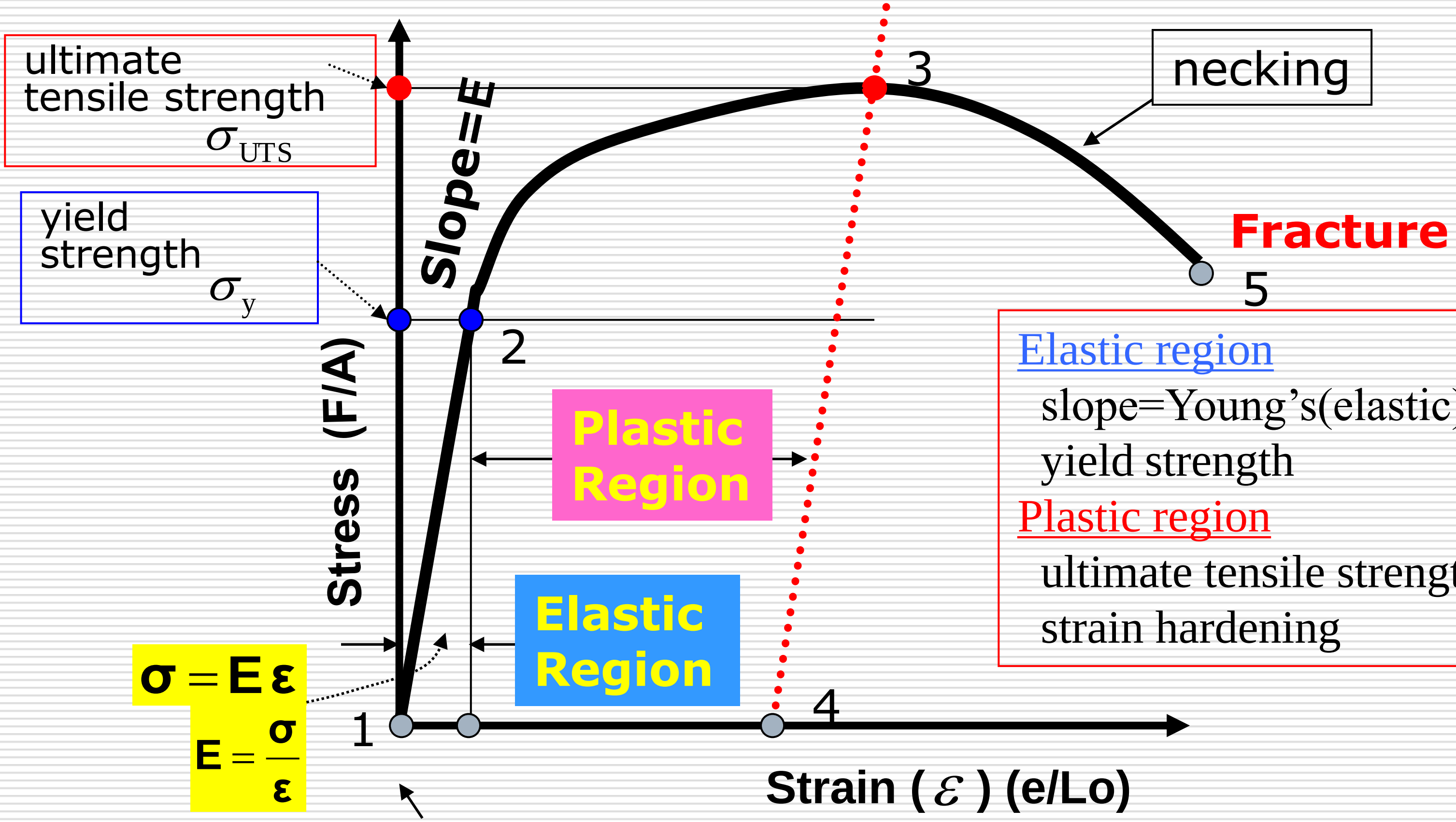
Plastic Region

Tensile Strength

Maximum Stress, that can be sustained

Fracture Point

Stress-Strain Diagram



Elastic region

slope=Young's(elastic) modulus

yield strength

Plastic region

ultimate tensile strength

strain hardening

Stress-Strain Diagram

- Elastic Region (Point 1 –2)

- The material will return to its original shape after the material is unloaded(like a rubber band).

- The stress is linearly proportional to the strain in this region.

$\boxed{\sigma = E\varepsilon}$ or $\boxed{E = \frac{\sigma}{\varepsilon}}$

σ : Stress (MPa)

E : Elastic modulus (Young's Modulus) (MPa)

ε : Strain (mm/mm)

- Point 2 : Yield Strength : a point at which permanent deformation occurs. (If it is passed, the material will no longer return to its original length.)

Stress-Strain Diagram

The ELASTIC Range Means:

- The strain, or elongation over a unit length, will behave linearly (as in y=mx +b) and thus predictable.

-The material will return to its original shape (Point 1) once an applied load is removed.

- The stress within the material is less than what is required to create a plastic behavior (deform or stretch significantly without increasing stress).

Stress-Strain Diagram

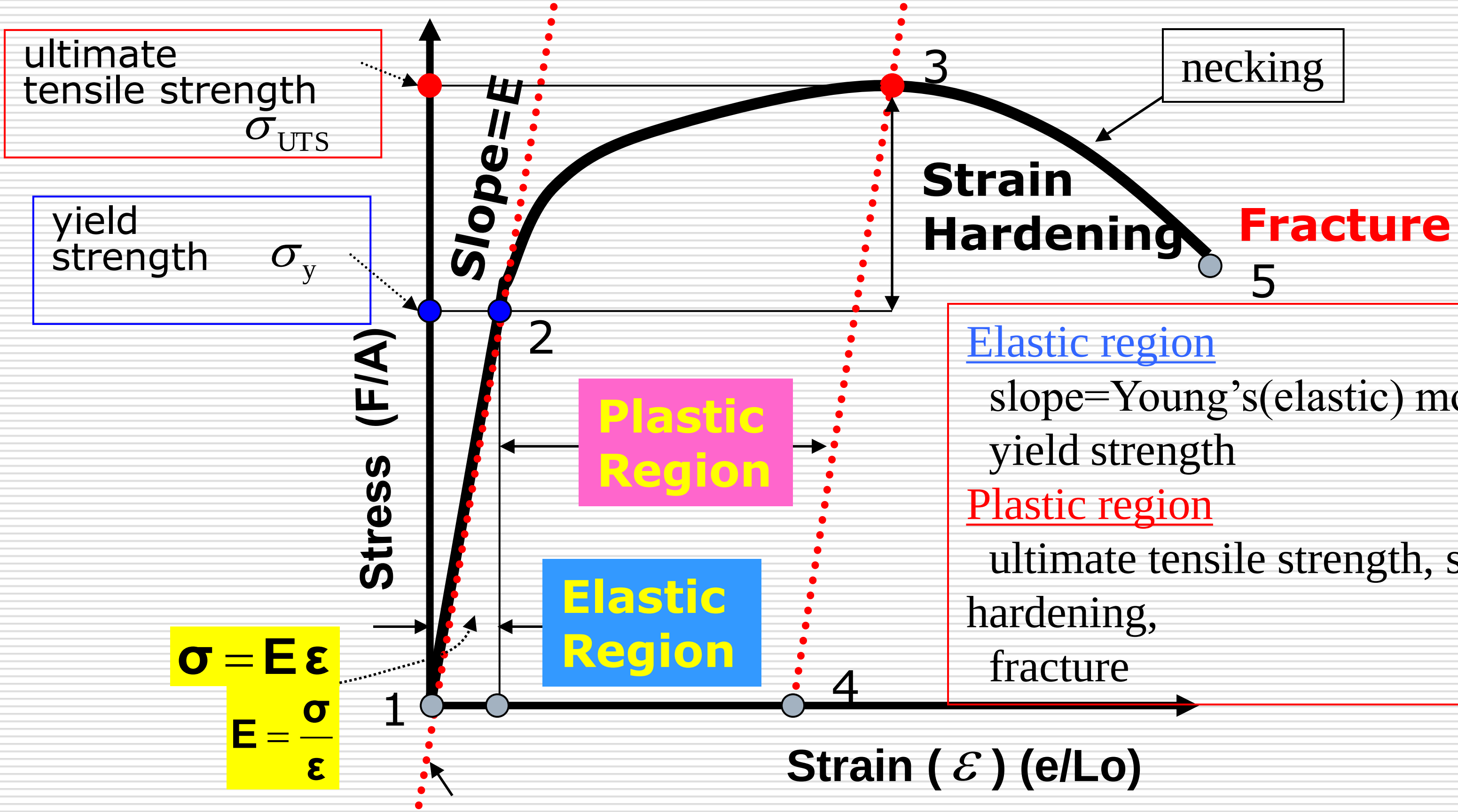
Plastic Region (Point 2 –3)

- If the material is loaded beyond the yield strength, the material will not return to its original shape after unloading.

- It will have some permanent deformation.

- The distance between Point 1 and 4 indicates the amount of permanent deformation.

Stress-Strain Diagram



Elastic region

slope=Young's(elastic) modulus

yield strength

Plastic region

ultimate tensile strength, strain hardening,

fracture

Stress-Strain Diagram

Tensile Strength (Point 3)

- The largest value of stress on the diagram is called Tensile Strength(TS) or Ultimate Tensile Strength (UTS)

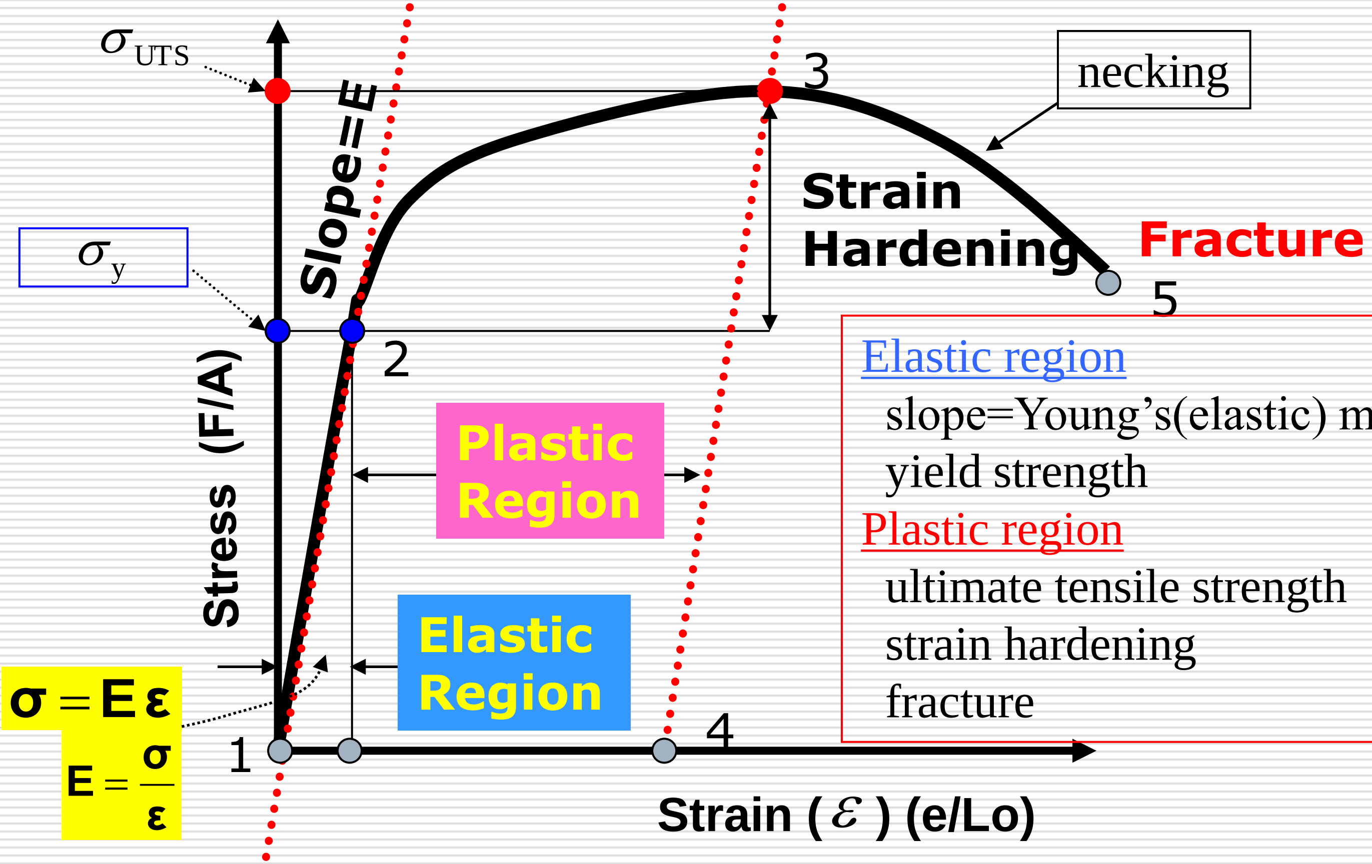
- It is the maximum stress which the material can support without breaking.

Fracture (Point 5)

- If the material is stretched beyond Point 3, the stress decreases as necking and non-uniform deformation occur.

- Fracture will finally occur at Point 5.

Stress-Strain Diagram



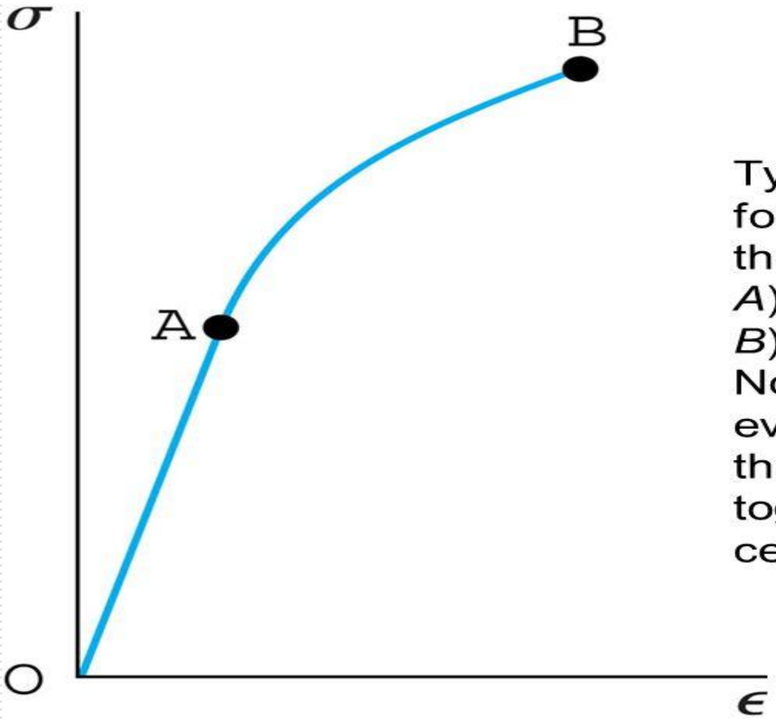
Elastic region

slope=Young’s(elastic) modulus
yield strength

Plastic region

ultimate tensile strength
strain hardening
fracture

Stress-Strain Diagram for Brittle material



Typical stress-strain diagram for a brittle material showing the proportional limit (point *A*) and fracture stress (point *B*)

No yielding, or necking is evident. For brittle materials that fail the pieces still fit together e.g. glass or ceramics.

Brittle and Ductile Fracture

Brittle vs. Ductile Fracture

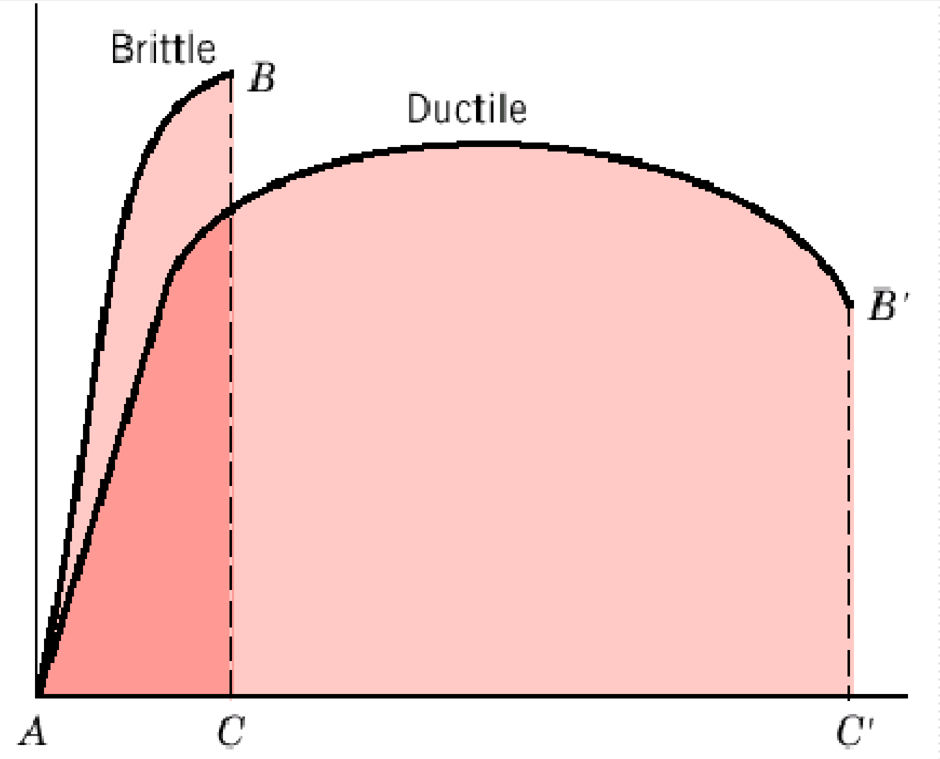
Ductile materials-extensive plastic

deformation and energy absorption

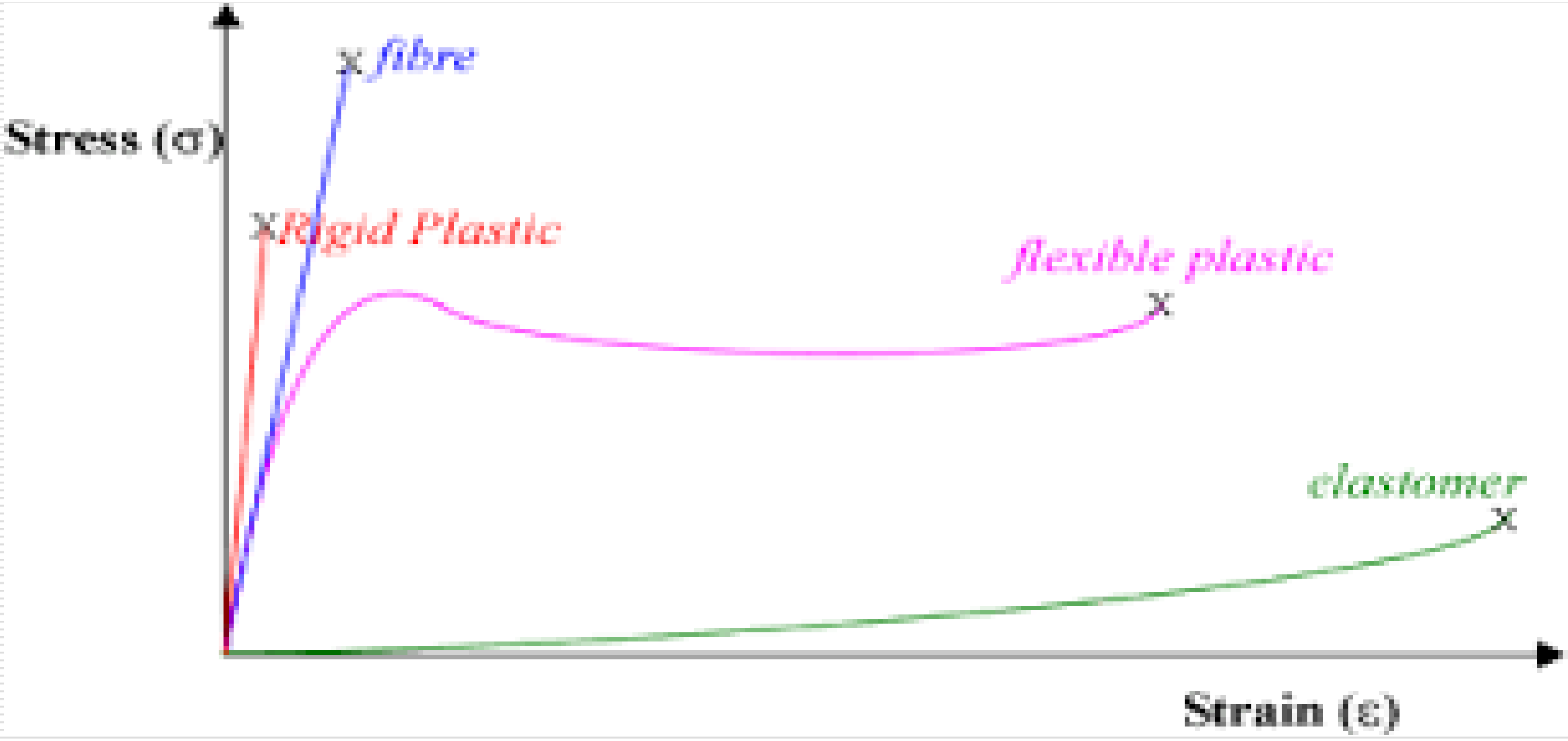
(“toughness”) before fracture

Brittle materials-little plastic deformation

and low energy absorption before fracture

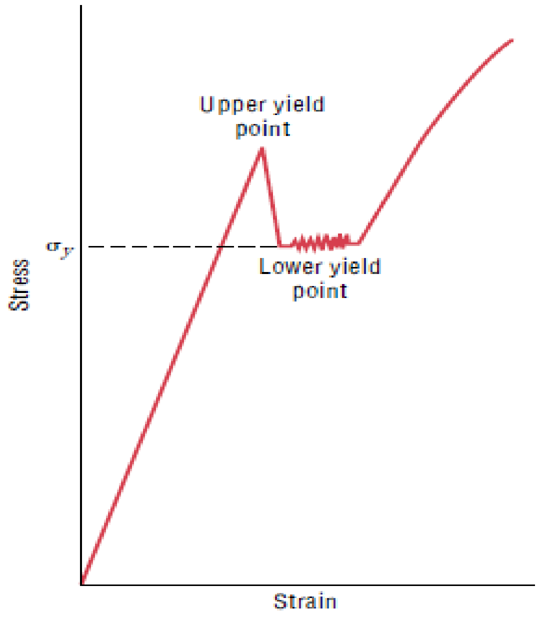


Stress-Strain Diagram for polymer



Yield Point Phenomenon in Mild steel

- The yield point phenomenon, which refers to a characteristic yielding pattern shown, is considered to occur due to the segregation of solute atoms around dislocations.
- It is believed that the yield point phenomena in iron and low carbon steels occur due to the segregation of impurity atoms carbon and/or nitrogen. These impurity solute atoms pin down or anchor the dislocations.
- Thus, deformation in this case requires an additional stress so as to free the dislocations from their anchored atmospheres.



Yield Point Phenomenon in Mild steel

- The increased stress required to set dislocations in motion, which is needed for plastic deformation, accounts for the upper yield point.
- Once dislocations have been freed from their atmospheres, the stress needed for their motion drops abruptly.
- It is this lowered stress that accounts for the lower yield point. The minor fluctuations in stress during the lower yield region arise because of the interaction of moving dislocations with the impurity solute atoms in their paths.

Types of Deformation of Material

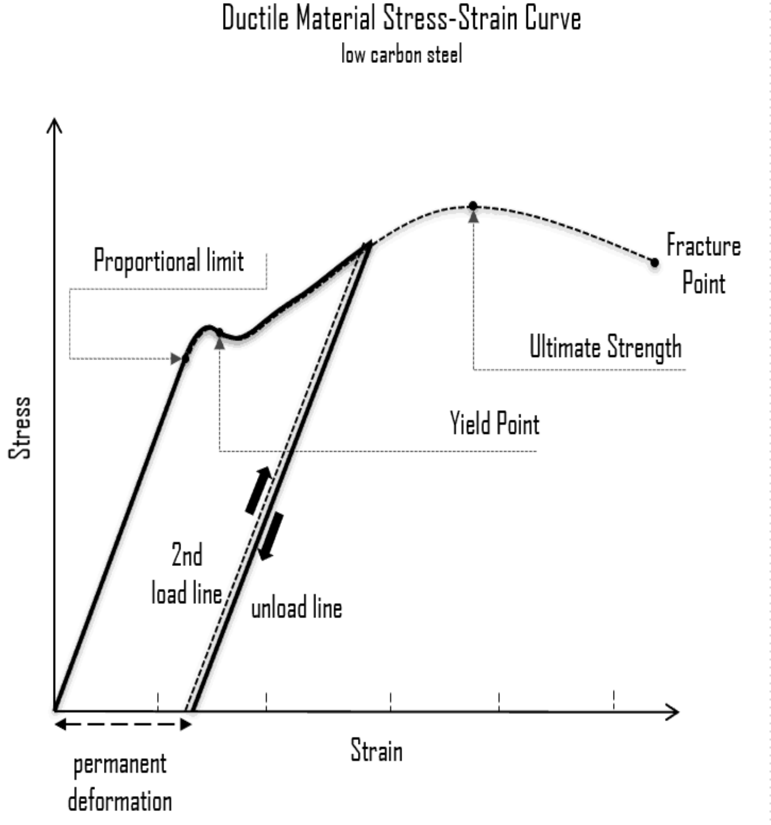
- There are basically two types of deformation of material are available within the material when they were loaded by external excitation force,

1. Elastic Deformation of Material

2. Plastic Deformation of Material

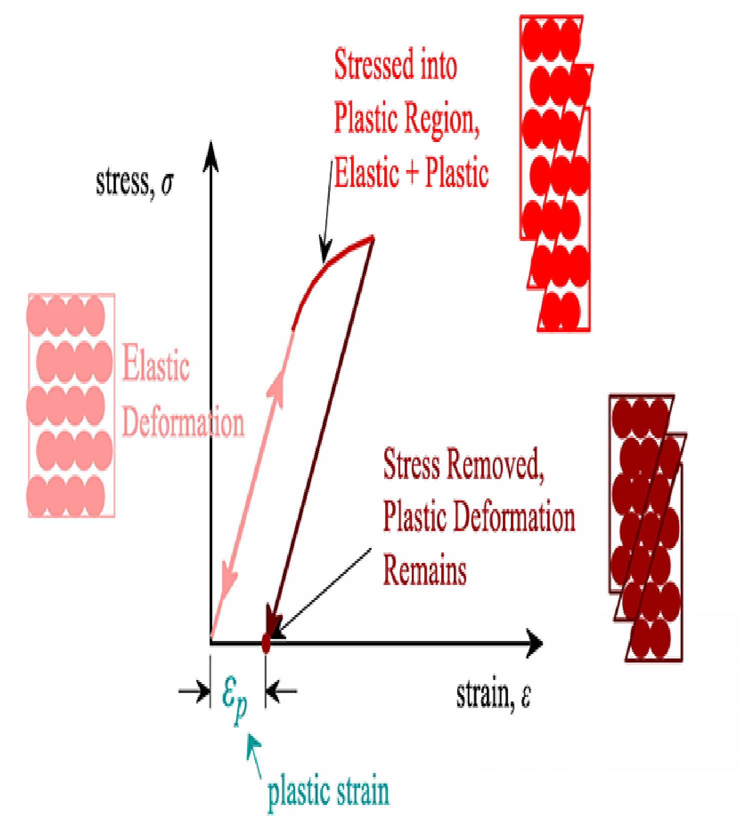
Elastic Deformation of Material

- Elastic Deformation. When a sufficient load is applied to a metal or other structural material, it will cause the material to change shape.
- A temporary shape change that is self-reversing after the force is removed, so that the object returns to its original shape, is called elastic deformation



Plastic Deformation of Material

- Plastic deformation is the permanent distortion that occurs when a material is subjected to tensile, compressive, bending, or torsion stresses that exceed its yield strength and cause it to elongate, compress, buckle, bend, or twist.



Comparison between the Elastic and Plastic Deformation

Elastic deformation

- It takes place over a short range of stress strain curve.
- In elastic deformation, which appears and disappears with the application and removal of stress.
- The elastic deformation is the starting of the progress of deformation.
- In elastic deformation, the strain approaches its maximum value after the stress reached its maximum value.

Plastic Deformation

- It takes place over a wide range of stress-strain curve.
- In permanent deformation, which obtained even after the removal of stress.
- The plastic deformation takes place after the elastic deformation is over.
- In plastic deformation, the strain occurs simultaneously with the application of stress.

Mechanisms of plastic deformation in metals

- Two prominent mechanisms of plastic deformation, namely ***slip and twinning*** **.**
- **Slip** is the prominent mechanism of plastic deformation in metals. It involves sliding of blocks of crystal over one other along definite crystallographic planes, called slip planes.
- It is analogous to a deck of cards when it is pushed from one end. Slip occurs when shear stress applied exceeds a critical value.

Mechanisms of plastic deformation in metals

- During slip each atom usually moves same integral number of atomic distances along the slip plane producing a step, but the orientation of the crystal remains the same.

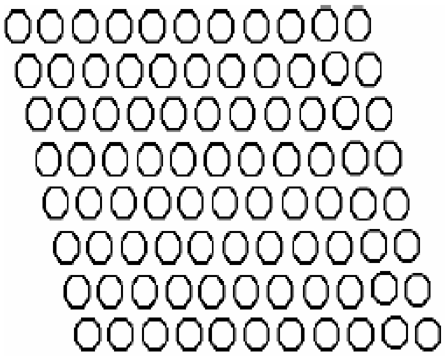
Twining :

- Portion of crystal takes up an orientation that is related to the orientation of the rest of the untwined lattice in a definite, symmetrical way.

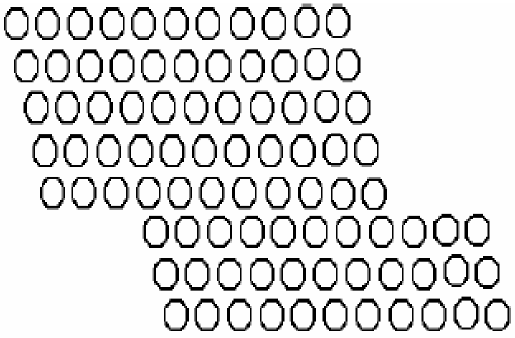
Mechanisms of plastic deformation in metals

- The twinned portion of the crystal is a mirror image of the parent crystal.
- The plane of symmetry is called twinning plane.
- The important role of twinning in plastic deformation is that it causes changes in plane orientation so that further slip can occur.

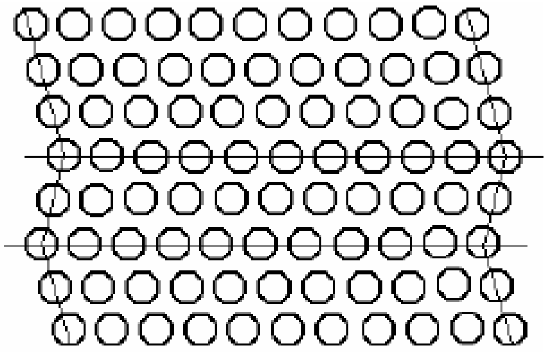
Mechanisms of plastic deformation in metals



Undeformed Crystal



After Slip

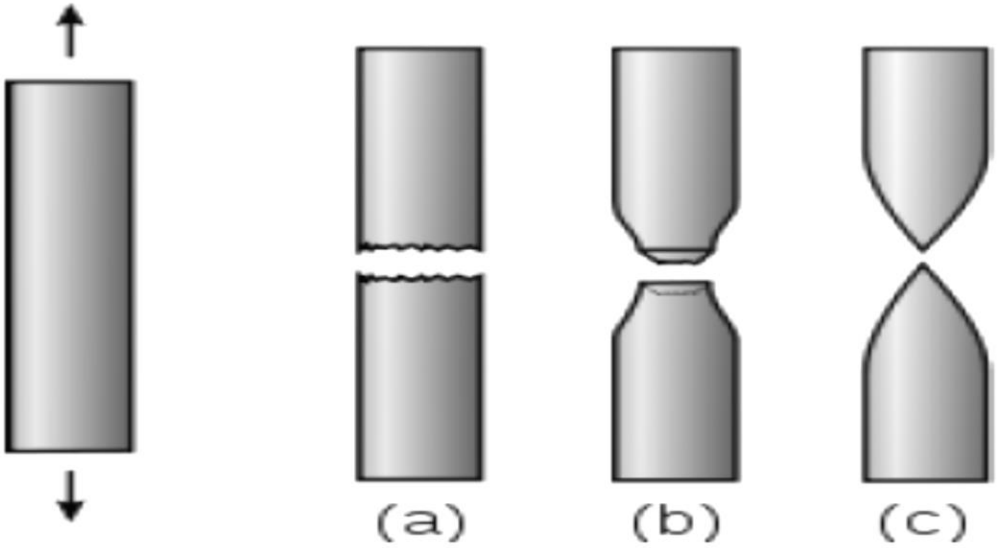


After Twinning

Types of Fractures

- The following are the main types of fractures that are available within the material when they were loaded by external excitation force.
- Ductile fracture of Material : is a type of fracture characterized by extensive deformation of plastic or "necking." This usually occurs prior to the actual fracture. The term "ductile rupture" refers to the failure of highly ductile materials. In such cases, materials pull apart instead of cracking
- Brittle fracture of Material : is the sudden, very rapid cracking of equipment under stress where the material exhibited little or no evidence of ductility or plastic degradation before the fracture occurs. Brittle fracture is often caused by low temperatures.

Brittle and Ductile Material fracture



Schematic appearance of round metal bars after tensile testing.

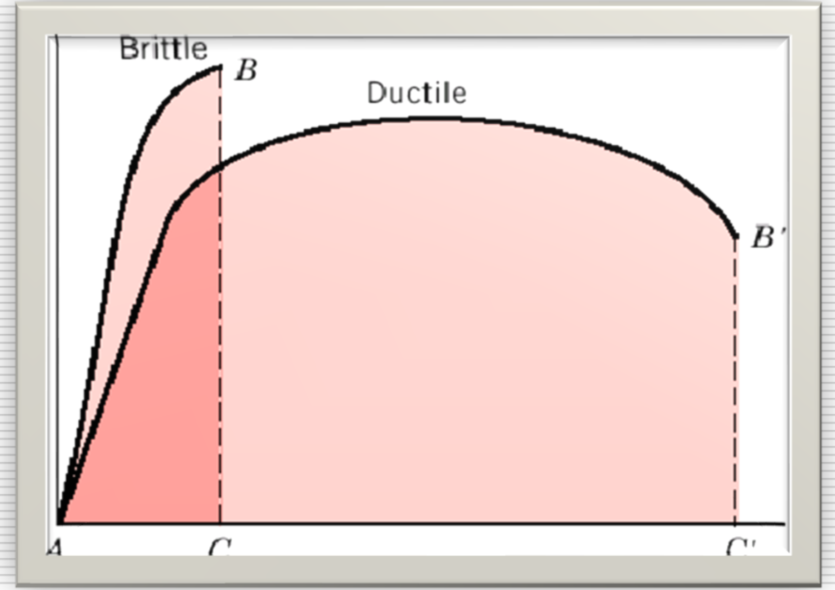
(a) Brittle fracture

(b) Ductile fracture

(c) Completely ductile fracture

Brittle and Ductile Material fracture

- Ductile materials - extensive plastic deformation and energy absorption (“toughness”) before fracture.
- Brittle materials - little plastic deformation and low energy absorption before fracture.



Different properties of non-metals

Properties of Ceramics

- Low density compared to metals
- High melting point or decomposition temperature
- High hardness and very brittle
- High elastic modulus and moderate strength
- Low toughness
- High electrical resistivity
- Low thermal conductivity
- High temperature wear resistance
- Thermal Shock resistance
- High corrosion resistance
- In crystalline ceramics the crack propagation is usually through the grains (transgranular) and along specific crystallographic (or cleavage) planes, which are planes of high atomic density
- *Main drawback is brittleness and low toughness*

Properties of Composite

- High strength to weight ratio (low density high tensile strength) or high specific strength ratio.
- High creep resistance
- High tensile strength at elevated temperatures
- High toughness
- Generally perform better than steel or aluminum in applications where cyclic loads are encountered leading to potential fatigue failure (i.e. helicopter blades).
- Impact loads or vibration – composites can be specially formulated with high toughness and high damping to reduce these load inputs.
- Some composites can have much higher wear resistance than metals.

Properties of Polymers

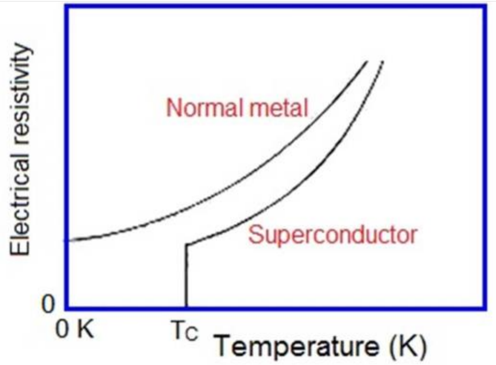
1. Poor tensile strength
2. Poor temperature resistance
3. Low mechanical properties.
4. Economical
5. Polymers can be produced transparent or in different colours
6. Excellent surface finish can be obtained
7. Polymers can be produced with close dimensional tolerances
8. Good mouldability
9. Low coefficient of friction
10. Good corrosion resistance
11. Low density

Electrical Properties

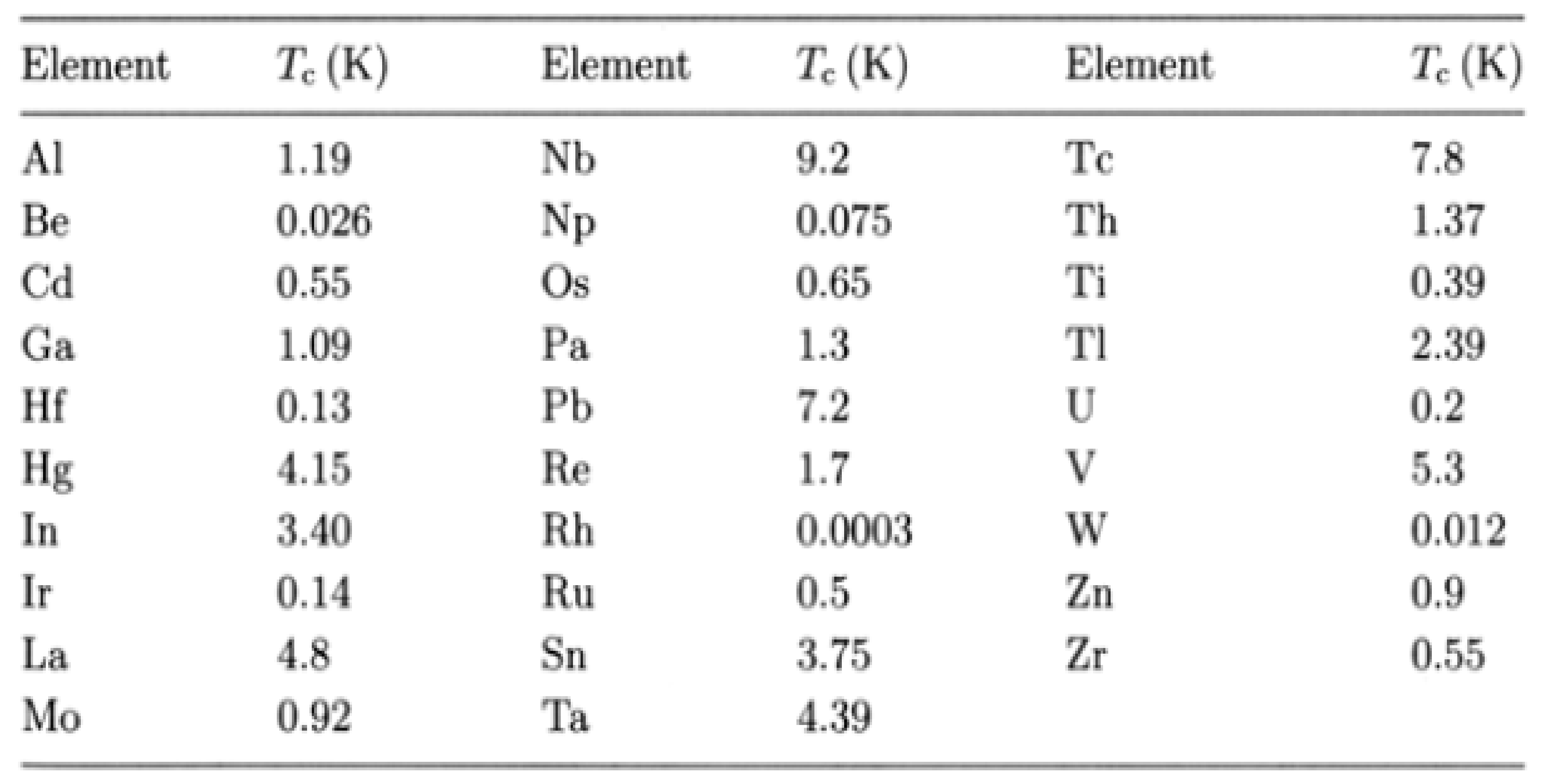
Superconductivity : Certain metal exhibit zero resistivity when they are cooled below absolute zero temperature. This property is referred as **Superconductivity**.

Superconductivity

- Superconductivity is disappearance of electrical resistance below a certain temperature.
- The temperature below which superconductivity is attained is known as the *critical temperature*, T_C.
- The superconducting behavior is represented in a graphical form in the figure below.



Superconductivity



Element	T_c (K)	Element	T_c (K)	Element	T_c (K)
Al	1.19	Nb	9.2	Tc	7.8
Be	0.026	Np	0.075	Th	1.37
Cd	0.55	Os	0.65	Ti	0.39
Ga	1.09	Pa	1.3	Tl	2.39
Hf	0.13	Pb	7.2	U	0.2
Hg	4.15	Re	1.7	V	5.3
In	3.40	Rh	0.0003	W	0.012
Ir	0.14	Ru	0.5	Zn	0.9
La	4.8	Sn	3.75	Zr	0.55
Mo	0.92	Ta	4.39		

Superconductivity Applications

Superconductors are used in

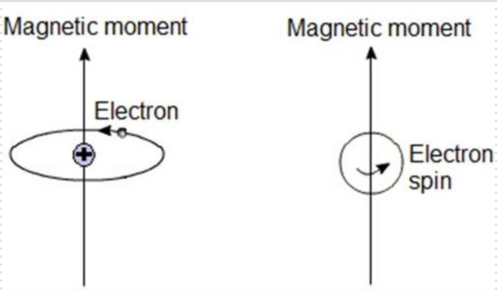
- Magnetic elevated trains which can reach very high velocity
- MRI scan machines (Medical science, Brain imaging)
- High efficiency electric generators
- Superconducting Quantum Interference Device (SQUID)

A SQUID is a very sensitive magnetometer used to measure extremely small or hidden magnetic fields

Magnetic Properties

Magnetic moments

- Being a moving charge, electrons produce a small magnetic field having a magnetic moment along the axis of rotation.
- The spin of electrons also produces a magnetic moment along the spin axis.
- Magnetism in a material arises due to alignment of magnetic moments.

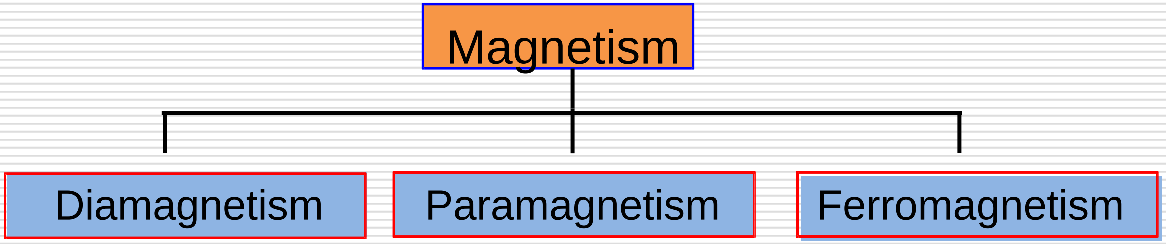


Magnetization

- With the application of a magnetic field, magnetic moments in a material tend to align and thus increase the magnitude of the field strength.

Magnetism

- Depending on the existence and alignment of magnetic moments with or without application of magnetic field, three types of magnetism can be defined.


Magnetism

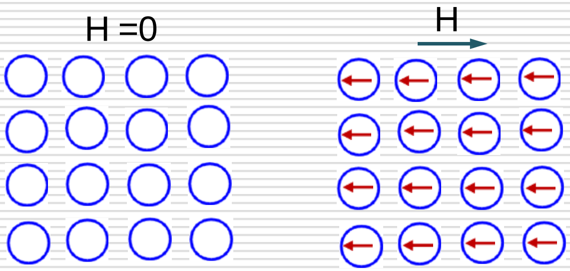
Diamagnetism

Paramagnetism

Ferromagnetism

Diamagnetism

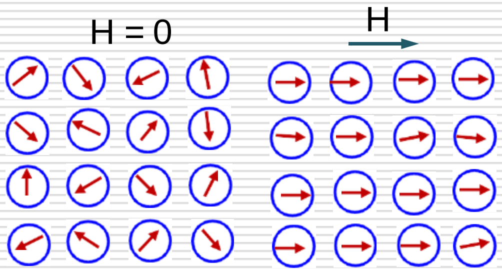
- Diamagnetic materials are those in which the electron motions are such that they produce net zero magnetic moment in the absence of any magnetic field. Typically these are atoms with closed or filled outer electron shells.
- Diamagnetism is a weak form of magnetism which arises only when an external field is applied.
- There is no magnetic dipoles in the absence of a magnetic field and when a magnetic field is applied the dipole moments are aligned opposite to field direction.



Diamagnetic materials: Al_2O_3, Si, Zn

Paramagnetism

- In a paramagnetic material the cancellation of magnetic moments between electron pairs is incomplete and hence magnetic moments exist without any external magnetic field.
- However, the magnetic moments are randomly aligned and hence no net magnetization without any external field.
- When a magnetic field is applied all the dipole moments are aligned in the direction of the field.



Paramagnetic materials: Al, Cr, Mo, Ti, Zr

Ferromagnetism

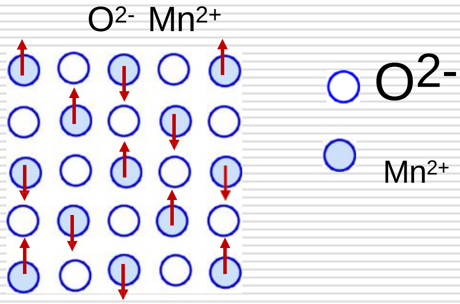
- Certain materials posses permanent magnetic moments in the absence of an external magnetic field. This is known as ferromagnetism.
- Permanent magnetic moments in ferromagnetic materials arise due to uncancelled electron spins by virtue of their electron structure.
- The coupling interactions of electron spins of adjacent atoms cause alignment of moments with one another.
- Example: transition metal iron(BCC α Ferrite), cobalt, nickel.

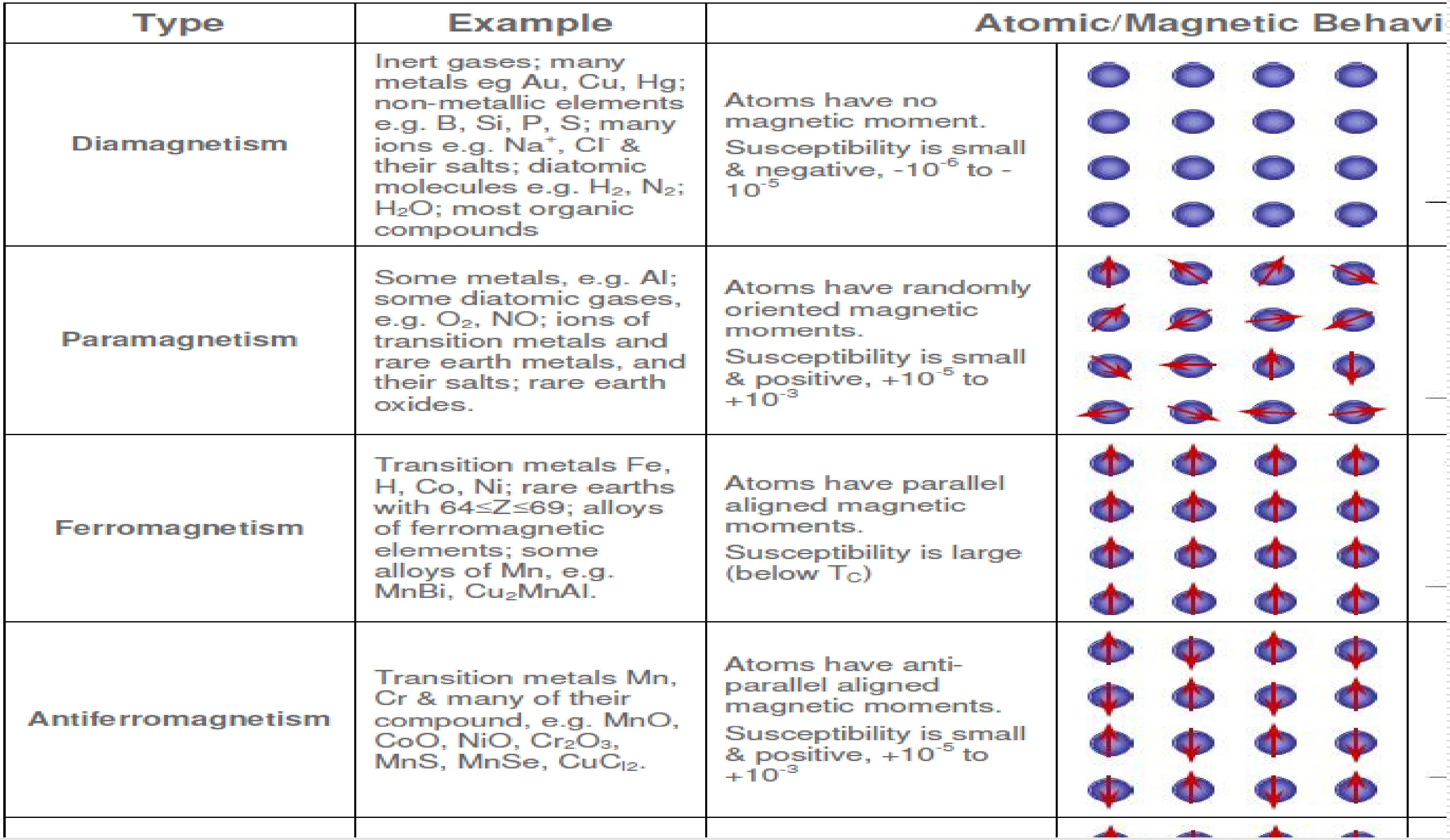
Antiferromagnetism

- ☐ These are materials in which electron spins associated with magnetic atoms at particular crystallographic sites are ordered yet oriented with respect to each other in such a manner that their net magnetization is equal to zero.
- ☐ This is the case below a particular temperature, called as Neel temperature (TN) above which the material behaves as a paramagnet.

Antiferromagnetism

- If the coupling of electron spins results in anti parallel alignment then spins will cancel each other and no net magnetic moment will arise.
- This is known as antiferromagnetism. MnO is one such example.
- In MnO, O^{2-} ions have no net magnetic moments and the spin moments of Mn^{2+} ions are aligned anti parallel to each other in adjacent atoms.

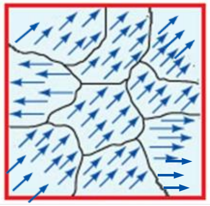




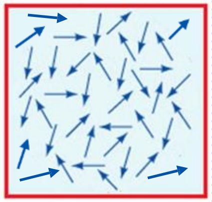
Type	Example	Atomic/Magnetic Behavi	
Diamagnetism	Inert gases; many metals eg Au, Cu, Hg; non-metallic elements e.g. B, Si, P, S; many ions e.g. Na^+, Cl^- & their salts; diatomic molecules e.g. H_2, N_2; H_2O; most organic compounds	Atoms have no magnetic moment. Susceptibility is small & negative, -10^{-6} to -10^{-5}	
Paramagnetism	Some metals, e.g. Al; some diatomic gases, e.g. O_2, NO; ions of transition metals and rare earth metals, and their salts; rare earth oxides.	Atoms have randomly oriented magnetic moments. Susceptibility is small & positive, $+10^{-5}$ to $+10^{-3}$	
Ferromagnetism	Transition metals Fe, H, Co, Ni; rare earths with $64 \leq Z \leq 69$; alloys of ferromagnetic elements; some alloys of Mn, e.g. MnBi, Cu_2MnAl.	Atoms have parallel aligned magnetic moments. Susceptibility is large (below T_C)	
Antiferromagnetism	Transition metals Mn, Cr & many of their compound, e.g. MnO, CoO, NiO, Cr_2O_3, MnS, MnSe, CuC_{l2}.	Atoms have anti-parallel aligned magnetic moments. Susceptibility is small & positive, $+10^{-5}$ to $+10^{-3}$	

Effect of Temperature

- The atomic vibration increases with increasing temperature and this leads to misalignment of magnetic moments. Above a certain temperature all the moments are misaligned and the magnetism is lost. This temperature is known as Curie temperature, Tc.
- Ferro and ferrimagnetic materials turn paramagnetic above curie point. For Fe Tc = 768 °C, Co – 1120 °C, Ni – 335 °C.



Below T_c



Above T_c

Thermal Properties

ISSUES TO ADDRESS...

- How do materials respond to the application of heat?
- How do we define and measure...
  - -- heat capacity?
  - -- Specific Heat?
  - -- thermal expansion?
  - -- thermal conductivity?
- How do the thermal properties of ceramics, metals, and polymers differ?

Heat Capacity

The ability of a material to absorb heat

- Quantitatively: The energy required to produce a unit rise in temperature for one mole of a material.

heat capacity (J/mol-K) → $C = \frac{dQ}{dT}$ ← energy input (J/mol)

← temperature change (K)

- Two ways to measure heat capacity:

C_p : Heat capacity at constant pressure.
C_v : Heat capacity at constant volume.

C_p usually > C_v

- Heat capacity has units of $\frac{\text{J}}{\text{mol}\cdot\text{K}}\left(\frac{\text{Btu}}{\text{lb}-\text{mol}\cdot{}^{\circ}\text{F}}\right)$

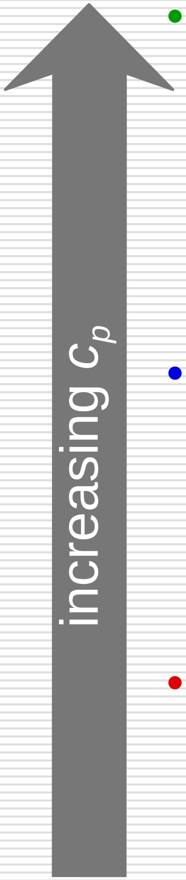
Difference between Heat Capacity and Specific Heat Capacity

Difference between Heat Capacity and Specific Heat Capacity are :

(1) Heat Capacity of the substance is defined as the amount of heat required to raise the temperature of the substance by 1oC whereas Specific Heat Capacity is defined as the amount of heat required to raise the temperature by 1oC of unit mass of substance.

(2) Specific Heat Capacity does not depend on mass of substance whereas Heat Capacity depends on mass of substance

Specific Heat: Comparison



Material	c_p (J/kg-K) at room T
Polymers	
Polypropylene	1925
Polyethylene	1850
Polystyrene	1170
Teflon	1050
Ceramics	
Magnesia (MgO)	940
Alumina (Al_2O_3)	775
Glass	840
Metals	
Aluminum	900
Steel	486
Tungsten	138
Gold	128

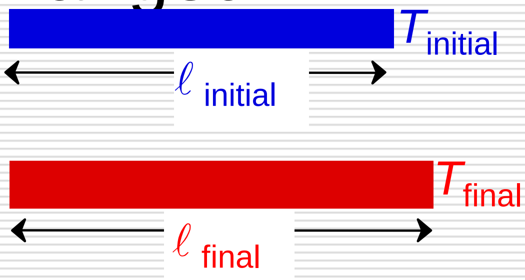
c_p (specific heat): (J/kg-K)

C_p (heat capacity): (J/mol-K)

Selected values from Table 19.1, *Callister & Rethwisch 8e*.

Thermal Expansion

Materials change size when temperature is changed



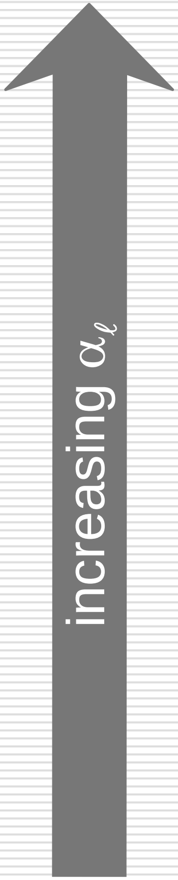
$T_{final} > T_{initial}$

$$\frac{l_{final} - l_{initial}}{l_{initial}} = \alpha_l (T_{final} - T_{initial})$$

linear coefficient of thermal expansion (1/K or 1/ºC)

Coefficient of Thermal Expansion : The coefficient of thermal expansion describes how the size of an object changes with a change in temperature. Specifically, it measures the fractional change in size per degree change in temperature at a constant pressure.

Coefficient of Thermal Expansion: Comparison



Material	α_ℓ (10^{-6}/°C) at room *T*
• Polymers	
Polypropylene	145-180
Polyethylene	106-198
Polystyrene	90-150
Teflon	126-216
• Metals	
Aluminum	23.6
Steel	12
Tungsten	4.5
Gold	14.2
• Ceramics	
Magnesia (MgO)	13.5
Alumina (Al_2O_3)	7.6
Soda-lime glass	9
Silica (cryst. SiO_2)	0.4

Polymers have larger α_ℓ values because of weak secondary bonds

Thermal Expansion: Example

Ex: A copper wire 15 m long is cooled from 40 to -9ºC. How much change in length will it experience?

- Answer: For Cu

$$\alpha_\ell = 16.5 \text{ x } 10^{-6} \ (^\circ\text{C})^{-1}$$

$$\Delta\ell = \alpha_\ell \ell_0 \Delta T = [16.5 \text{ x } 10^{-6} (1/^\circ\text{C})](15 \text{ m})[40^\circ\text{C} - (-9^\circ\text{C})]$$

$$\Delta\ell = 0.012 \text{ m} = 12 \text{ mm}$$

Thermal Conductivity

The ability of a material to transport heat.

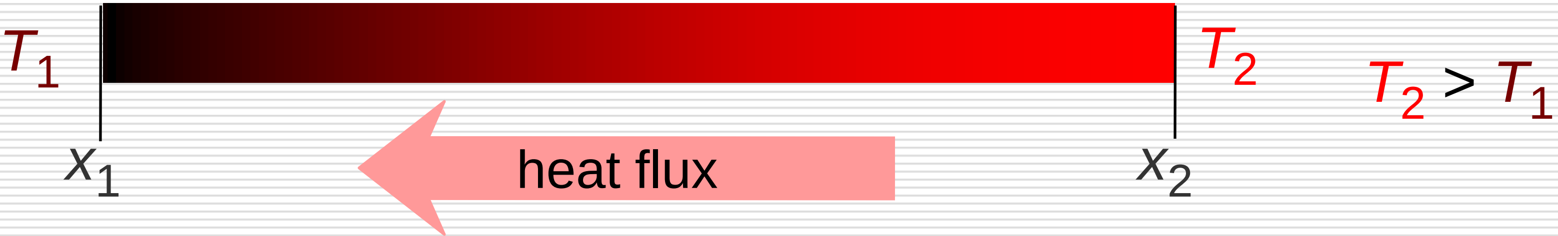
Fourier's Law

$$q = -k\frac{dT}{dx}$$

heat flux
(J/m²-s)

temperature gradient

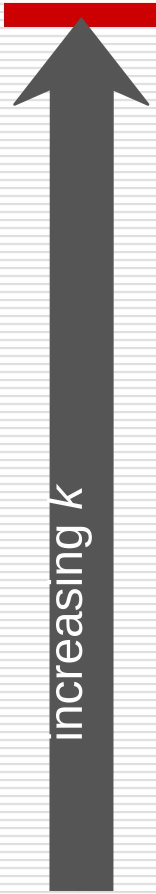
thermal conductivity (J/m-K-s)



- Atomic perspective: Atomic vibrations and free electrons in hotter regions transport energy to cooler regions.

Thermal Conductivity : The **thermal conductivity** of a material is a measure of its ability to conduct **heat**

Thermal Conductivity: Comparison



Material	*k* (W/m-K)	Energy Transfer Mechanism
Metals		
Aluminum	247	atomic vibrations and motion of free electrons
Steel	52	
Tungsten	178	
Gold	315	
Ceramics		
Magnesia (MgO)	38	atomic vibrations
Alumina (Al_2O_3)	39	
Soda-lime glass	1.7	
Silica (cryst. SiO_2)	1.4	
Polymers		
Polypropylene	0.12	vibration/rotation of chain molecules
Polyethylene	0.46-0.50	
Polystyrene	0.13	
Teflon	0.25	

Selected values from Table 19.1, *Callister & Rethwisch 8e*.

Thermal Conductivity of Materials

Material	κ (W m^{-1} K^{-1})	comments
Silver	422	room T metals feel cold
Copper	391	great for pulling away heat
Gold	295	
Aluminum	205	
Stainless Steel	10–25	why cookware uses S.S.
Glass, Concrete,Wood	0.5–3	buildings
Many Plastics	~0.4	room T plastics feel warm
G-10 fiberglass	0.29	strongest insulator choice
Stagnant Air	0.024	but usually moving…
Styrofoam	0.01–0.03	can be better than air!

Summary

The thermal properties of materials include:

- **Heat capacity**:
  - -- energy required to increase a mole of material by a unit *T*
  - -- energy is stored as atomic vibrations
- **Coefficient of thermal expansion**:
  - -- the size of a material changes with a change in temperature
  - -- polymers have the largest values
- **Thermal conductivity**:
  - -- the ability of a material to transport heat
  - -- metals have the largest values

THANK YOU