ADVANCE MATERIAL & CHARECTERIZATION (MME-169)

UNIT 2
HARDNESS

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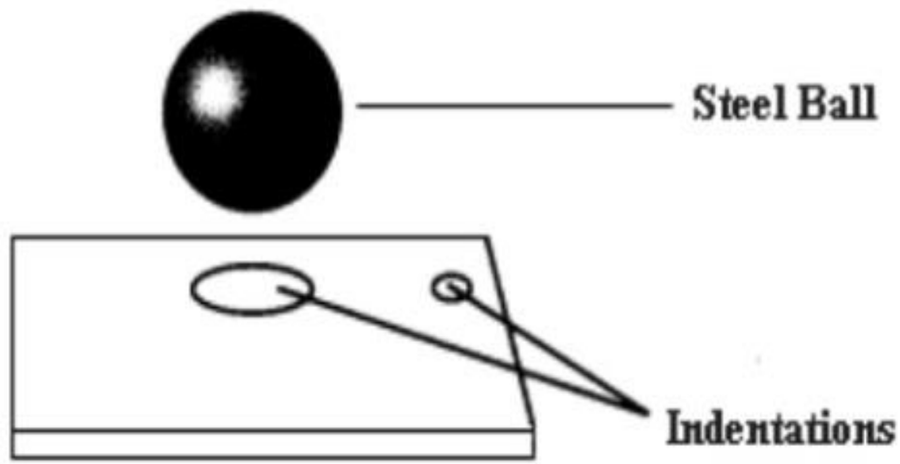
Hardness

- It is a measure of a material's **resistance to localized plastic deformation** (e.g. A small dent or a scratch).
- Hardness tests are performed more frequently than any other mechanical test for several reasons:

1. They are **simple and inexpensive**
2. The test is **non-destructive**
3. Other mechanical properties often may be estimated from hardness data, such as tensile strength.



Types of Hardness Tests

Different types of hardness tests are:

- Rockwell Hardness Tests
- Brinell Hardness Tests
- Vickers and Knoop Hardness Tests

Rockwell Hardness Tests

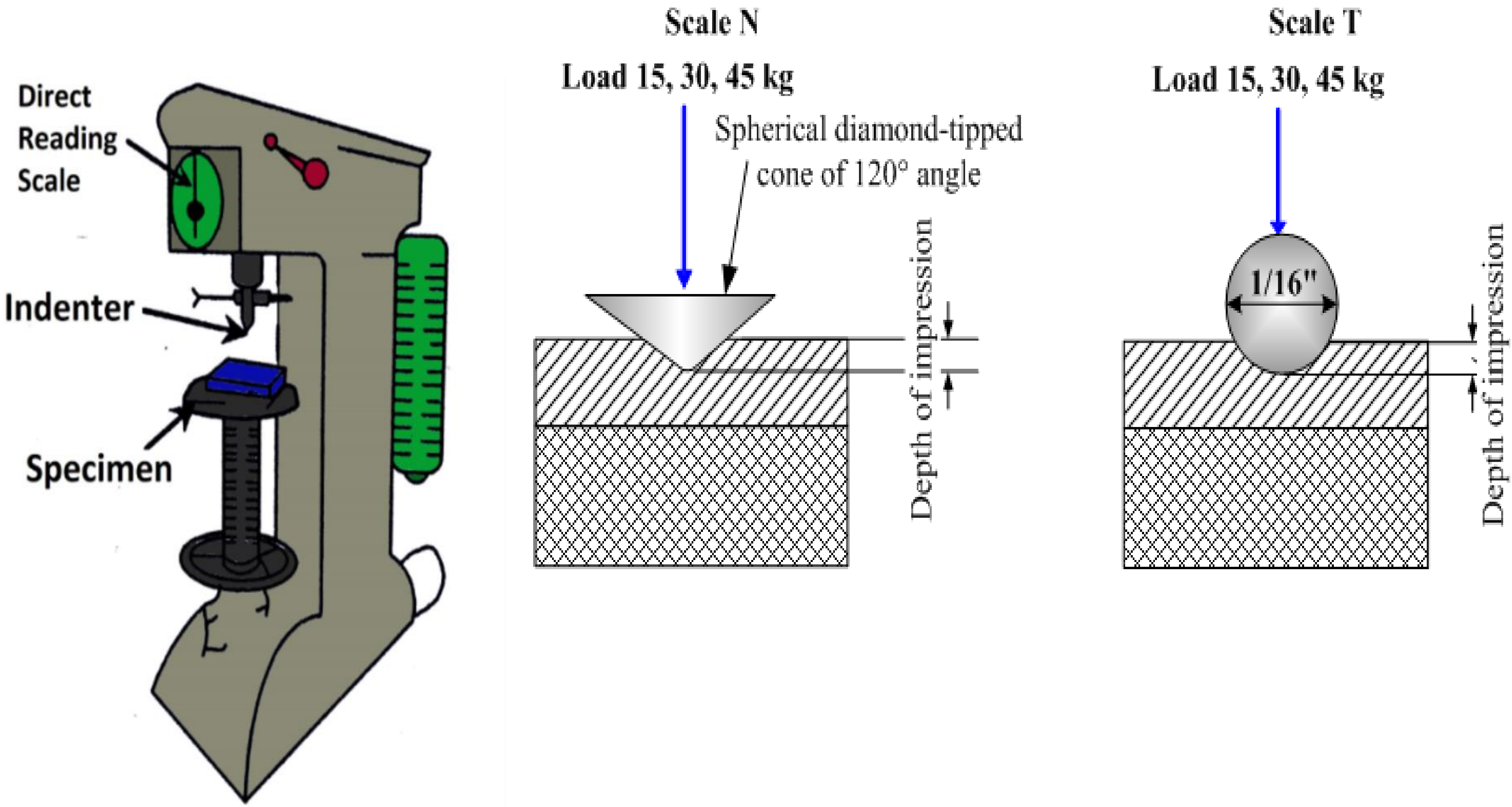
- The Rockwell tests constitute most common method used to measure hardness because they are so **simple to perform and require no special skills.**
- **Several different scales may be utilized from possible combinations of various indenters and different loads**, which permit the testing of all metal alloy and as well as some polymers.
- Indenters include **spherical and hardened steel balls having diameters of 1/16, 1/8,1/4 and 1/2 inch** and a conical diamond indenter, which is used for the hardest material.
- Types of Rockwell tests:

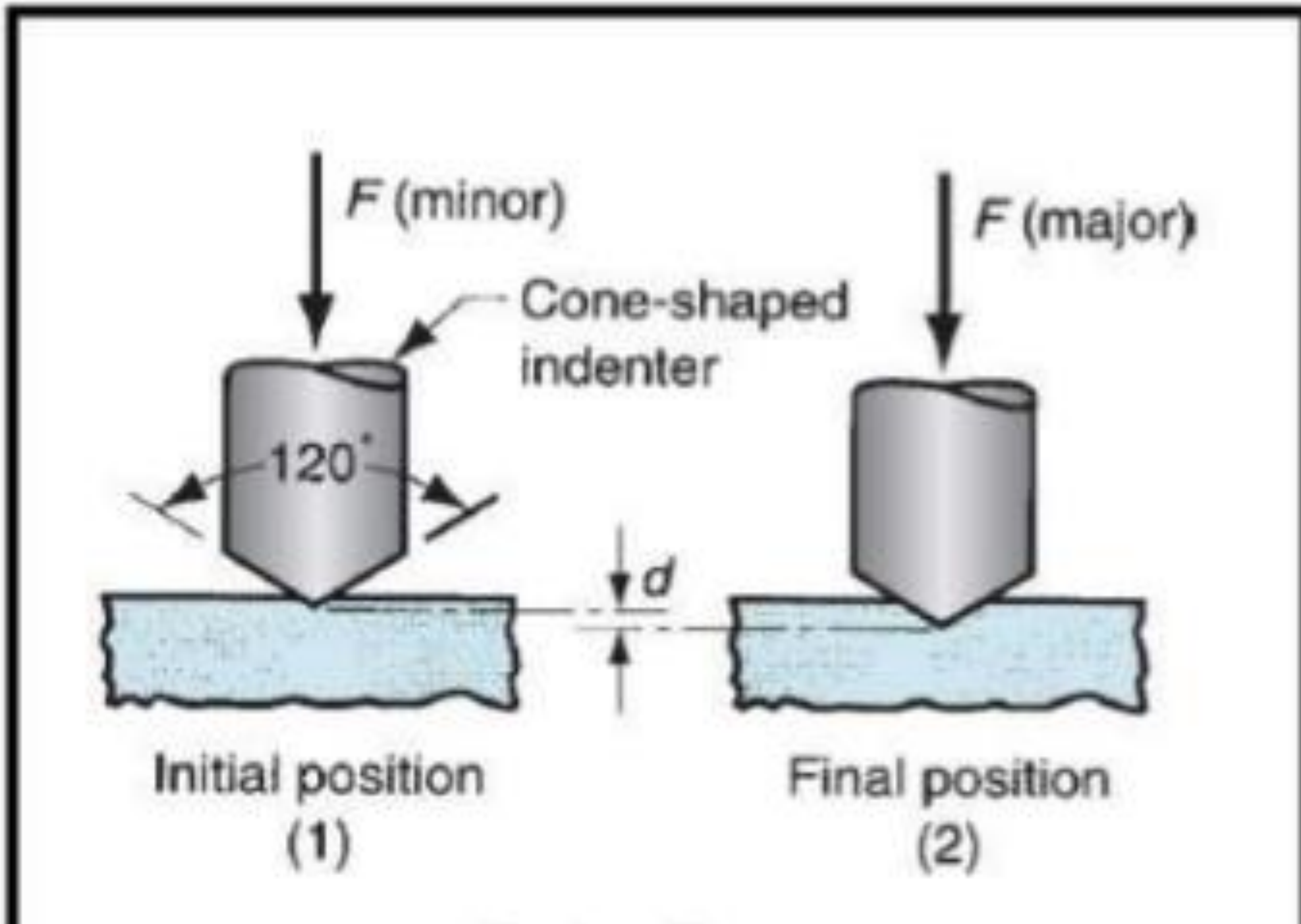
Rockwell (Minor load is 10 kg and major load are 60,100 and 150 kg)

Superficial Rockwell (Minor load is 3 kg and major load are 15, 30 and 45 kg)

For both the scale designated y the **symbol HR**

Rockwell Superficial Hardness Test




F (minor)
F (major)
Cone-shaped indenter
120°
d
Initial position (1)
Final position (2)
Rockwell

Rockwell Hardness Scale

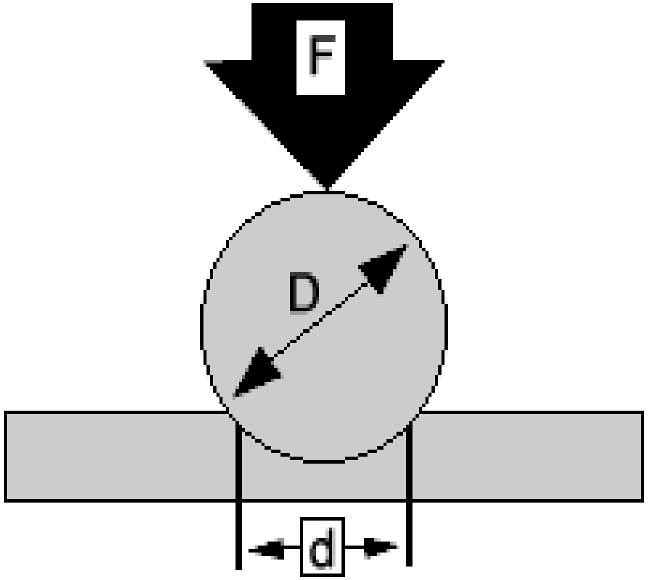
Scale symbol	Penetrator	Major load (kg.)	Dial number
A	Diamond	60	Black
B	1/16-inch ball	100	Red
C	Diamond	150	Black
D	Diamond	100	Black
E	1/8-inch ball	100	Red
F	1/16-inch ball	60	Red
G	1/16-inch ball	150	Red
H	1/8-inch ball	60	Red
K	1/8-inch ball	150	Red

Brinell Hardness

- The diameter of the hardened steel (or tungsten carbide) indenter is 10 mm.

- Standard loads range between 500 and 3000kg in 500 kg increments; during a test, the load is maintained constant for a specified time (between 10 and 30 sec).

- The Brinell hardness number, HB, is a function of both the magnitude of the load and the diameter of the resulting indentation.

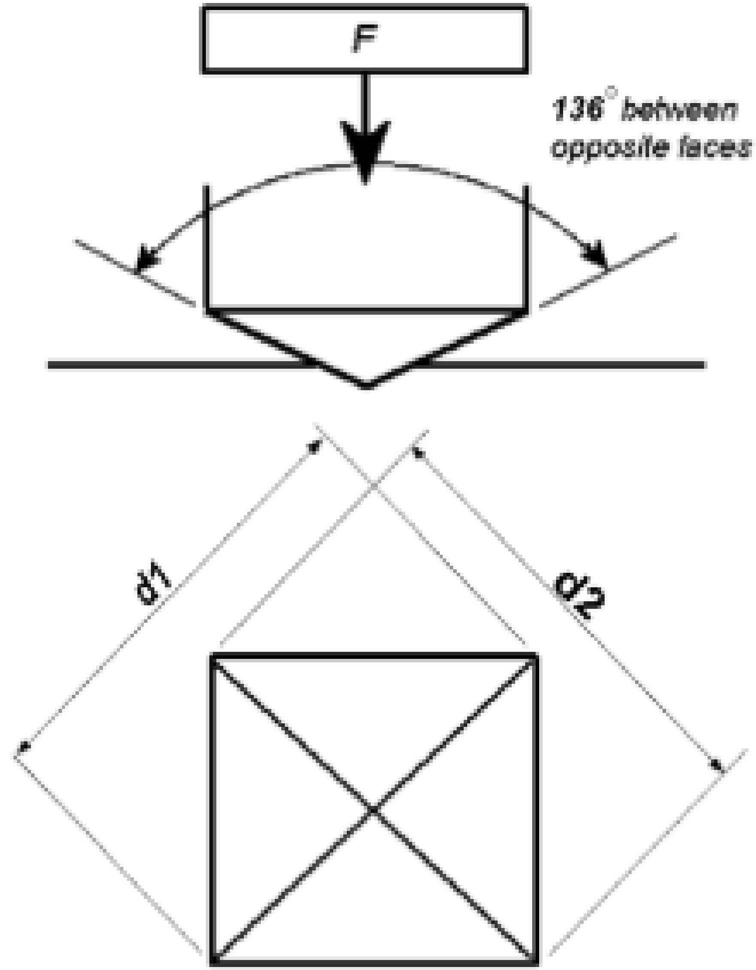


$$HB = \frac{2F}{\pi D\left(D - \sqrt{D^2 - d^2}\right)}$$

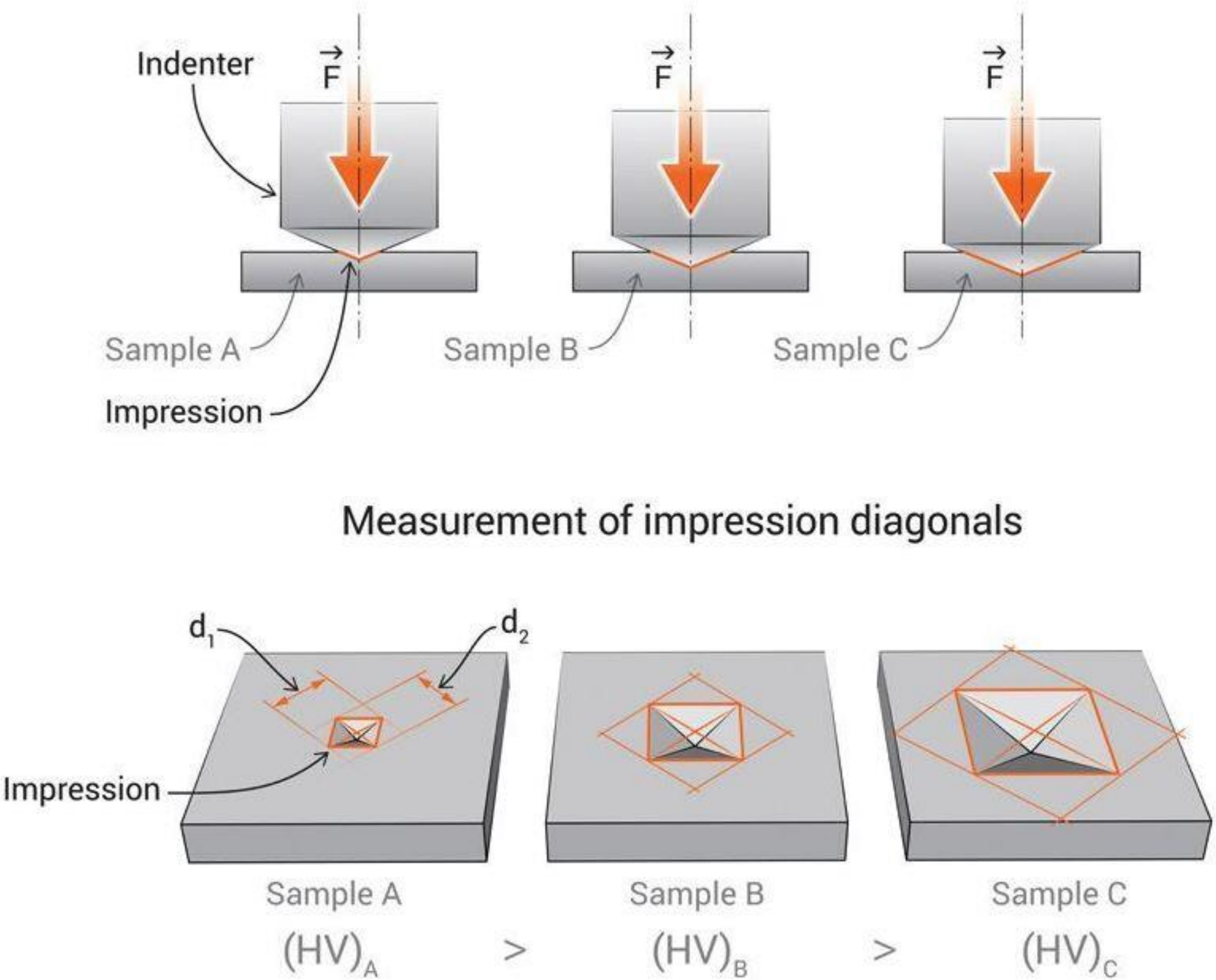
Vickers and Knoop Hardness Tests

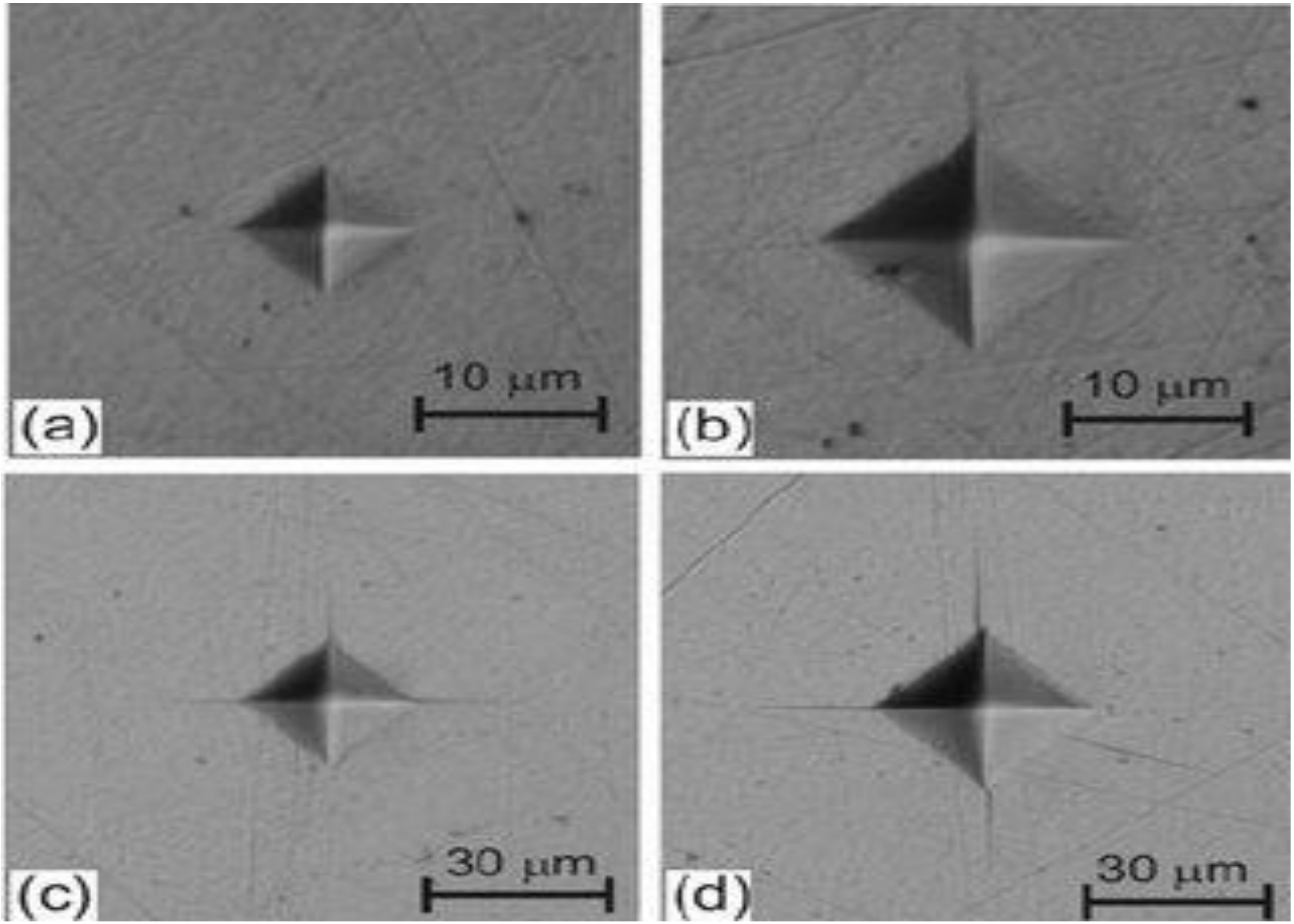
- In both the test a very small diamond indenter having pyramidical geometry is forced into the surface of the specimen.
- Applied loads are much smaller than for Rockwell and Brinell, ranging between 1 and 1000 g.
- The resulting impression is observed under a microscope and measured.
- The Vickers and Knoop hardness numbers are designated by HV and HK respectively.
- Knoop and Vickers are referred to as micro-indentation testing methods on the basis of indenter size.
- Knoop is used for testing brittle materials such as ceramics.

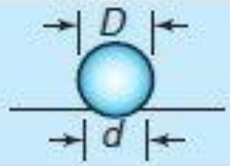
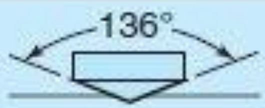
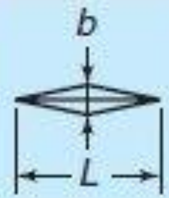
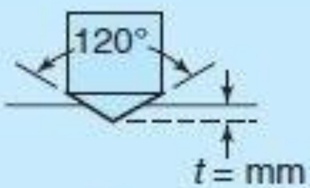
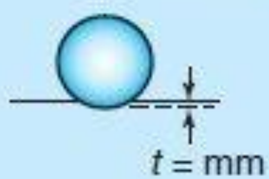
Vicker's Hardness



Vicker's Hardness




10 µm
(a)
10 µm
(b)
30 µm
(c)
30 µm
(d)

Test	Indenter	Shape of indentation: Side view	Shape of indentation: Top view	Load, P	Hardness number
Brinell	10-mm steel or tungsten-carbide ball			500 kg 1500 kg 3000 kg	$HB = \dfrac{2P}{(\pi D)\left(D - \sqrt{D^2 - d^2}\right)}$
Vickers	Diamond pyramid			1–120 kg	$HV = \dfrac{1.854P}{L^2}$
Knoop	Diamond pyramid	 $L/b = 7.11$ $b/t = 4.00$		25 g–5 kg	$HK = \dfrac{14.2P}{L^2}$
Rockwell					
A, C, D	Diamond cone			60 kg 150 kg 100 kg	HRA, HRC, HRD $= 100 - 500t$
B, F, G	$\frac{1}{16}$-in. diameter steel ball			100 kg 60 kg 150 kg	HRB, HRF, HRG $= 130 - 500t$
E	$\frac{1}{8}$-in. diameter steel ball			100 kg	HRE $= 130 - 500t$

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FRACTURE

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Fracture

The separation of a body into two or more pieces under the application of stress.

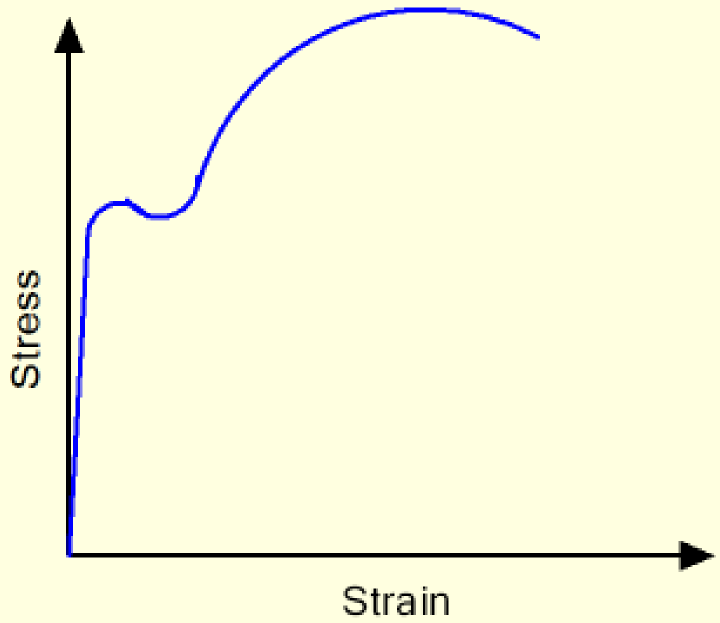
Types of fracture

- Ductile fracture
- Brittle fracture

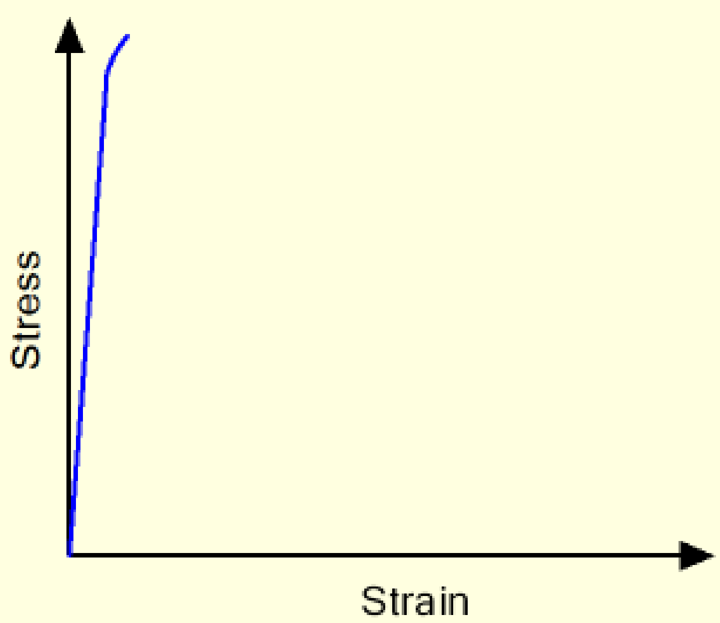
Ductile materials - extensive plastic deformation and energy absorption ("toughness") before fracture

Brittle materials - little plastic deformation and low energy absorption before fracture

Stress-Strain curve for ductile and brittle materials

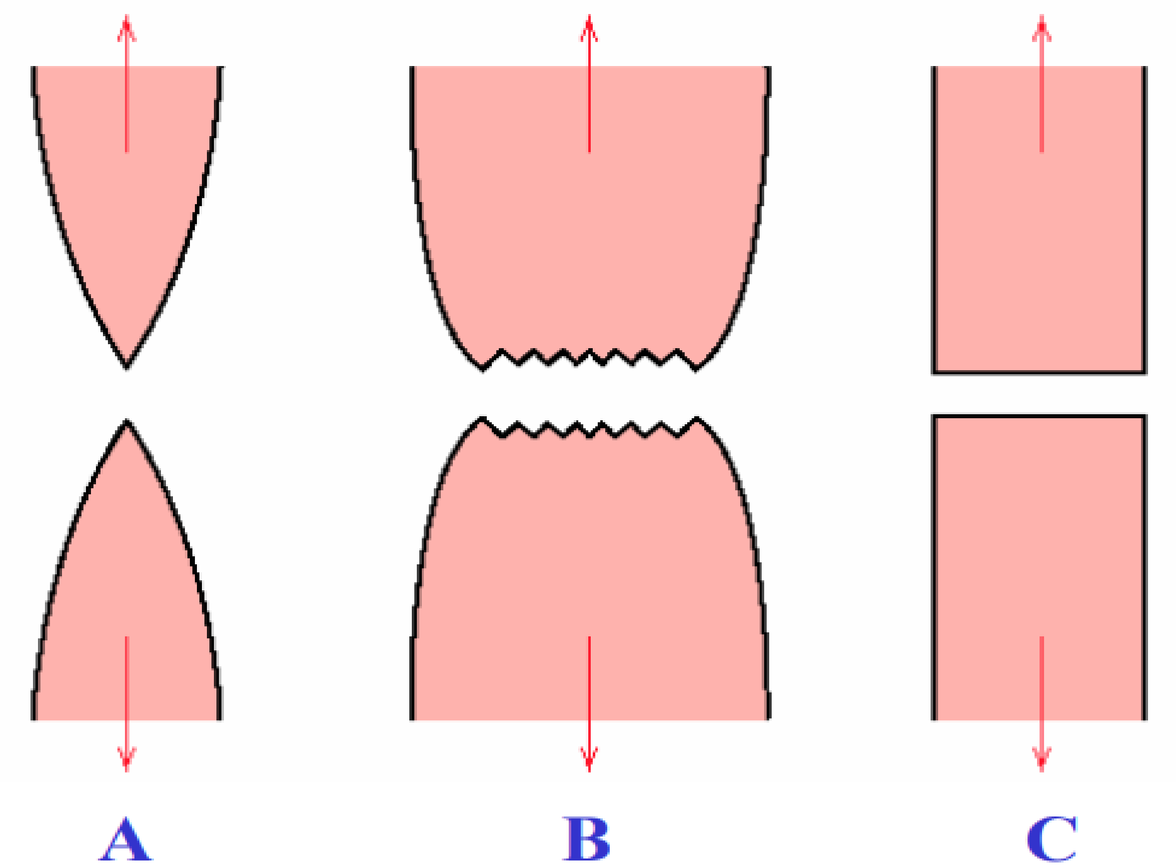


Typical Ductile Material



Typical Brittle Material

Fracture



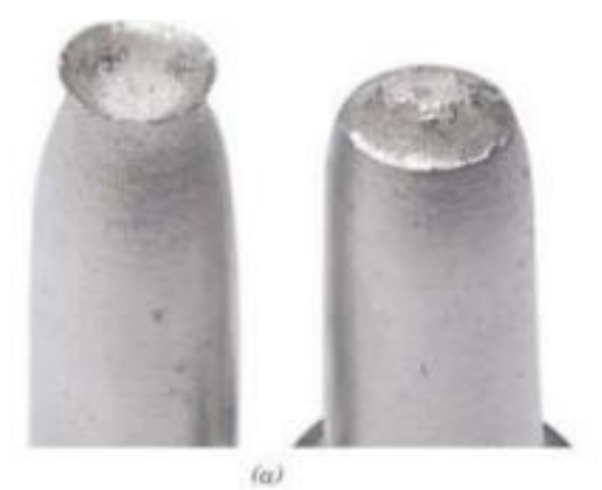
A. Very ductile, soft metals (e.g. Pb, Au) at room temperature, other metals, polymers, glasses at high temperature.

B. Moderately ductile fracture, typical for ductile metals

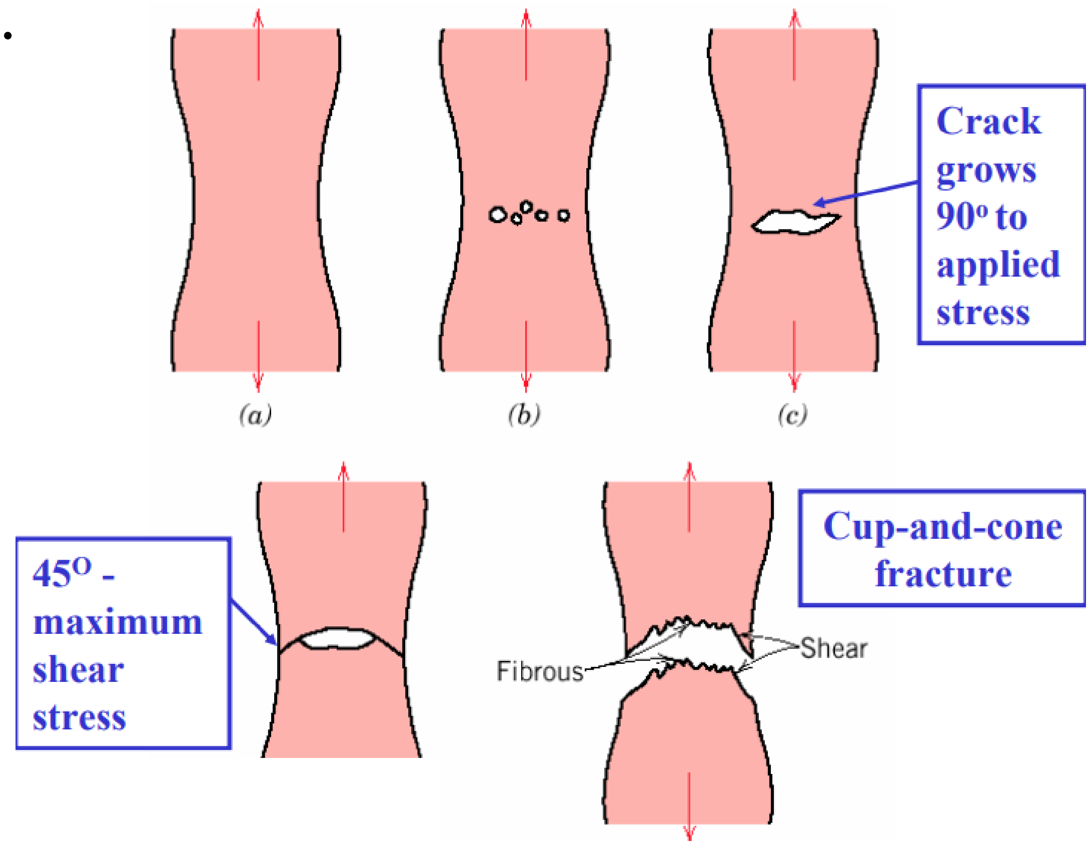
C. Brittle fracture, cold metals, ceramics.

Ductile fracture

Ductile Fracture in the converse and involves large plastic deformation before separation.



cup-and-cone fracture



(a) Necking

(b) Formation of microvoids

(c) Coalescence of microvoids to form a crack

(d) Crack propagation by shear deformation

(e) Fracture

Brittle fracture

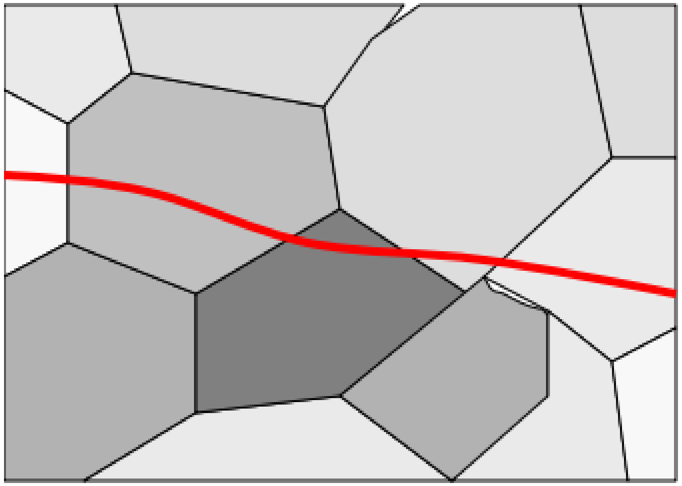
Brittle Fracture involves fracture without any appreciable plastic deformation (i.e. energy absorption).

brittle fracture

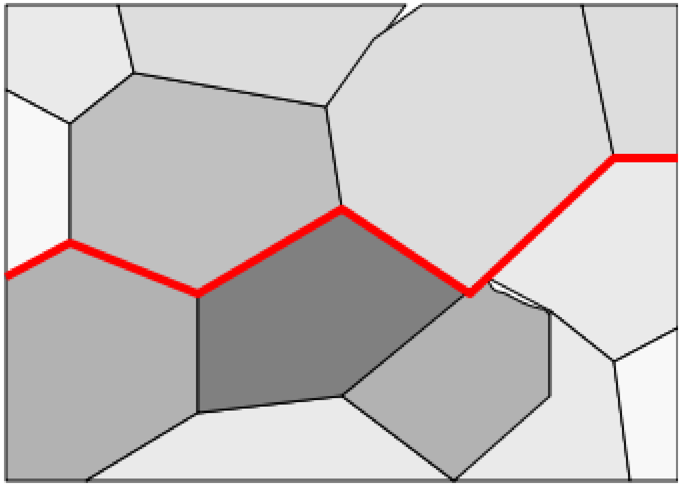
Types of Brittle fracture

Transgranular fracture: Fracture cracks pass through grains. Fracture surface have faceted texture because of different orientation of cleavage planes in grains.

Intergranular fracture: Fracture crack propagation is along grain boundaries (grain boundaries are weakened or embrittled by impurities segregation etc.)

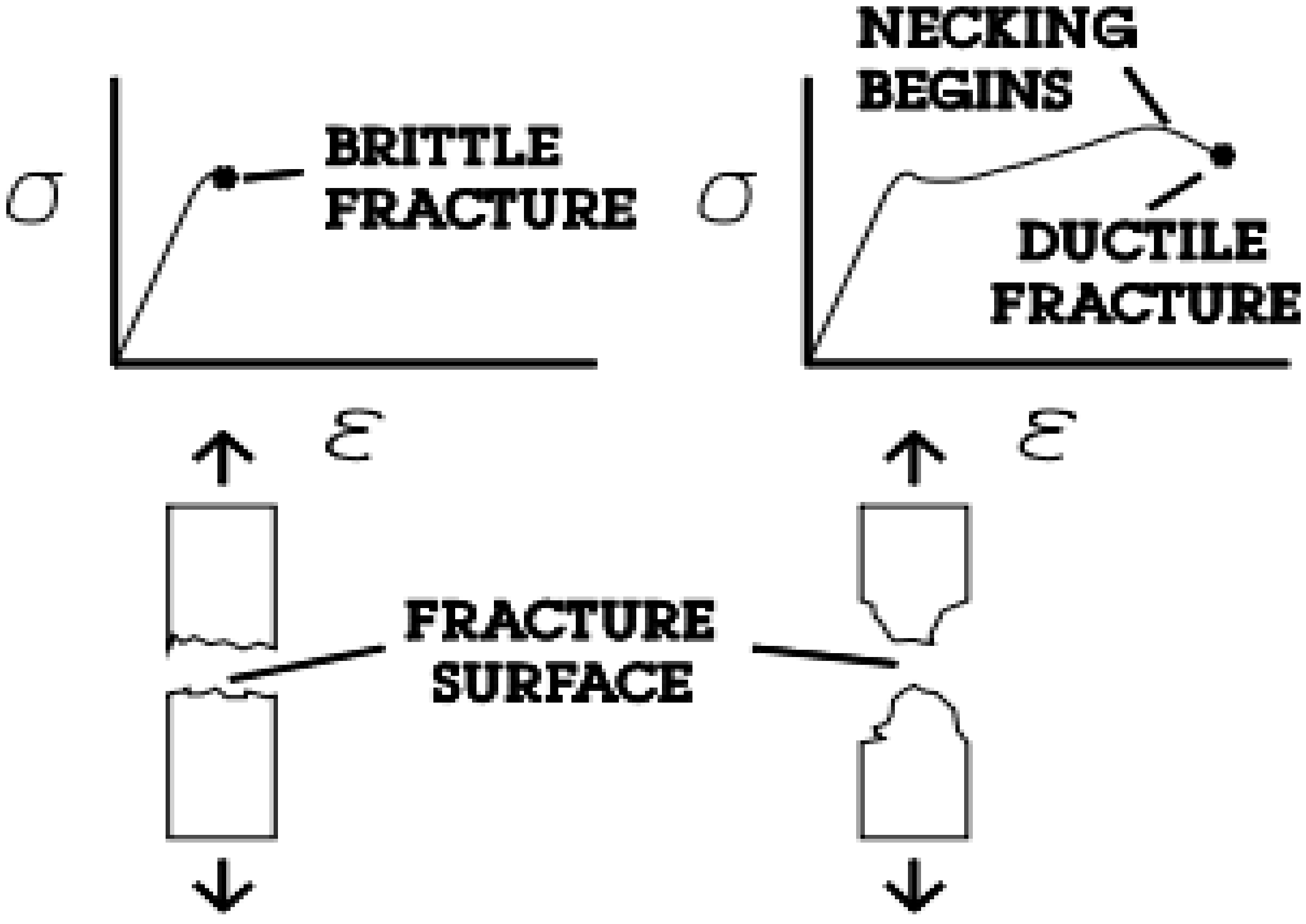


Transgranular fracture



Intergranular fracture

Brittle vs. Ductile fracture



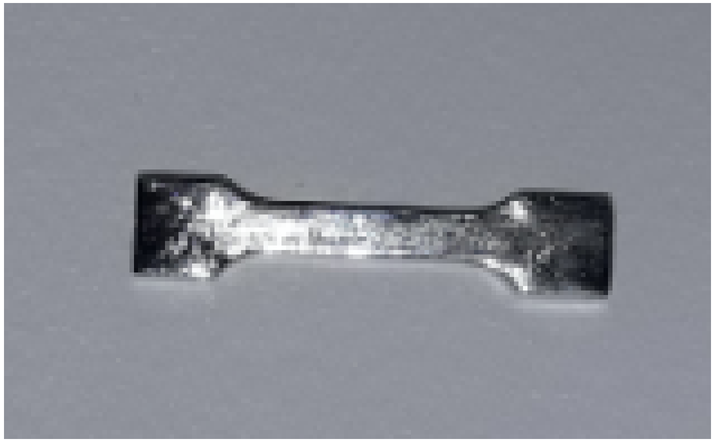
Dog-bone shape specimen

Universal Testing Machine

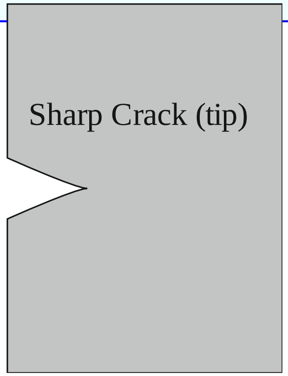
The tensile test (or fracture test with crack presence) performed on Universal Testing Machine (UTM) INSTRON 3369,

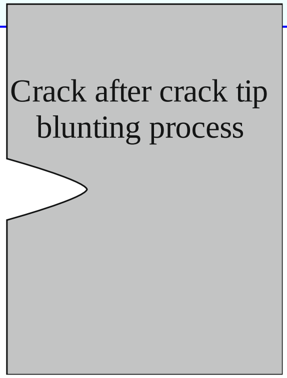
applied load of 50KN and pull rate of 2mm/min

According to ASTM E8 size of sample is of $30\times7\times2.5$ mm^3 dimension and gauge length $12\ mm$



- **Fracture mechanics** is the subject of study, wherein the a materials resistance to fracture is characterized. In other words the 'tolerance' of a material to crack propagation is analyzed*.
- Crack propagation can be *steady* (i.e. slowly increasing crack length with time or load) or can be *catastrophic* (unsteady crack propagation, leading to sudden failure of the material)$.
- *'What dislocation is to slip, crack is to fracture'.*
- Under tensile loading if the stress exceeds the yield strength the material, the material begins to plastically deform. The area under the stress-strain curve is designated as the *toughness* in uniaxial tension. Toughness relates to the energy absorbed to fracture.
- Similarly, in the presence of cracks we arrive at a *material parameter*, which characterizes the toughness of the material in the presence of cracks→ the **fracture toughness**.
- In *most* materials, even if the material is macroscopically brittle (i.e. shows very little plastic deformation in a uniaxial tension test), there might be some ductility at the microscopic level. This implies that in most materials the crack tip is not 'infinitely' sharp, but is *blunted* a little (blunting occurs by plastic deformation). This further avoids the stress singularity at the crack tip as we shall see later.

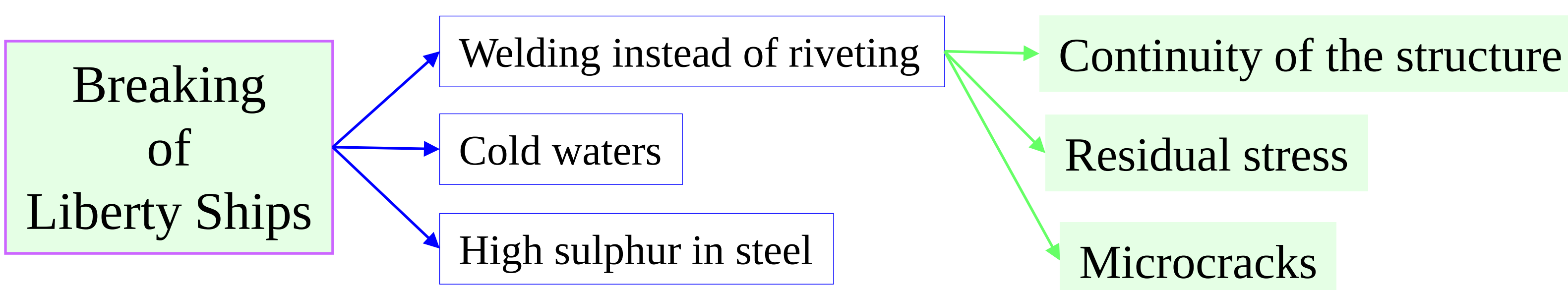




$ *One of the important goals of material/component design is to avoid catastrophic failure. If crack propagation is steady, then we can practice preventive maintenance (i.e. replace the component after certain hours of service) → this cannot be done in the case of catastrophic failure.*

* *Amongst its many other goals!*

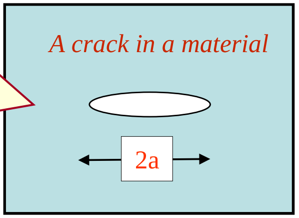
- The subject of Fracture mechanics has its origins in the failure of WWII Liberty ships. In one of the cases the ship virtually broke into two with a loud sound, when it was in the harbour– i.e. not in ‘fighting mode’.
- This was caused by lack of fracture toughness at the weld joint, resulting in the propagation of ‘brittle cracks’ (i.e. crack propagation will little plastic deformation). The full list of factors contributing to this failure is in the figure below.
- It is seen that welding was done for faster production, but this resulted in micro-cracks and residual stresses, which led to brittle crack propagation. The problem became ‘global’ as this provided continuity of crack path across plates (so instead of one plate breaking the entire ship ‘broke’). High sulphur in steel contributed to the brittleness of the plates.
- Due to the cold sea waters the ships were harboured in, the hull material underwent a phenomenon known as ‘ductile to brittle transition (DBT)’ (about which we will learn more in this chapter).
- Ironically, this ‘death’ of ships lead to the ‘birth’ of fracture mechanics as a systematic field of study.

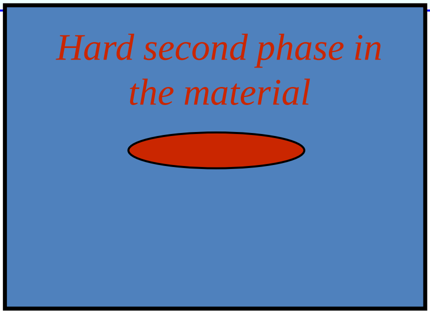


What is a crack?

- As we have seen crack is an amplifier of ‘far-field’ mean stress. The sharper the crack-tip, the higher will be the stresses at the crack-tip. It is a region where atoms are ‘debonded’ and an internal surface exists (this internal surface may be connected to the external surface).
- Cracks can be sharp in brittle materials, while in ductile materials plastic deformation at the crack-tip blunts the crack (leading to a lowered stress at the crack tip and further alteration of nature of the stress distribution).
- Even void or a through hole in the material can be considered a crack. Though often a crack is considered to be a discontinuity in the material with a ‘sharp’ feature (i.e. the stress amplification factor is large).
- A second phase (usually hard brittle phase) in a lens/needle like geometry can lead to stress amplification and hence be considered a crack. Further, (in some cases) debonding at the interface between the second phase and matrix can lead to the formation of an interface cracks.
- As the crack propagates fresh (internal) surface area is created. The *fracture surface* energy required for this comes from the strain energy stored in the material (which could further come from the work done by externally applied loads). In ductile materials energy is also expended for plastic deformation at the crack tip.
- A crack reduces the stiffness of the structure *(though this may often be ignored)*.

Though often in figures the crack is shown to have a large lateral extent, it is usually assumed that the crack does not lead to an appreciable decrease in the load bearing area [i.e. crack is a local stress amplifier, rather than a ‘global’ weakener– by decreasing the load bearing area].





Characteristics of Cracks

Cracks can be characterized looking into the following aspects.

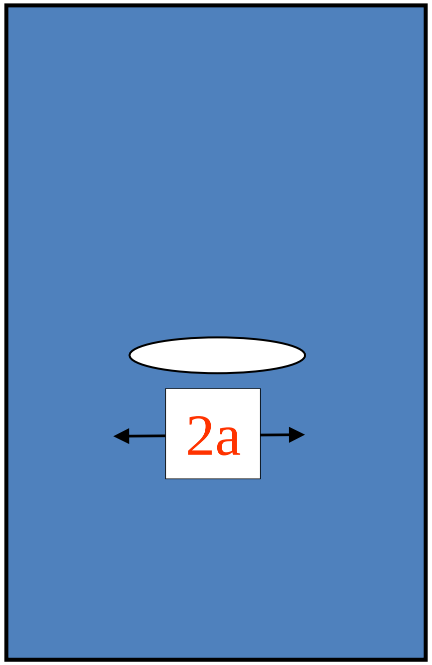
- Its connection with the external free surface:

  (i) completely internal,

  (ii) internal cracks with connections to the outer surfaces,

  (iii) Surface cracks.

  • Cracks with some contact with external surfaces are exposed to outer media and hence may be prone to oxidation and corrosion (cracking). We will learn about stress corrosion cracking later.
- Crack length (the deleterious effect of a crack further depends on the type of crack (i, ii or iii as above).
- Crack tip radius (the sharper the crack, the more deleterious it is). Crack tip radius is dependent of the type of loading and the ductility of the material.
- Crack orientation with respect to geometry and loading. We will see modes of loading in this context soon.



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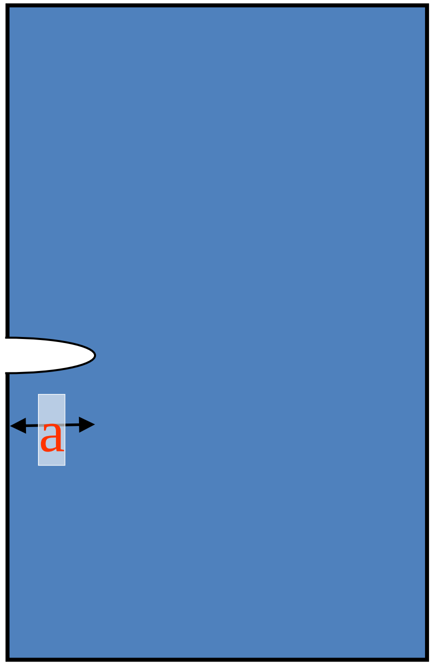
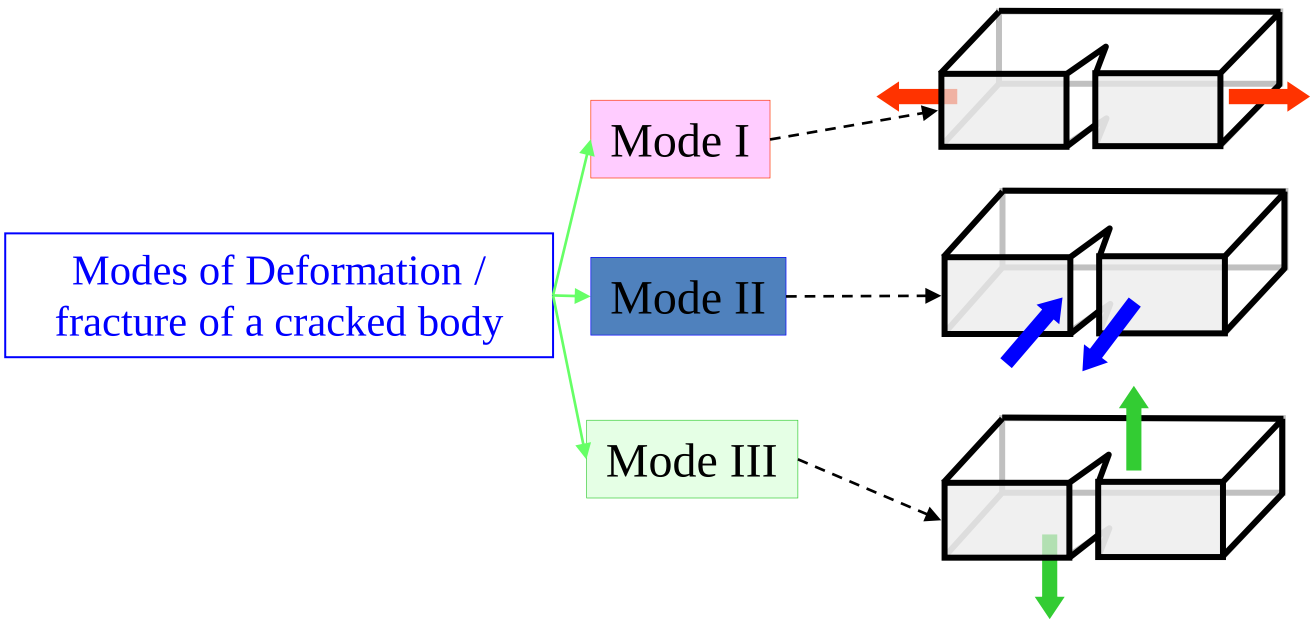
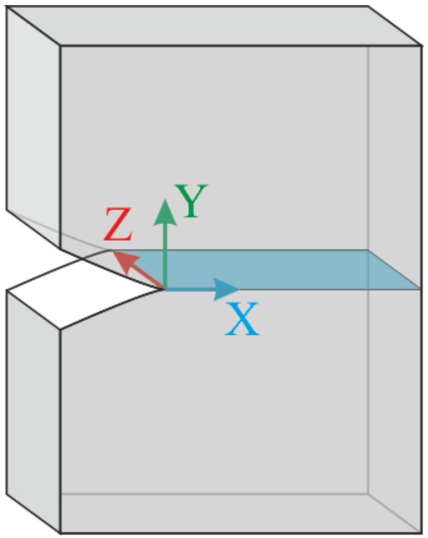


Modes of deformation of a cracked body (modes of fracture)

How many ways are there to load a cracked body?

- Three ideal cases of loading of a cracked body can be considered, which are called the modes of deformation:
  - Mode I: Opening mode
  - Mode II: Sliding mode
  - Mode III: Tearing mode
- In the general case (for a crack in an arbitrarily shaped body, under an arbitrary loading), the mode is not pure (i.e. is mixed mode). The essential aspects of fracture can be understood by considering mode I.





Important note: the loading specified and the geometry of the specimen illustrated for Mode II & III above do not give rise to pure Mode II and II deformation (other constraints or body shapes are required).

Fracture: Important Points

- One of the goals of fracture mechanics is to derive a material property (the fracture toughness), which can characterize the mechanical behaviour of a material with flaws (cracks) in it.
- Fracture can broadly be classified into Brittle and Ductile fracture. This is usually done using the macroscopic ductility observed and usually not taking into account the microscale plasticity, which could be significant. A ductile material is one, which yields before fracture.
- Further, one would like to avoid brittle fracture, wherein crack propagation leading to failure occurs with very little absorption of energy (in brittle fracture the crack may grow unstably, without much predictability).
- Three factors have a profound influence on the nature of fracture:
  (i) temperature, (ii) strain rate, (iii) the state of stress.
- Materials which behave in a brittle fashion at low temperature may become ductile at high temperatures. When strain rate is increased (by a few orders of magnitude) a ductile material may start to behave in a brittle fashion.

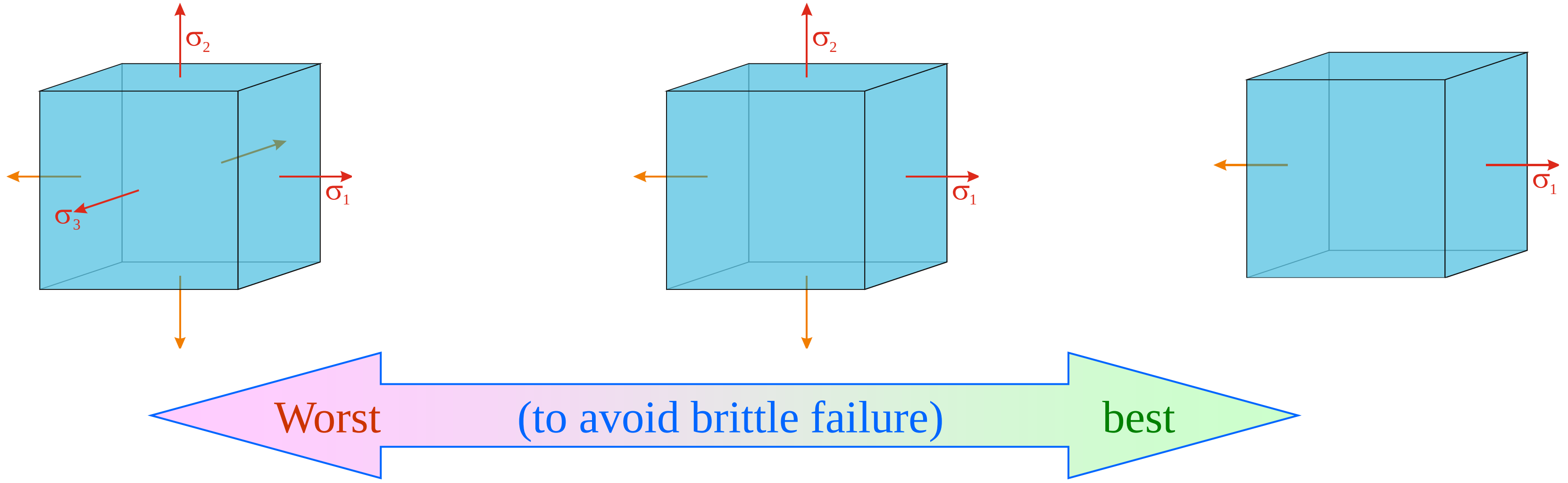
Ductile material : $\sigma_y < \sigma_f$

Factors affecting (the nature of) fracture
- Temperature
- Strain rate
- State of stress

Fracture
- Ductile
- Brittle
  - Promoted by
    - Low Temperature
    - High Strain rate
    - Triaxial state of State of stress

Why do high strain rate, low temperature and triaxial state of stress promote brittle fracture?

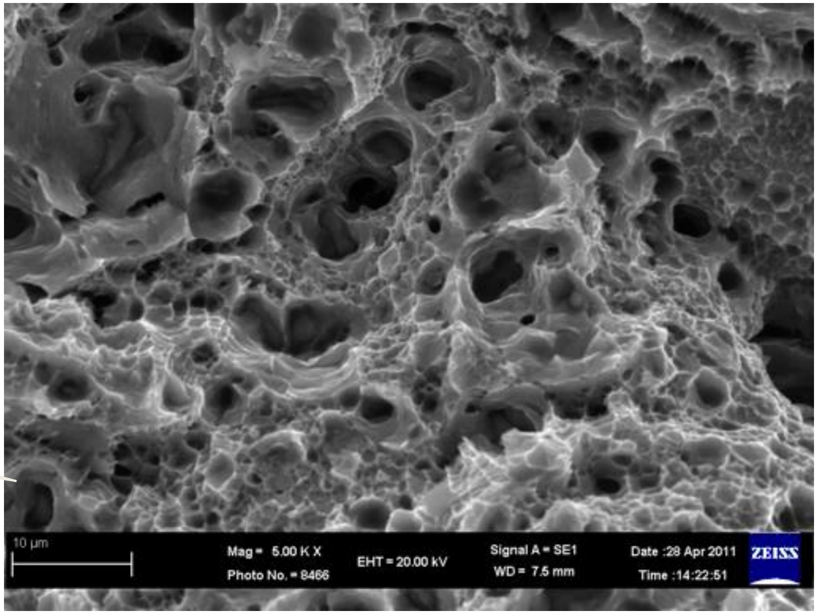
- High strain rate (by not giving sufficient time) and low temperature essentially have a similar effect of not allowing thermally activated motion of dislocations (i.e. 'not helping' plastic deformation by slip).
- In specific cases some of the slip systems being active at high temperatures may become inactive at low temperatures.
- By triaxial state of stress (SoS) we mean tensile stresses of *same sign* along 'y' and 'z' also.
- Triaxial SoS does not promote crack propagation, but suppresses plastic deformation *(click on link below to know more)*. Since plastic deformation is suppressed the crack tip remains sharp, thus promoting brittle fracture. Click here to know more about which state of stress is good for plastic deformation
- So for plastic deformation the following order is better: tri-axial < bi-axial < uni-axial.



Fractography

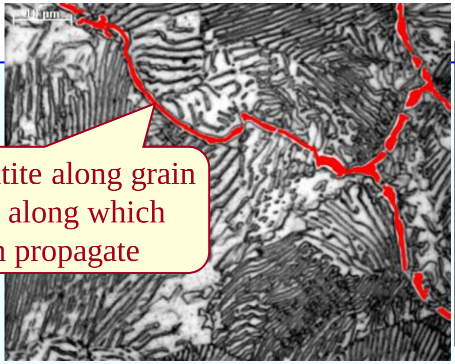
- Considerable amount of information can be gathered regarding the origin and nature of fracture by studying the fracture surface. In fatigue failure for instance, we can know the place of origin of cracks, stable crack propagation regime, etc.
- The fracture surface has to be maintained in pristine manner (i.e. oxidation, contact damage, etc. should be avoided) to get meaningful information from fractography.
- It should be noted that a sample which shows very little macroscopic ductility, may display microscopic ductility (as can be seen in a fractograph).
- Truly brittle samples show faceted cleavage planes, while ductile fracture surface displays a dimpled appearance.

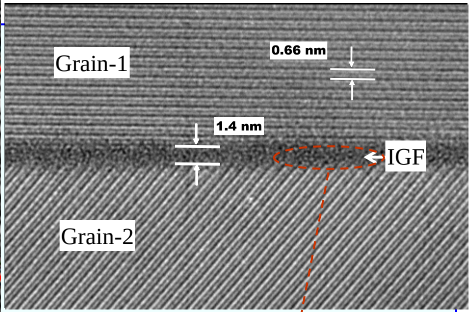
Fracture surface as seen in an SEM*



** The Scanning Electron Microscope (SEM) with a large depth of field is an ideal tool to do fractography.*

Classification of Fracture (based on various features)

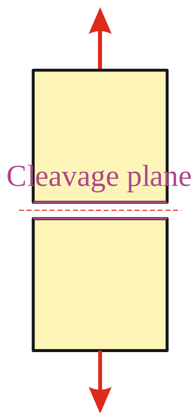


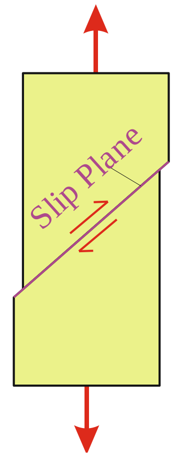


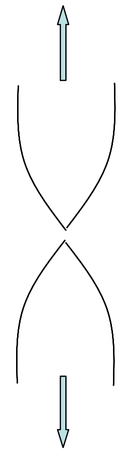
- Fracture can be classified based on:
  (i) Crystallographic mode,
  (ii) Appearance of Fracture surface,
  (iii) Strain to fracture,
  (iv) Crack Path, etc. (As in the table below).
- Presence of chemical species at the crack tip can lead to reduced fracture stress and enhanced crack propagation.
- Presence of brittle phase along the grain boundaries (Fe_3C along GB in steel, glassy phase at GB in Si_3N_4 ceramics) can lead to inter-granular crack propagation. This preferred 'weak' path along grain boundaries implies low energy expenditure during fracture (i.e. low fracture toughness).

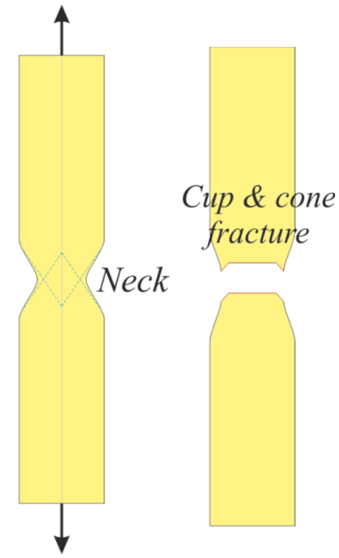
Behaviour described	Terms Used	
Crystallographic mode	Shear (ductile)	Cleavage (brittle)
Appearance of Fracture surface	Fibrous	Granular / bright
Strain to fracture	Ductile	Brittle
Path	Transgranular (crack propagates through the grains)	Intergranular (crack propagates through the grain boundaries)

Types of failure in an uniaxial tension test









Brittle	Shear	Rupture	Ductile fracture
Little or no deformation	Shear fracture of ductile single crystals	Completely ductile fracture of polycrystals	Ductile fracture of usual polycrystals
Observed in single crystals and polycrystals	Not observed in polycrystals	Very ductile metals like gold and lead neck down to a point and fail	Cup and cone fracture
Have been observed in BCC and HCP metals but not in FCC metals		*Here technically there is no fracture (there is not enough material left to support the load)*	Cracks may nucleate at second phase particles (void formation at the matrix-particle interface)

Crack growth and failure

Brittle Materials

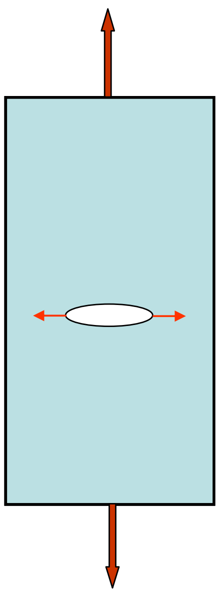
- Initially we try to understand crack propagation[$] in brittle materials (wherein the cracks are sharp and there is very little crack-tip plasticity). The is the domain of *Linear Elastic Fracture Mechanics (LEFM)*.
- For crack to propagate the necessary global criterion (due to Griffith) and the sufficient local criterion (due to Inglis) have to be satisfied (as in figure below). Global vs. Local
- The kind of loading/stresses also matters. Tensile stresses* tend to open up cracks, while compressive stresses tend to close cracks.

For crack growth to occur → It should be energetically favorable

For crack growth to occur → Sufficient stress concentration should exist at crack tip to break bonds

Crack growth criteria → Energy based (*Griffith*) — Global

Crack growth criteria → Stress based (*Inglis*) — Local

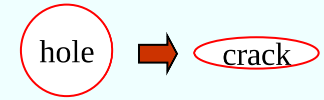


$ Note: the crack propagation we will study in this chapter will be quasi-static (i.e. elastic wave propagation due to crack growth is ignored)

** More on this later.*

Stress based criterion for crack propagation (Inglis criterion)

- In 1913 Inglis observed that the stress concentration around a hole (or a 'notch') depended on the radius of curvature of the notch. I.e. the far field stress (σ_0) is amplified near the hole. [(σ_{max} / σ_0) is the stress concentration factor (κ)].
- A 'flattened' (elliptical) hole (with a sharp tip) can be thought of as a crack.



$$\sigma_{max} = \sigma_0 \left[1 + 2\sqrt{\frac{c}{\rho}} \right] \xrightarrow{\textit{For sharp cracks}} \sigma_{max} \approx 2\sigma_0 \sqrt{\frac{c}{\rho}}$$

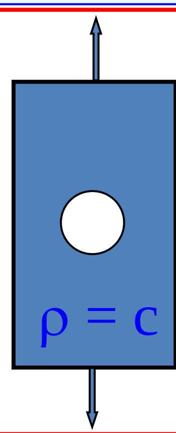
Sharper the crack, higher the stress concentration.

- σ_0 → applied "far field" stress
- σ_{max} → stress at hole/crack tip
- ρ → hole/crack tip radius
- c → length of the hole/crack

$$\kappa = \frac{\sigma_{max}}{\sigma_0}$$

- Sharper the crack (smaller the ρ) more the stress amplification (higher value of σ_{max}). A circular hole has a stress concentration factor of 3 [κ = 3].
- From Inglis's formula it is seen that the ratio of crack length to crack tip radius is important and not just the length of the crack.

- One way of understanding this formula is that if σ_{max} exceeds σ_t (the theoretical fracture stress), then the material fails (by the extension of the crack).
- This is in spite of the fact that the applied stress is of much lower magnitude than the theoretical fracture stress.



For a circular hole

$$\sigma_{max} = \sigma_0 \left[1 + 2\sqrt{\frac{c}{c}} \right]$$

$$\boxed{\sigma_{max} = 3\sigma_0}$$

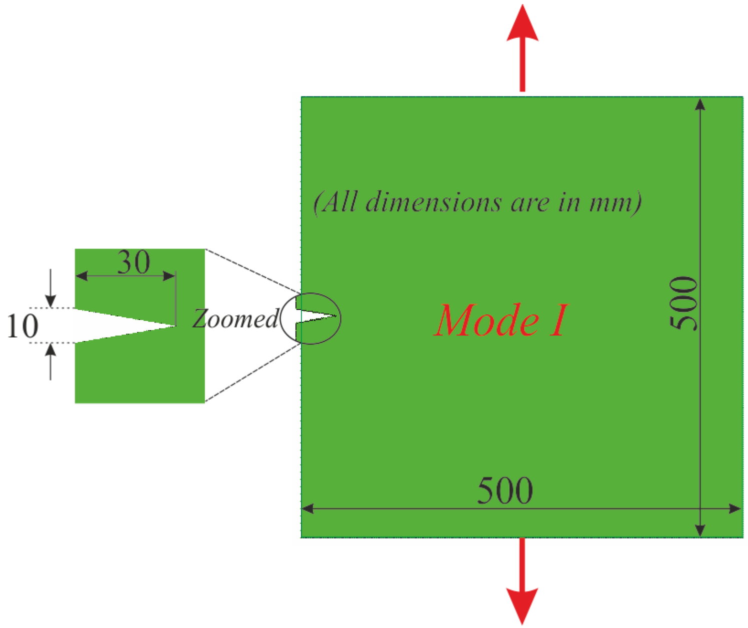
- For a crack to propagate the crack-tip stresses have to do work to break the bonds at the crack-tip. This implies that the ‘cohesive energy’ has to be overcome.
- If there is no plastic deformation or any other mechanism of dissipation of energy, the work done (energy) appears as the surface energy (of the crack faces).
- The fracture stress (σ_f) *(which is the ‘far field’ applied stress)* can be computed using this approach. Note that the fracture stress is of the order of E (i.e. in GPa).

$$\sigma_{cohesive} \approx \frac{E}{\pi}$$

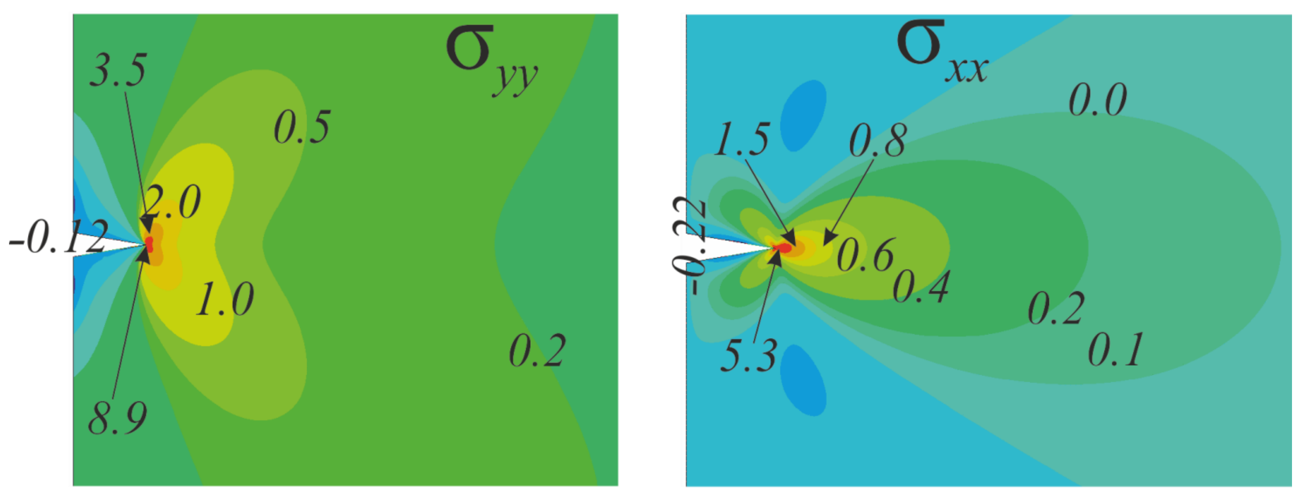
$$\sigma_f = \sqrt{\frac{E\gamma\rho}{4a_0c}}$$

- σ_f → fracture stress (applied “far-field”)
- ρ → crack tip radius
- c → length of the crack
- a_0 → Interatomic spacing

How do the crack tip stresses look like?



Plane strain condition



All contour values are in GPa

Griffith's criterion for brittle crack propagation

- We have noted that the crack length does not appear 'independently' (of the crack tip radius) in Inglis's formula. Intuitively we can feel that longer crack must be more deleterious.
- Another point noteworthy in Inglis's approach is the implicit assumption that sufficient energy is available in the elastic body to do work to propagate the crack. • *('What if there is insufficient energy?')* • *('What if there is no crack in the body?').* Also, intuitively we can understand that the energy (which is the elastic energy stored in the body) should be available in the proximity of the crack tip (i.e. energy available far away from the crack tip is of no use!).
- Keeping some of these factors in view, Griffith proposed conditions for crack propagation: (i) bonds at the crack tip must be stressed to the point of failure (as in Inglis's criterion), (ii) the amount of strain energy released (by the 'slight' unloading of the body due to crack extension) must be greater than or equal to the surface energy of the crack faces created.
- The second condition can be written as:

$$\boxed{\frac{dU_s}{dc} \geq \frac{dU_\gamma}{dc}}$$

- $U_s \rightarrow$ strain energy
- $U_\gamma \rightarrow$ surface energy
  (Energy per unit area: [J/m^2])
- dc → ('infinitesimal') increase in the length of the crack ('c' is the crack length)

Essentially this is like energy balance (with the '=' sign) → the surface energy for the extended crack faces comes from the elastically stored energy (in the fixed displacement case)

We look at the formulae for U_s and U_γ next.

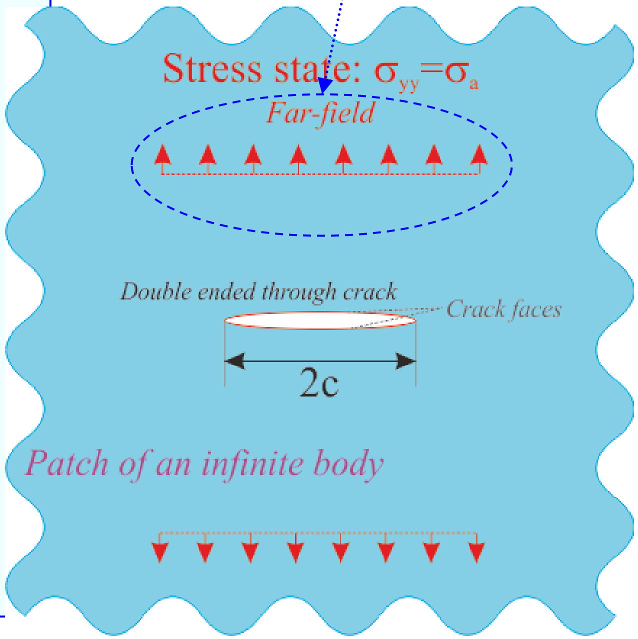
- The strain energy released on the introduction of a very narrow elliptical double ended crack of length '2c' in a infinite plate of unit width (depth), under an uniform stress σ_a is given by the formula as below.

$$\text{Reduction in elastic energy} = \Delta U = \left(U_{\text{without crack}} - U_{\text{with crack}}\right) = U_s = \frac{\pi c^2 \sigma_a^2}{E}$$

Should be written with a –ve sign if $\Delta U = (U_{final} - U_{initial})$

- This is because the body with the crack has a lower *elastic* energy stored in it as compared to the body without the crack (additionally, the body with the crack is less stiffer). Also, the assumption is that the introduction of a crack does not alter the far-field stresses (or the load bearing area significantly).
- Notes:
  - The units of U_s is [J/m] (Joules per meter depth of the crack→ as this is a through crack).
  - Though U_s has a symbol of energy, it is actually a difference between two energies (i.e. two states of a body→ one with a crack and one without).
  - Half crack length 'c' appears in the formula.
  - E is assumed constant in the process (the apparent modulus will decrease slightly).
  - σ_a is the 'far field' stress (this may result from displacements rather than from applied forces– see note later).

For now we assume that these stresses arise out of 'applied' displacements



- The formula for U_s can be appreciated by considering the energy released from a circular region of diameter $2c$ as in the figure below. (The region is cylindrical in 3D).
- The energy released is:

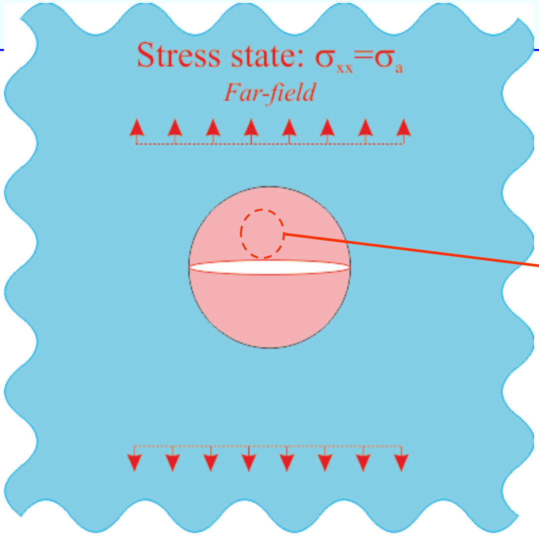
$$\text{Elastic energy released from a circular region} = U_s^{\text{circular region}} = \frac{1}{2}\frac{\sigma_a^2}{E}\left(\pi c^2\right) \quad (1)$$

- The computation of the actual energy released is more involved and is given by the formula as noted before:

$$\boxed{U_s = \frac{\pi c^2 \sigma_a^2}{E}}$$

Plane stress condition

Hence $\dfrac{\partial U_s}{\partial c} = \dfrac{2\pi c \sigma_a^2}{E}$



Energy released from this circular region is given by the formula (1) as above (not a true value, but to get a feel of the predominant region involved).

- For a body in plane strain condition (i.e. ~ *thick* in the z-direction, into the plane of the page), E is replaced with $E/(1-\nu^2)$:

$$\boxed{U_s = \frac{\pi c^2 \sigma_a^2}{\left(E/(1-\nu^2)\right)}}$$

Plane strain condition

As plane strain is more severe on the material it is better to do experiments in plane strain condition.

ADVANCE MATERIAL & CHARECTERIZATION (MME-169)

UNIT 2

IMPACT STRENGTH AND CREEP FAILURE

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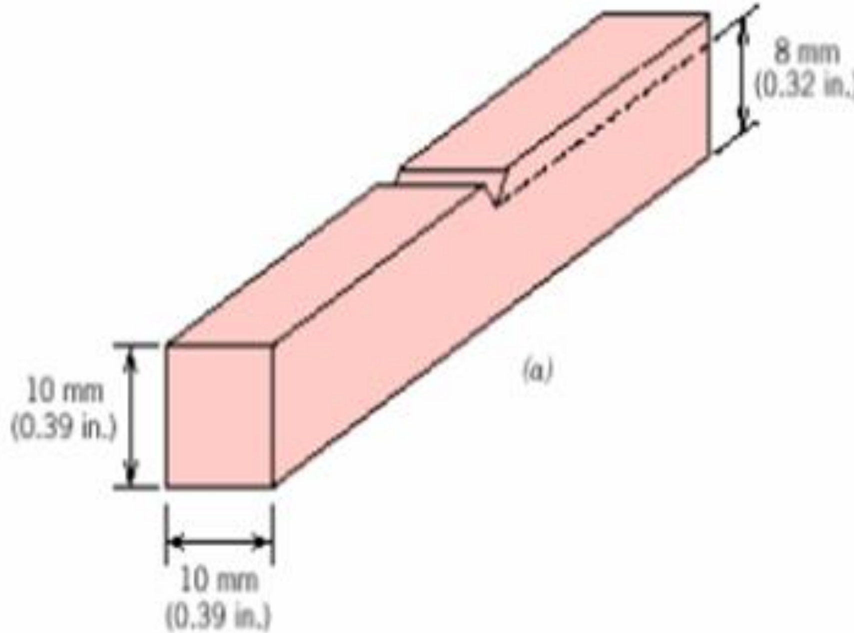
Impact Strength

The ability of a materials to sustain impact forces until fracture occurred known as its impact strength.

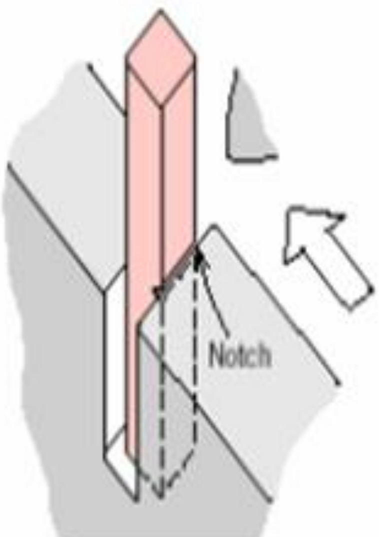
Types of impact test are;

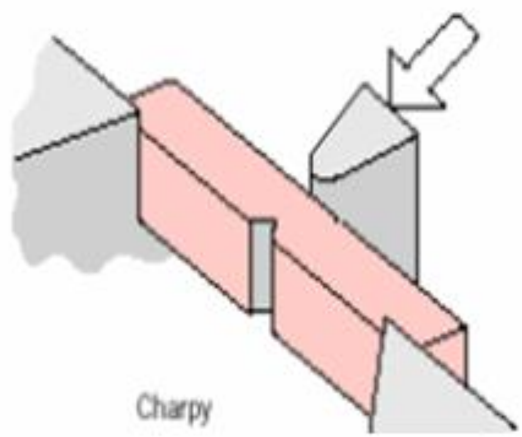
- Izod impact test
- Charpy impact test

Impact test



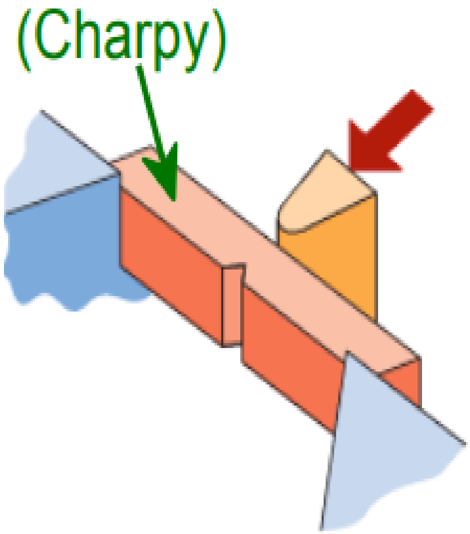
Izod

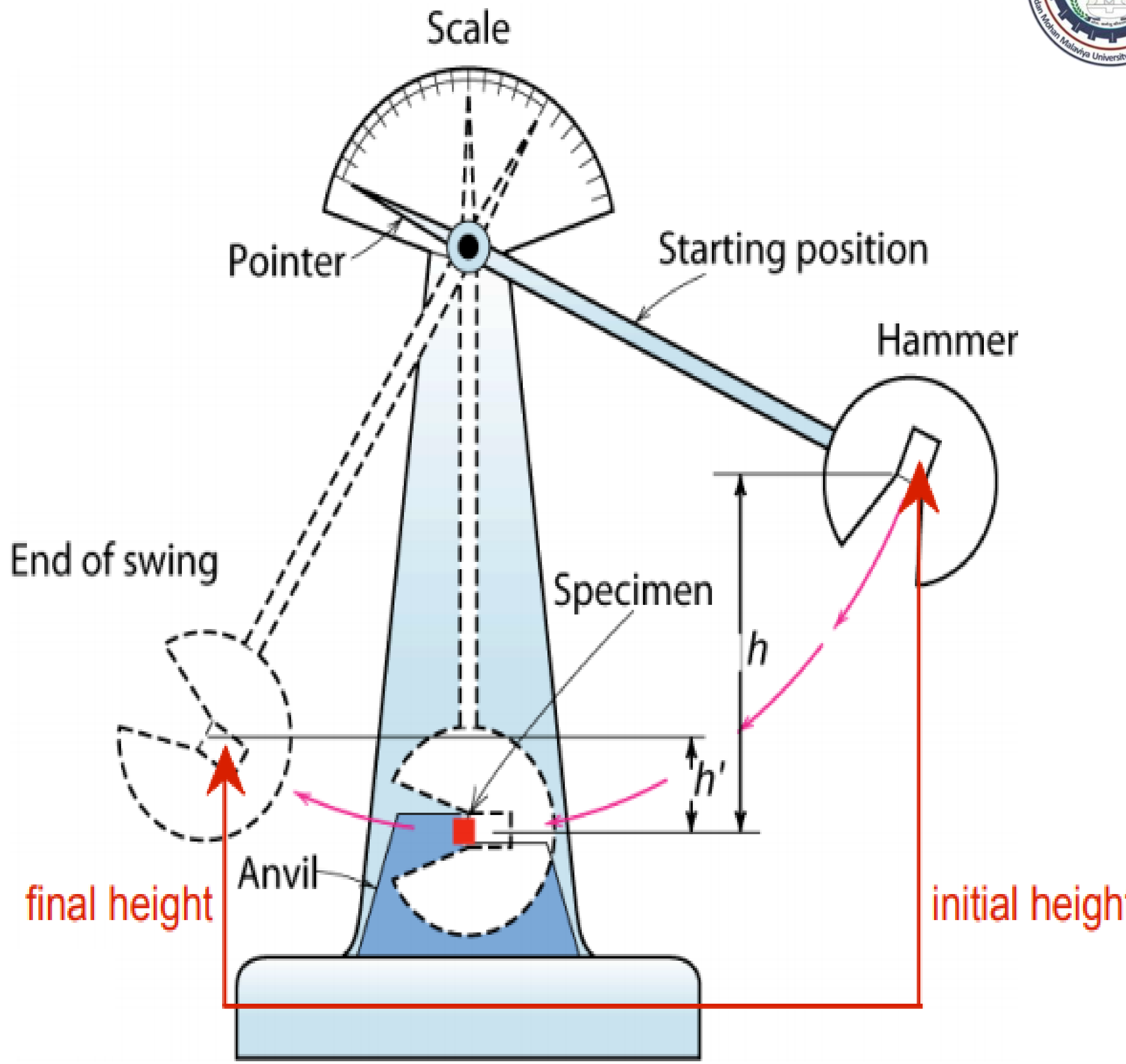




Charpy

Charpy Impact Test





	Charpy Impact Testing	Izod Impact Testing
Materials Tested	Metals	Plastics & Metals
Types of Notches	U-notch and V-notch	V-notch only
Position of the Specimen	Horizontally, notch facing away from the pendulum	Vertically, notch facing toward the pendulum
Striking Point	Middle of the sample	Upper Tip of the sample
Common Specimen Dimensions	55 x 10 x 10 mm	64 x 12.7 x 3.2 mm (plastic) or 127 x 11.43 mm round bar (metal)
Common Specifications	ASTM E23, ISO 148, or EN 10045-1	ASTM D256, ASTM E23, and ISO 180

Toughness

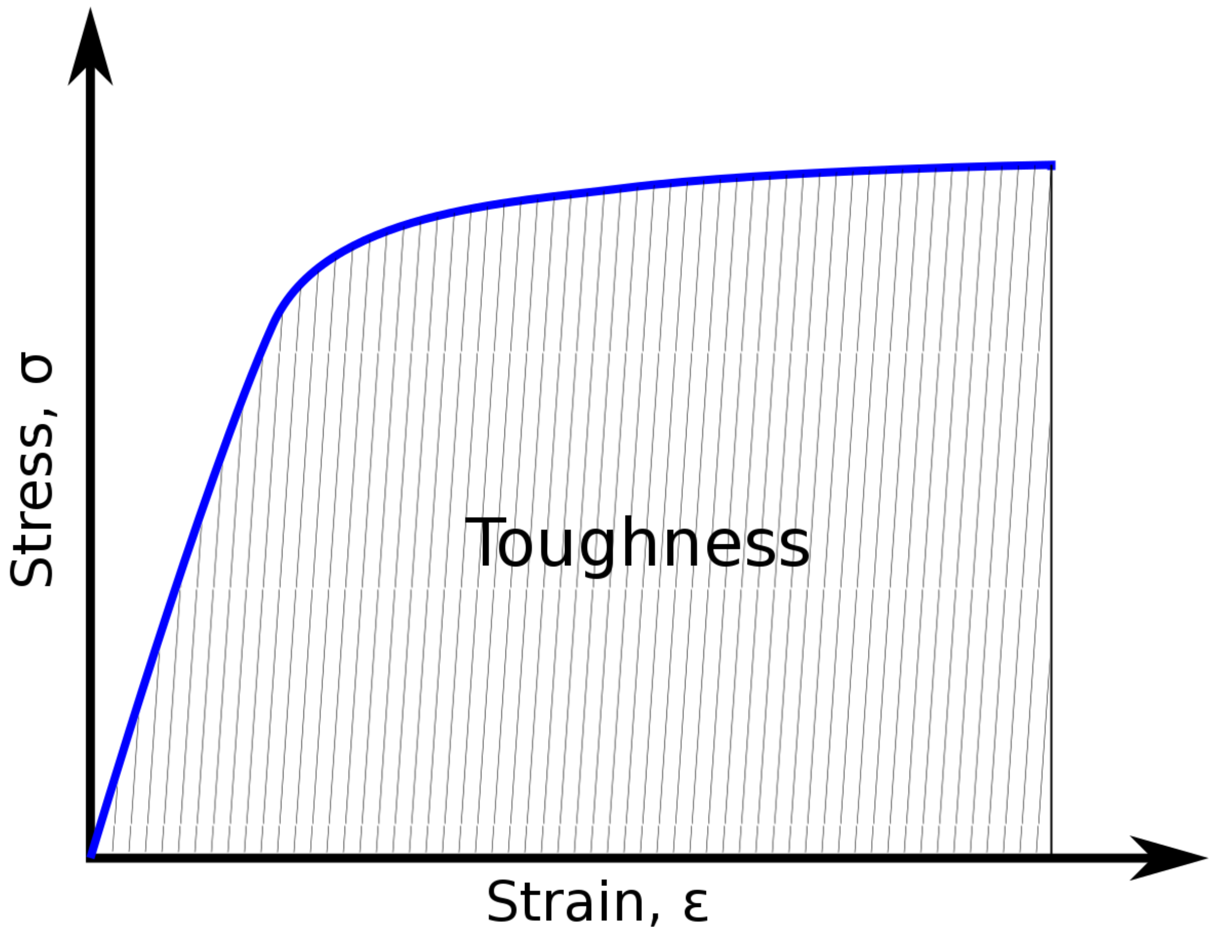
Toughness is the ability of the material to absorb energy during plastic deformation upto fracture.

.A material with high strength and high ductility will have more toughness than a material with low strength and high ductility.

Toughness is a good combination of strength and ductility.

one way to measure toughness is by calculating the area under the stress strain curve from a tensile test. This value is simply called “material toughness” and it has units of energy per volume.

Material toughness equates to a slow absorption of energy by the material.


Stress, σ
Toughness
Strain, ε

Creep failure

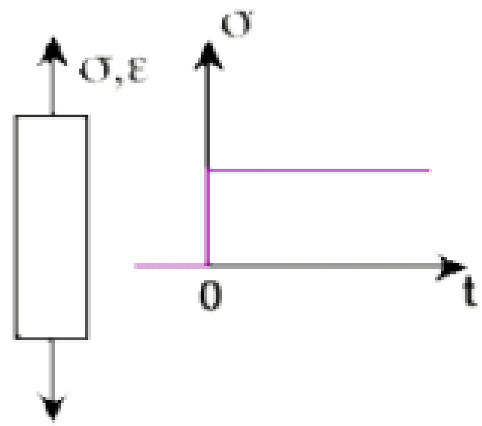
Creep is a **time-dependent and permanent** deformation of materials when subjected to a constant load at a **high temperature** (> 0.4 T_m). Examples: turbine blades, steam generators.

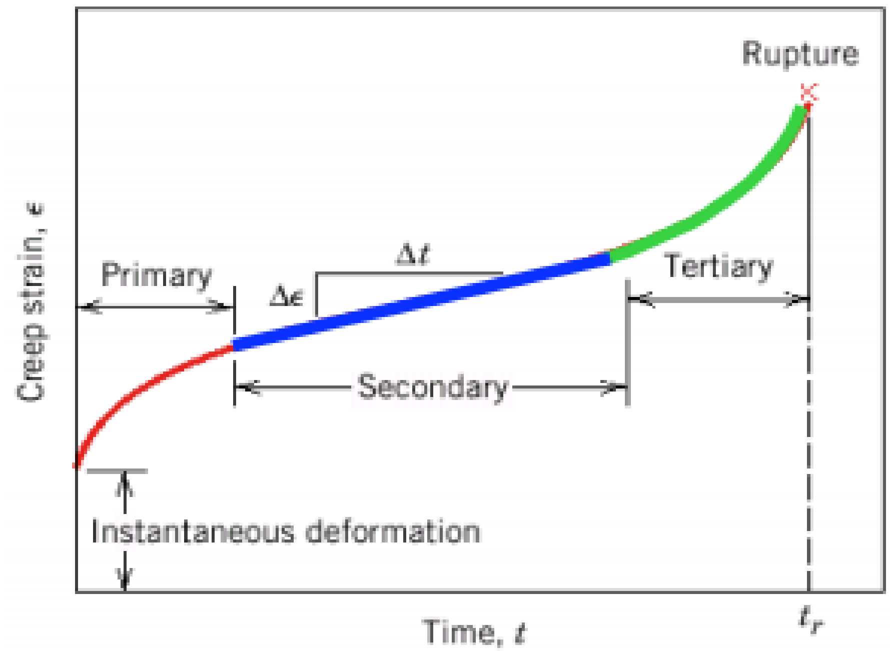
Creep rate – Stress & Temperature effects

- Two most important parameter that influence creep rate are: stress and temperature.
- With increase in either stress or temperature (a) instantaneous elastic strain increases (b) steady state creep rate increases and (c) rupture lifetime decreases.

Creep Failure

- Occurs at elevated temperature, T > 0.4 T_{melt}
- Deformation at a constant stress changes with time.





Primary Creep: slope (creep rate) decreases with time.

Secondary Creep: steady-state i.e., constant slope.

Tertiary Creep: slope (creep rate) increases with time, i.e. acceleration of rate.

ADVANCE MATERIAL & CHARECTERIZATION (MME-169)

UNIT 2

FLEXURAL STRENGTH

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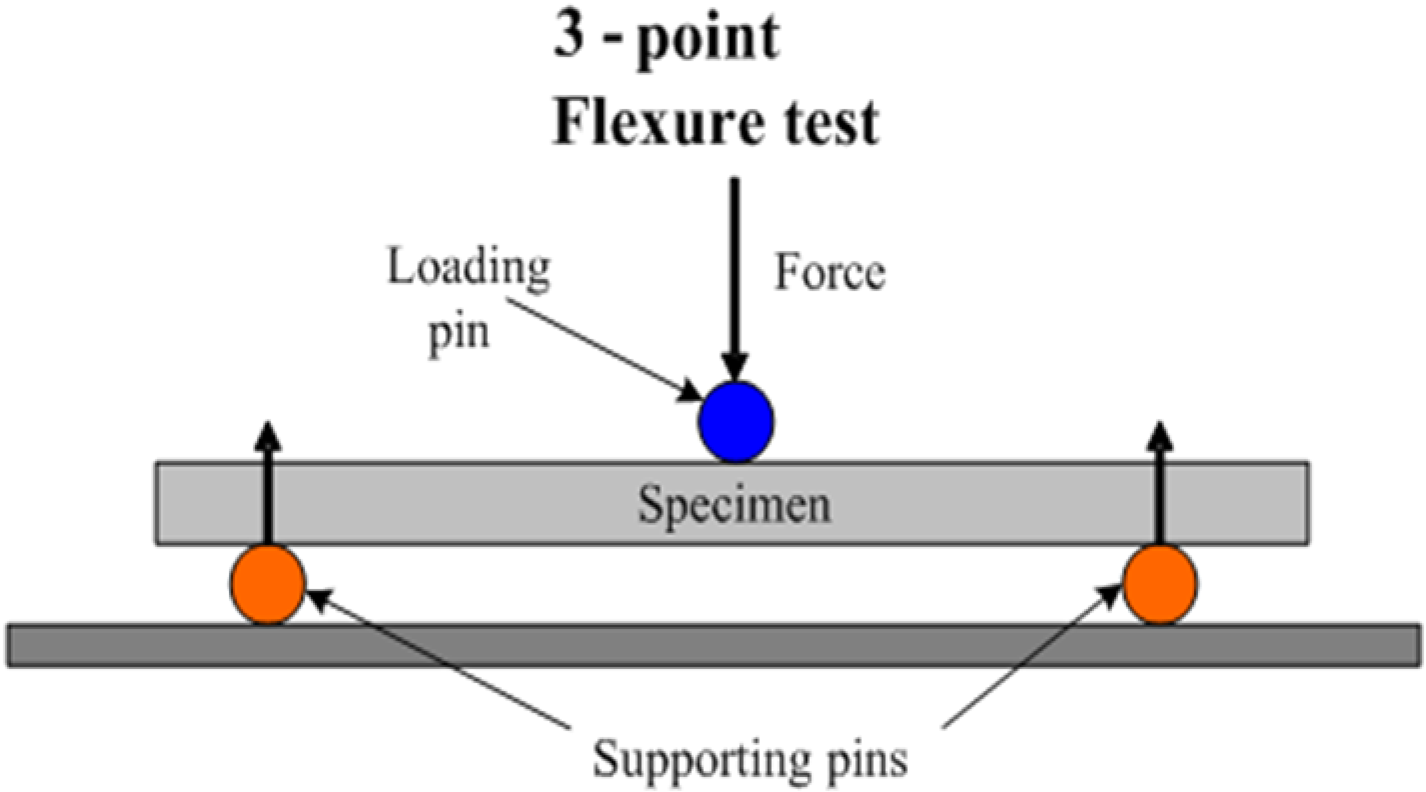
Flexural Strength (Bending Strength)

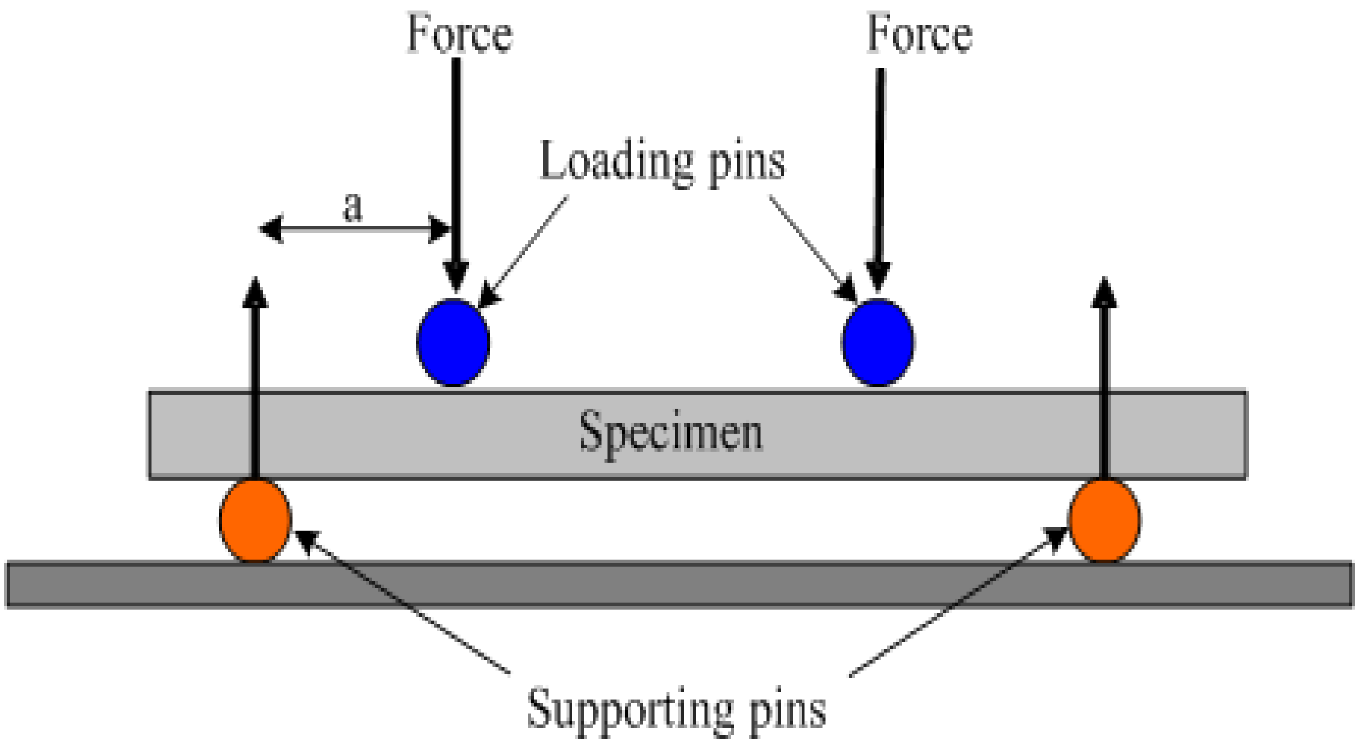
It is the ability of a material to sustain the bending forces before fracture.

Types of flexural test:

- **3-Point flexural test**
- **4-Point flexural test**


3 - point
Flexure test
Loading
pin
Force
Specimen
Supporting pins

4 - point
Flexure test



Flexural test

- The flexural or bending strength of the said composites was determined by using universal testing machine (UTM) following ASTM-E290 [ASTM standards], Instron 1195 for the specimen.
- The flexural strength for said composites can be calculated as,

$$FS = \frac{3PL}{2bt^2}$$

- Where, *P* is the maximum load, *b* the width of specimen and *t* the thickness of specimen and *L* is the span length of the sample.

	Flexural Test
Specimen Size	50 mm × 8mm × 8 mm
Span length	40 mm
Cross-head speed	2mm/s

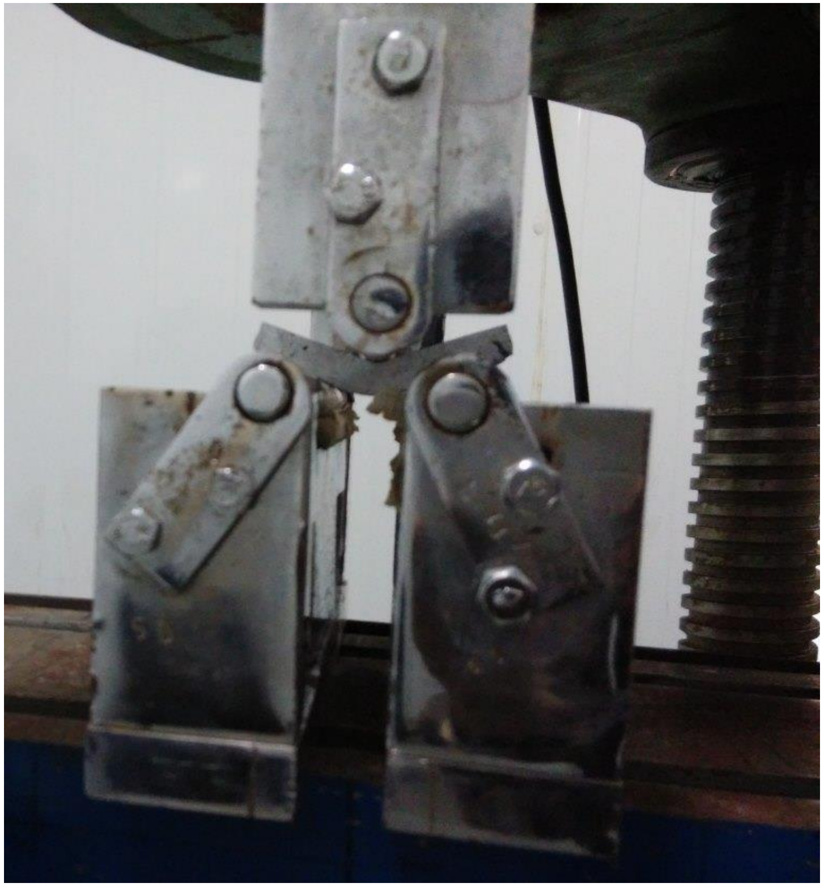


Figure Flexural strength testing machine (UTM)

ADVANCE MATERIAL & CHARECTERIZATION (MME-169)

UNIT 2

WORK HARDENING & SINGLE CRYSTAL GROWTH

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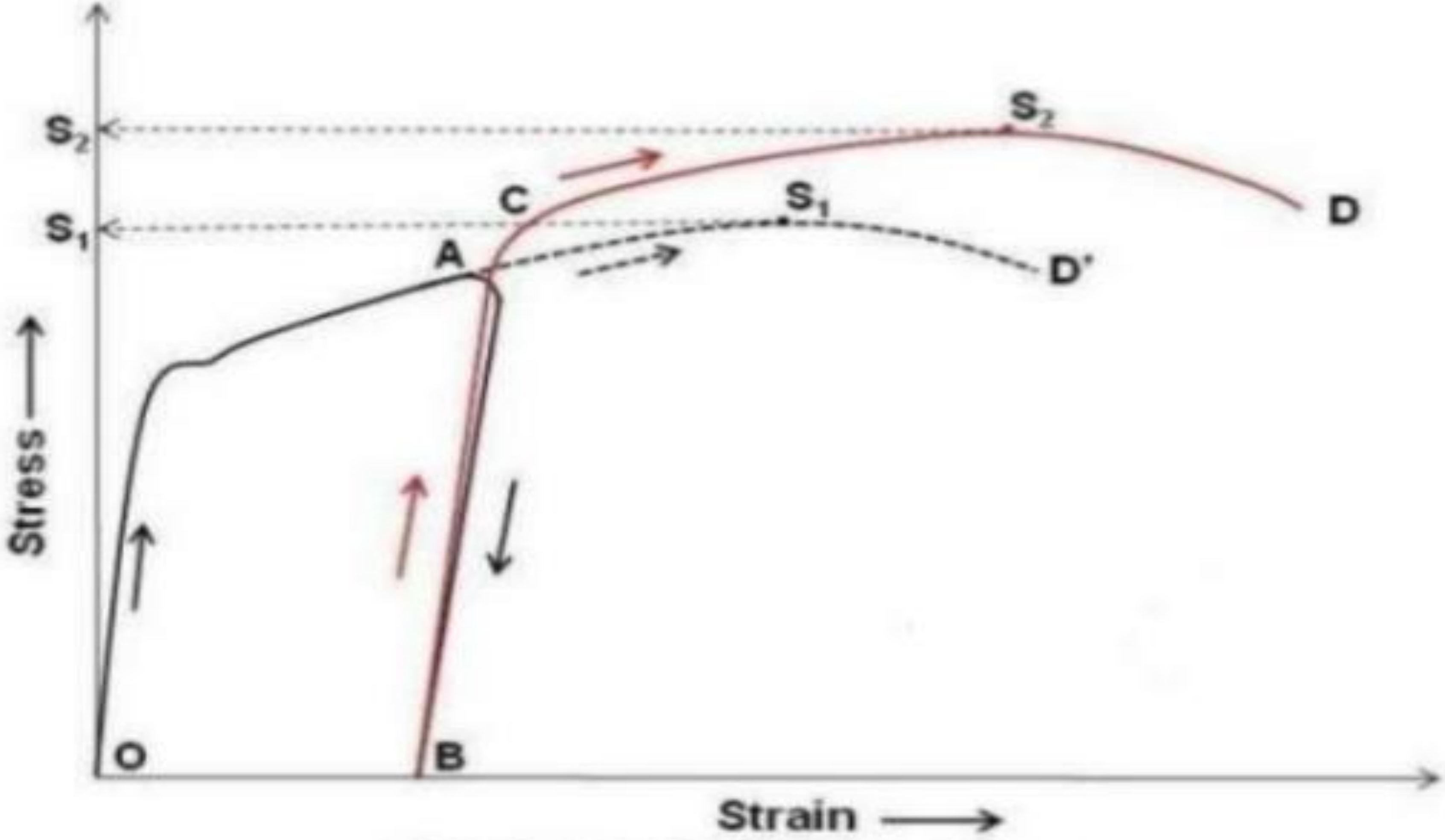
- What is Work Hardening?

  The phenomenon where ductile metals becomes stronger and harder when they are deformed plasticity is called work hardening.

- Work hardening is also known as strain hardening or cold working.

PRINCIPAL

- The ability of metal to plastically deform depends on the ability of dislocation to move.
- When loaded, the strain increase with stress and the curve reaches the point A in the plastic range.
- If at this stage , the specimen is unloaded , the strain does not recover along the original path AO , but moves along AB .



Work (Strain) Hardening

- If the specimen is reloaded immediately , the curve again rises from B to A ,but via another path , and reaches the point C , after which it will follow the curvature , if loading is continued .
- If the specimen would not have been unloaded , after point A , the stress–strain curve would have followed the dotted path AD’ .

- A comparison of paths ACD and AD shows that the cold working (plastic deformation) has increased the yield strength and ultimate strength of the metal.
- Increasing temp. lowers the rate of strain hardening and thus the treatment is given the usually at temp. well below the melting point of the material. This treatment is known as cold working.

- The consequence of strain hardening a material is improved strength and hardness but material ductility be reduced.
- After performing this process to the material their dislocation of atoms become more difficult which make the material stronger.

Advantages of Stain Hardening

- No heating required
- Better surface finish
- Superior dimensional control
- Better reproducibility and interchangeability
- Directional properties can be imparted into the metal
- Contamination problems are minimized

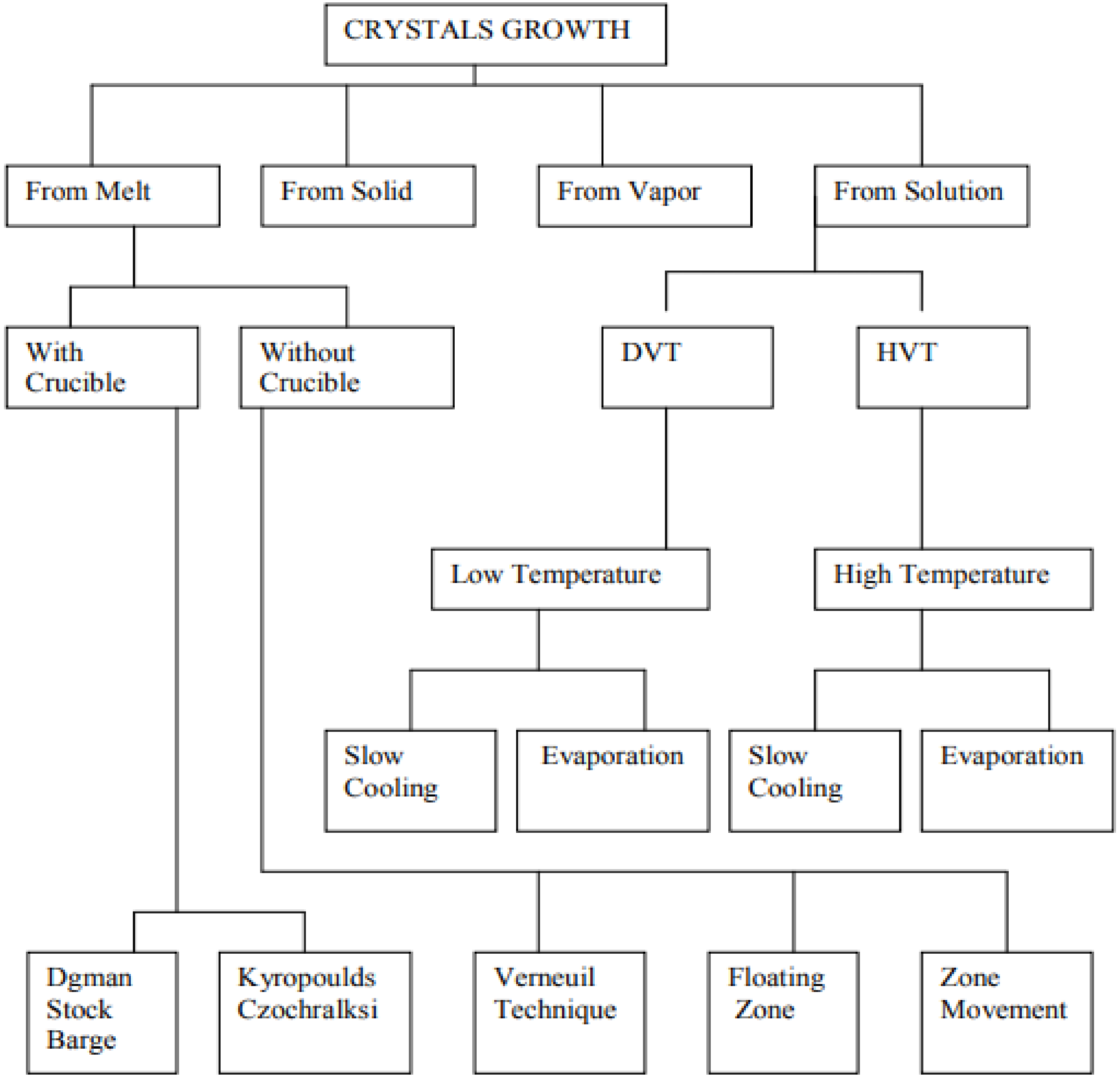
Single Crystal Growth

Single-crystal

- regular arrangement of basic building blocks (atoms, ions, molecules) is preserved on the macroscopic scale → structure anisotropy is mirrored in the physical property anisotropy

Single-crystal growth

- solid phase must be created under the physical conditions close to the thermodynamic equilibrium (stacking „atom-by-atom“ on the seed crystal surface)


CRYSTALS GROWTH
From Melt
From Solid
From Vapor
From Solution
With Crucible
Without Crucible
DVT
HVT
Low Temperature
High Temperature
Slow Cooling
Evaporation
Slow Cooling
Evaporation
Dgman Stock Barge
Kyropoulds Czochralksi
Verneuil Technique
Floating Zone
Zone Movement

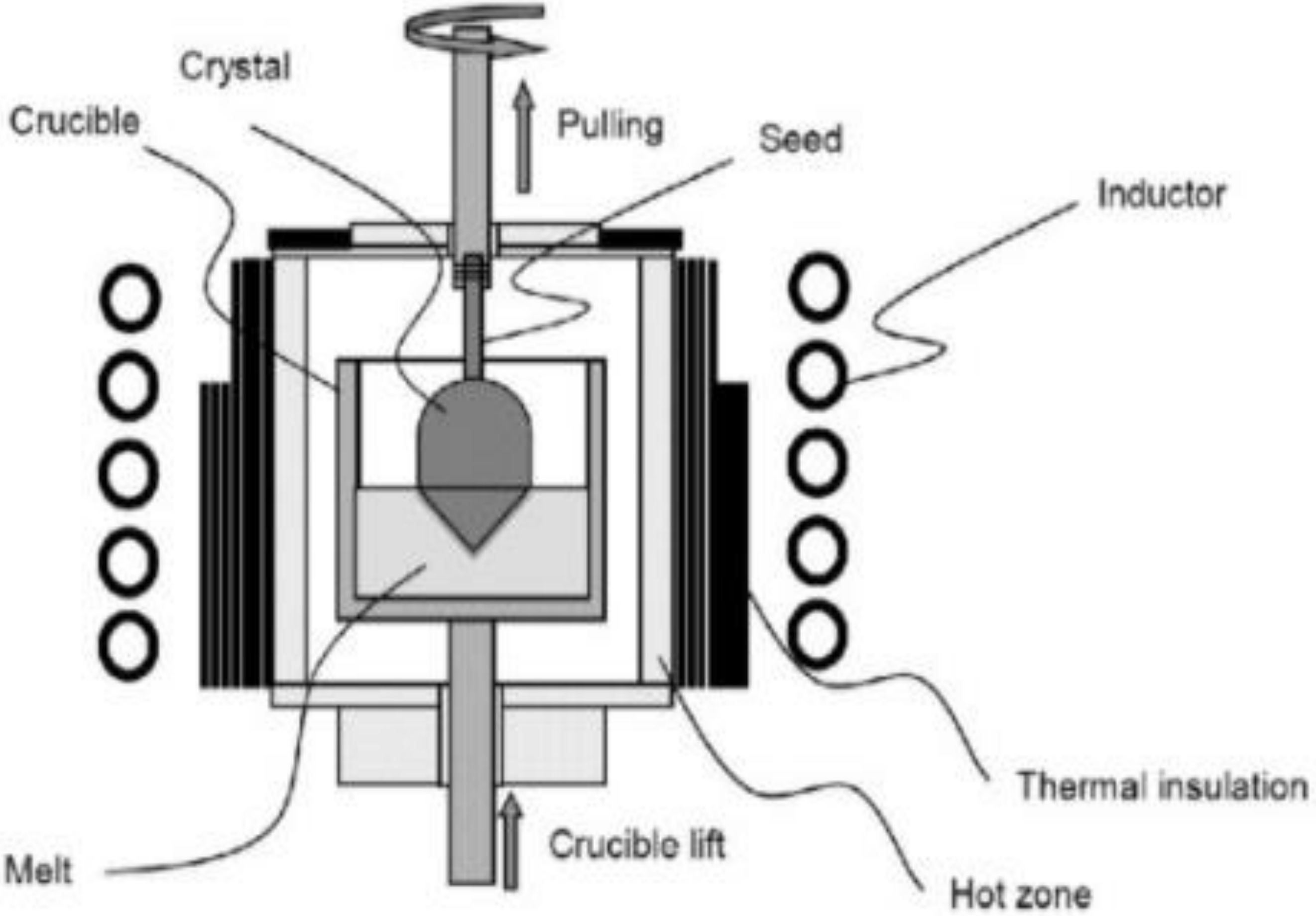
Czochralski Method

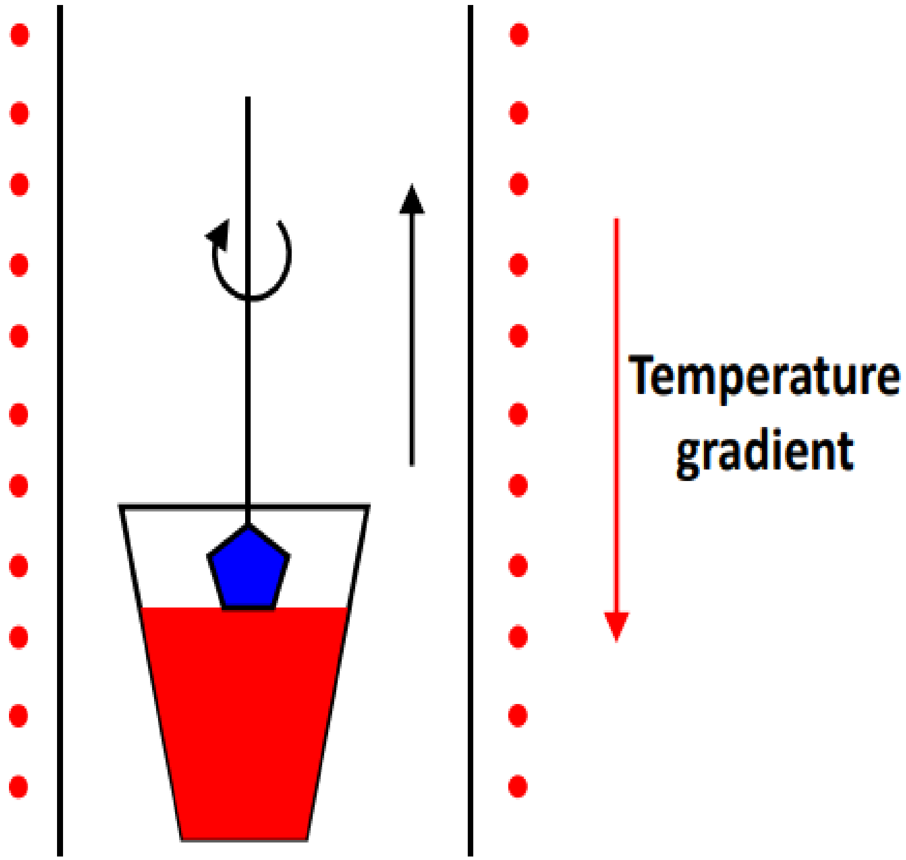
This method is widely used for growing semi conducting material crystal. The shape of the crystal is free from the constraint due to the shape of the crucible. In this method the charge is melted and maintained at a temperature slightly above the melting point.

The pulling rod is lowered to just touch the melt. Since the rod is at lower temperature of melt occurs at the point tip of the pulling rod. The crystal is pulled slowly.

The rate of pulling upon various factors like thermal conductivity, latent heat of fusion of charge and rate of cooling of the pulling rod. The seed is rotated to keep the grow crystal uniform and cylindrical.

Czochralski Method





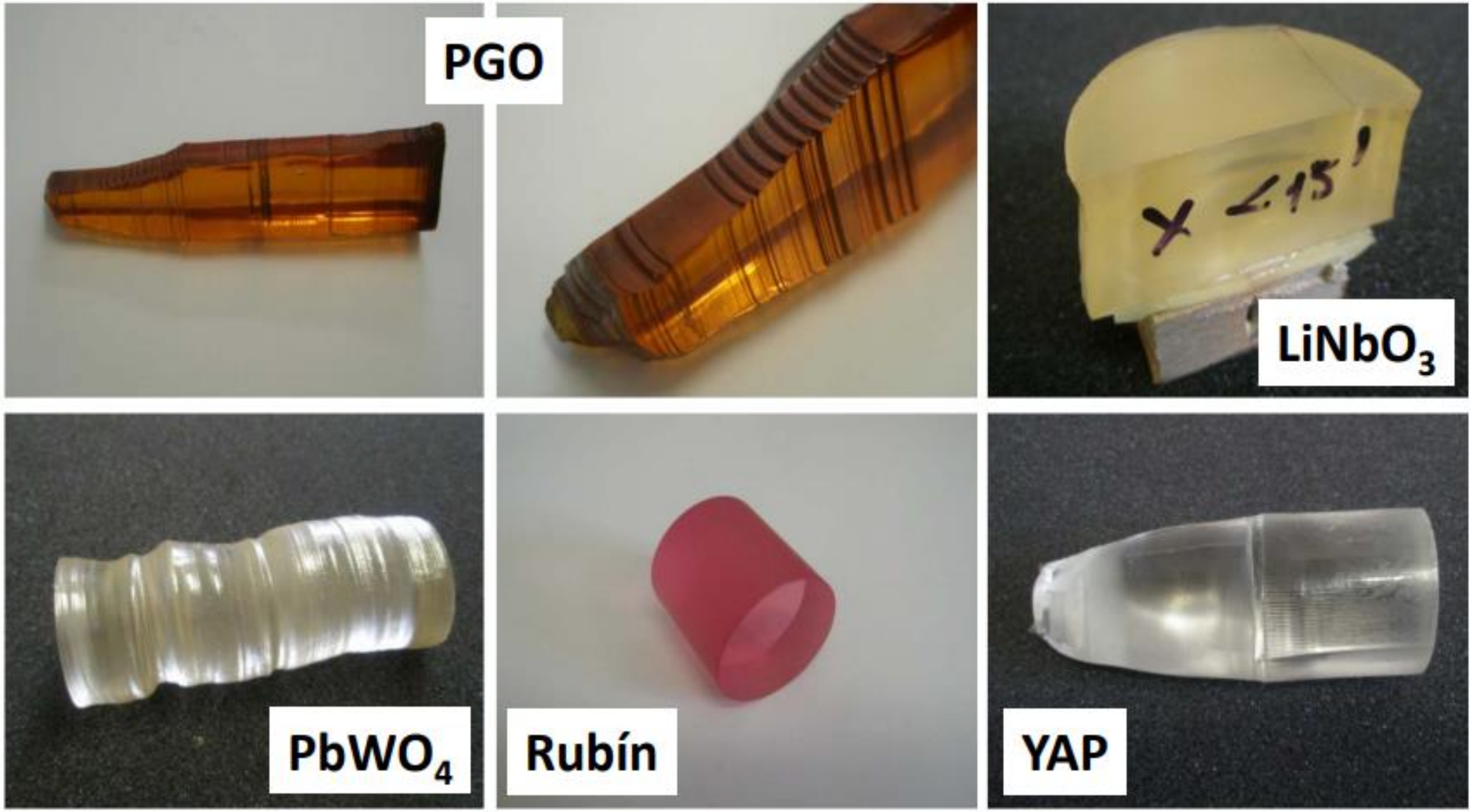
Advantage:

- This method is used to grow large single crystals. Thus it is used extensively in the semiconductor industry.
- There is no direct contact between the crucible walls and the crystal which helps to produce unstressed single crystal.

Disadvantage:

- In general this method is not suitable for incongruently melting compounds and of course the need for a seed crystal of the same composition limits is used as tool for exploratory synthetic research.

Czochralski method materials



Bridgmann method

This technique was named after its inventor Bridgemann in 1925, Stockbarger in1938.

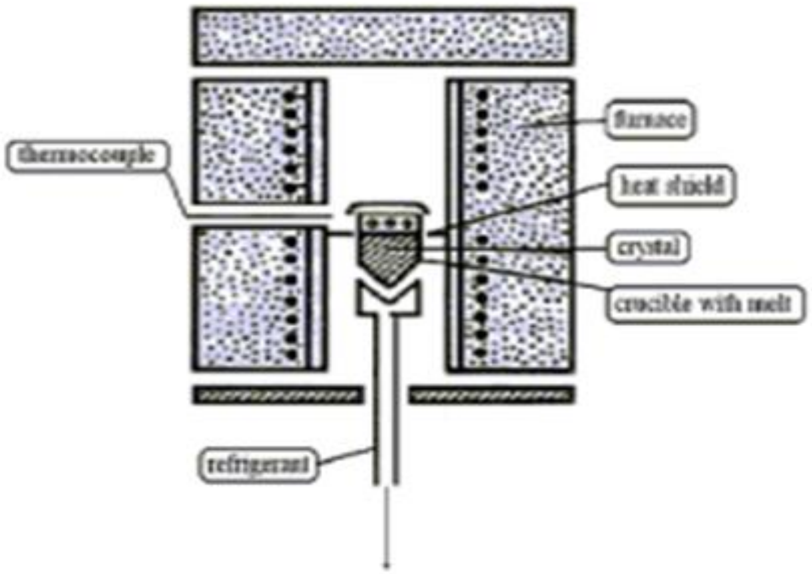
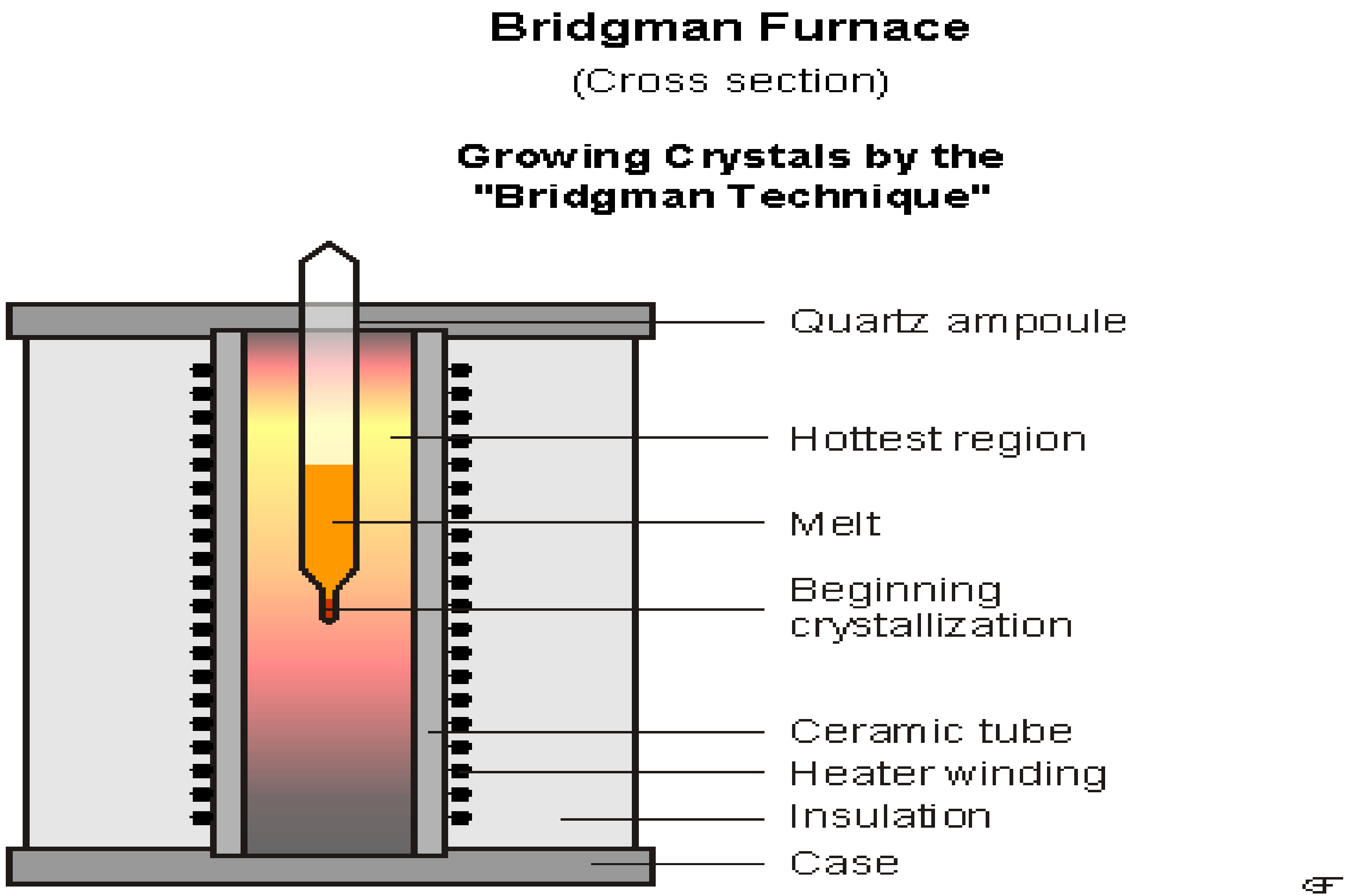


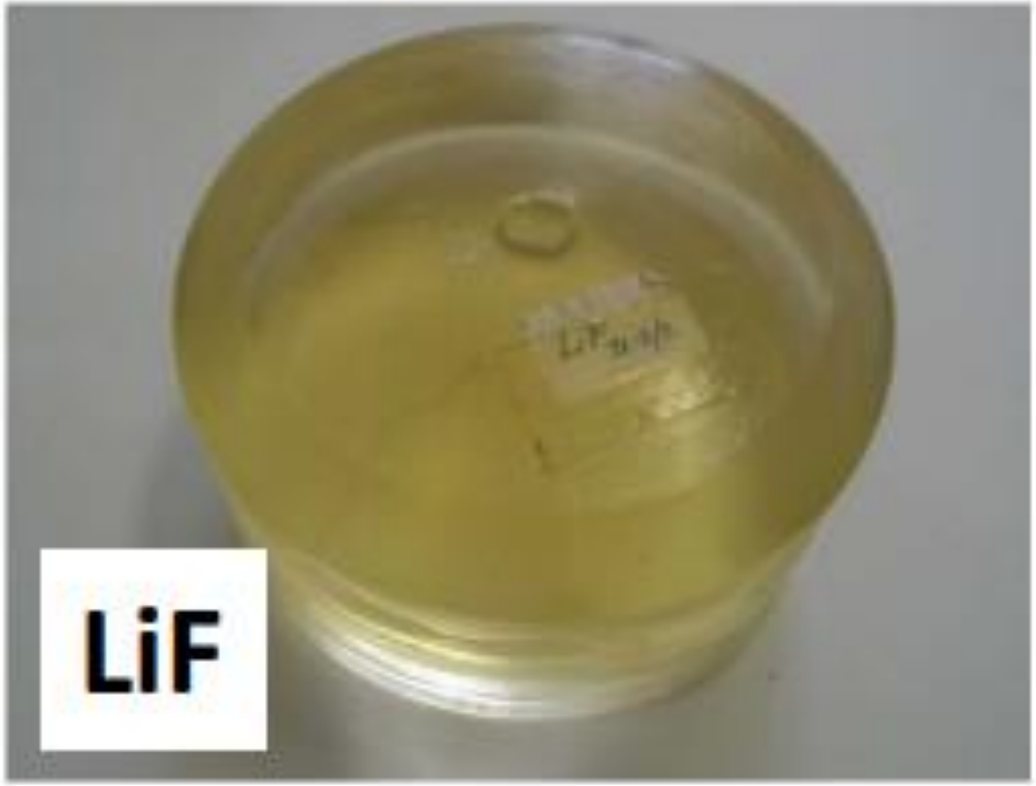
Figure. Bridgmann method

The Bridgmann technique is a method of growing single crystal ingots or boules. The method involves heating polycrystalline material in a container above its melting point and slowly cooling it from one end where a seed crystal is located. Single crystal material is progressively formed along the length of the container,the process can be carried out in a horizontal or vertical geometry.

Bridgman-Stockbarger Method



Bridgman-Stockbarger Method material



Advantage:

- This method is technically simple.
- This technique is low cost.
- Selecting the appropriate container can produce crystal of pre assigned diameter.

Disadvantage:

- The compression of the solid by the contracting container during cooling can lead to the development of stresses high enough to nucleate dislocations in the material.

ADVANCE MATERIAL & CHARECTERIZATION (MME-169)

UNIT 2
WEAR

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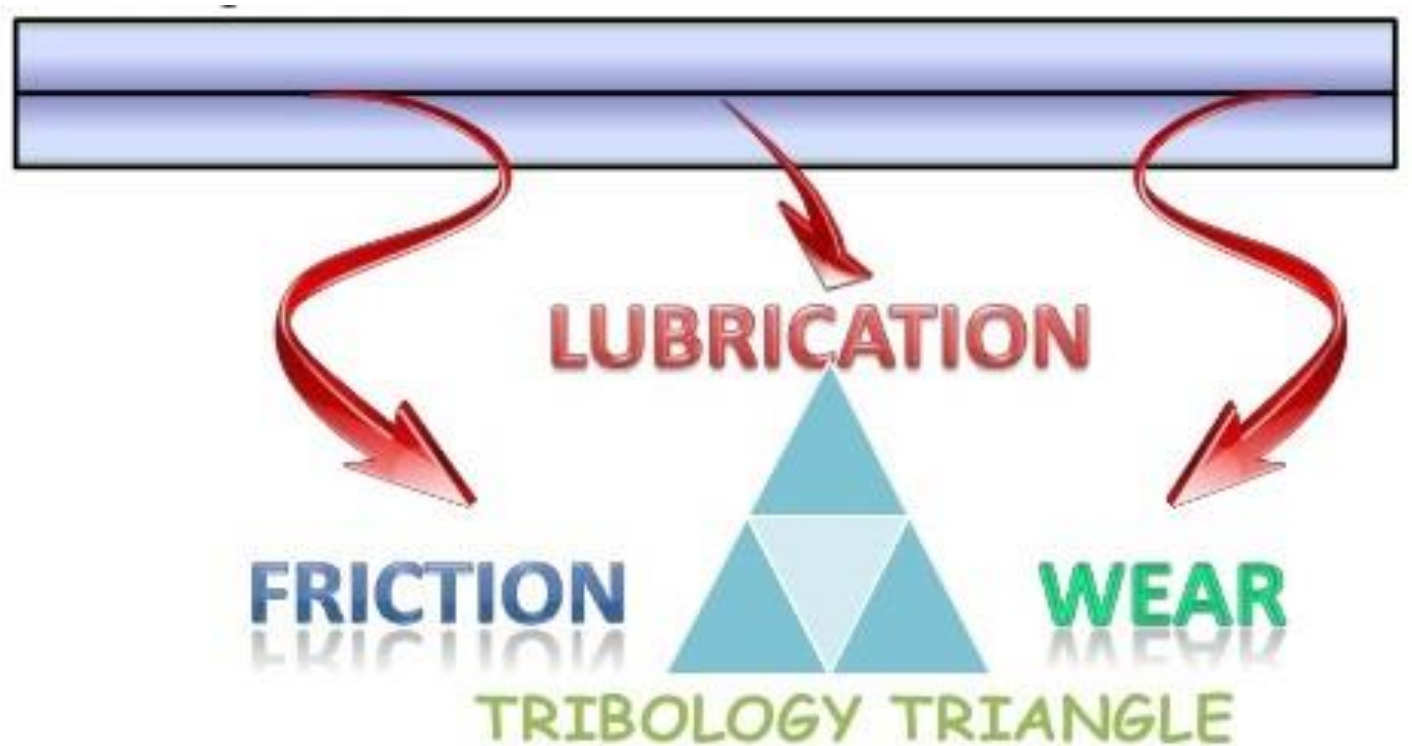
What is Tribology?

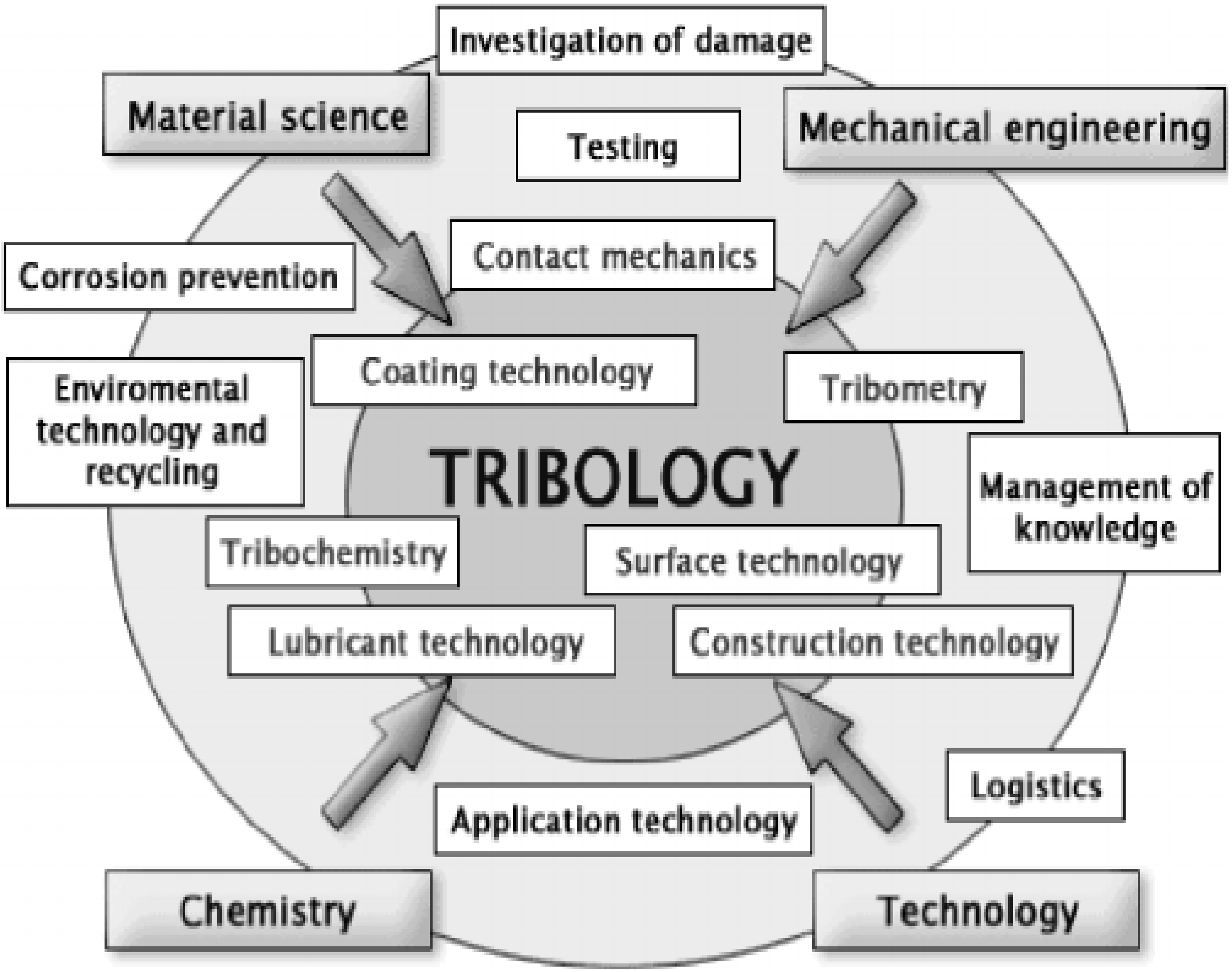
- **TRIBOS** is Greek word, which means **Rubbing process.**
- **Tribology is the science and technology of interacting surfaces in relative motion.**
- It tries to explain everything that happens when things rub together.



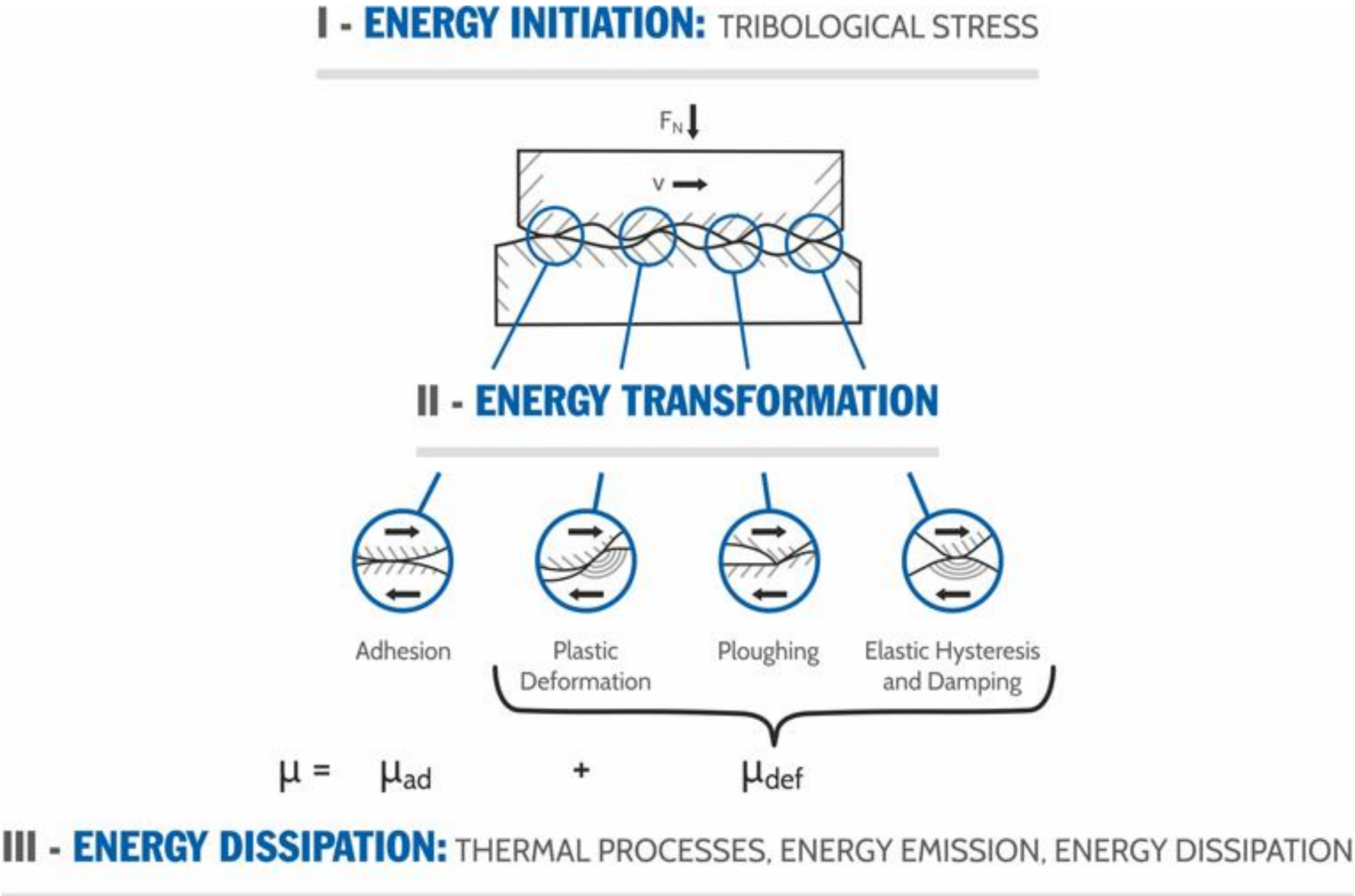
How Tribology came in to Picture?

- In the early 1960s, there was a dramatic increase in the reported failures of plant and machinery due to wear and associated causes, some causing heavy financial losses. Continuous processes made machinery breakdowns more costly and serious than ever.
- This trend was recognized by specialists involved in the subjects of **friction, wear, and lubrication.**
- Several research studies reported on the impact of wear, corrosion, and friction on machinery, manufacturing productivity, and costs.
- As a result, tribology became a mainstream field of science, and many universities offer it as part of their mechanical engineering department curriculum.

Interaction of Tribology with other sciences



Wear Mechanism



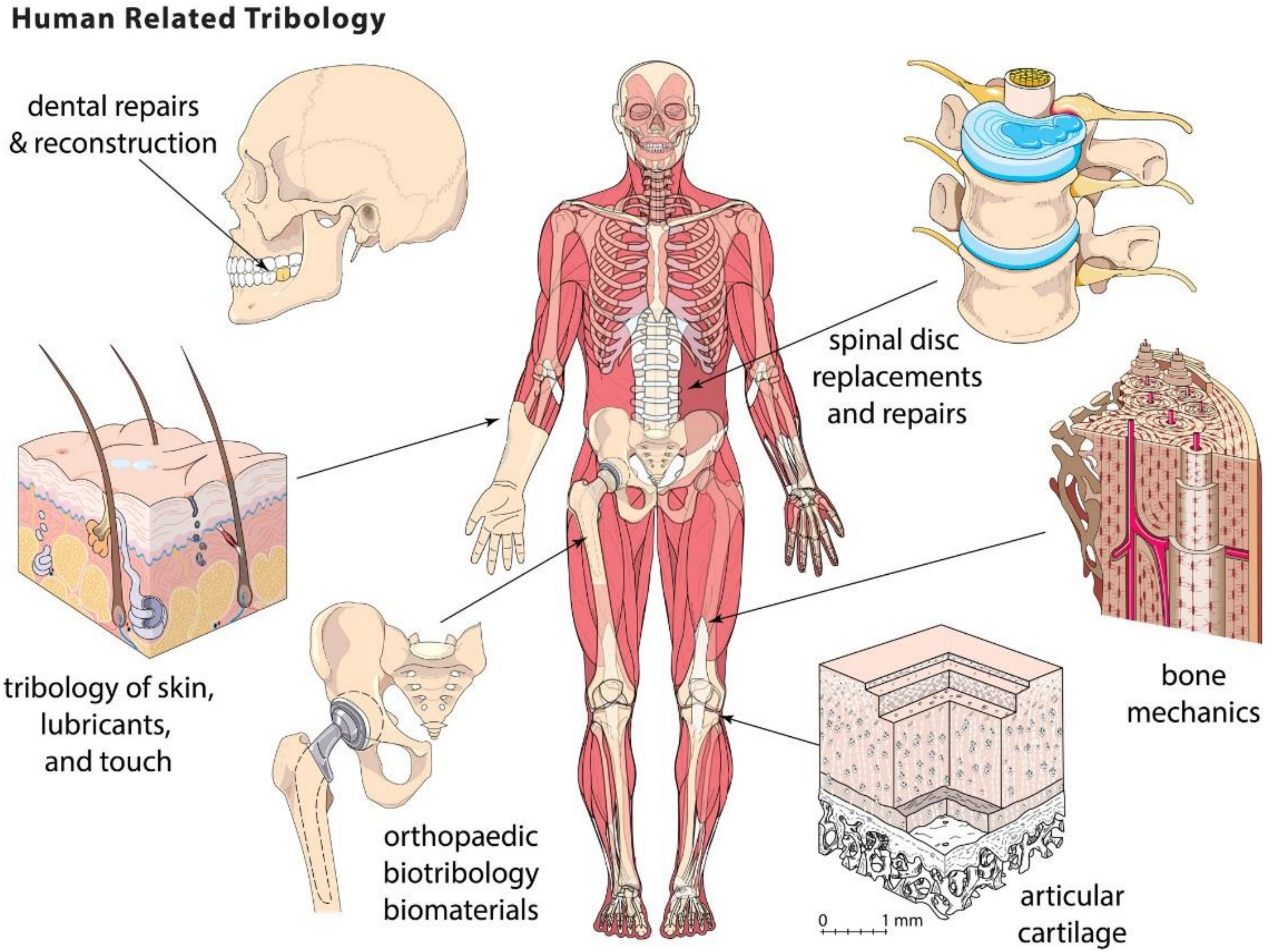
Resource- https://www.ggbearings.com/en/company/tribology

Modern Applications of Tribology

The early focus of tribology was on improving operation and extending the lifecycle of industrial machinery. Today, those principles and design benefits are making a major impact in a variety of modern applications, such as

- Micro- and Nano-tribology
- Alternative energies like Wind Turbine
- Green methodologies
- Bio-tribology: Tribology in Biomedical etc.

Bio-tribology: Tribology in Biomedical



Resource- http://www.tribonet.org

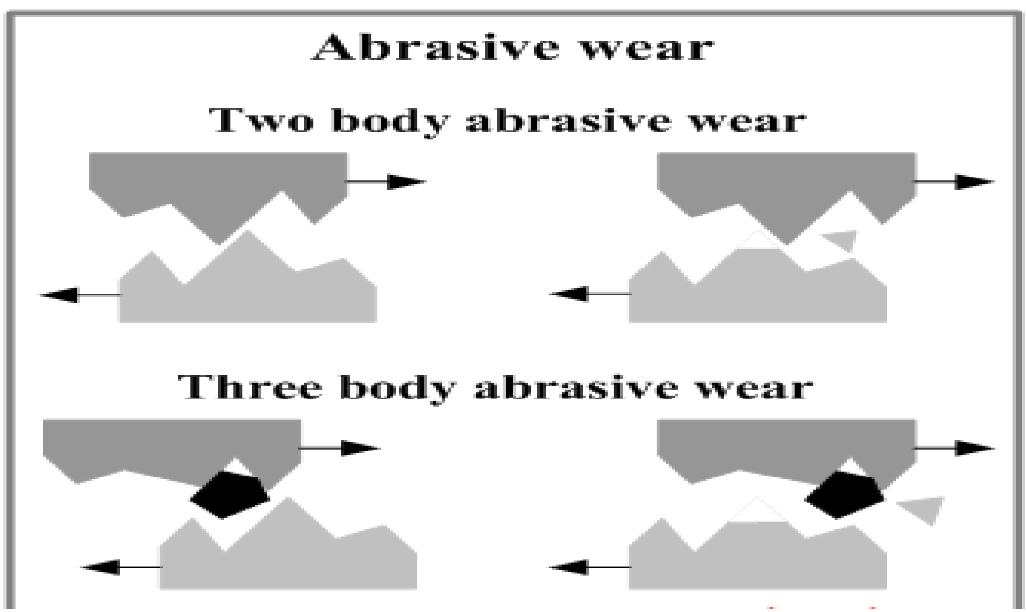
Wear

- Wear is defined as the removal of material from a solid surface by the action of another surface. Wear is damage to a solid surface usually involving progressive loss of materials, owing to relative motion between the surface and a contacting substance or substances.

- The types of the wear are:

1. Adhesive wear (Material transfer from one surface to another surface)
2. Abrasive wear (Two body & Three body abrasive)
3. Surface fatigue (Surface of a material weekend by cyclic loading)
4. Erosive wear (Due to the impact of solid or liquid particles)

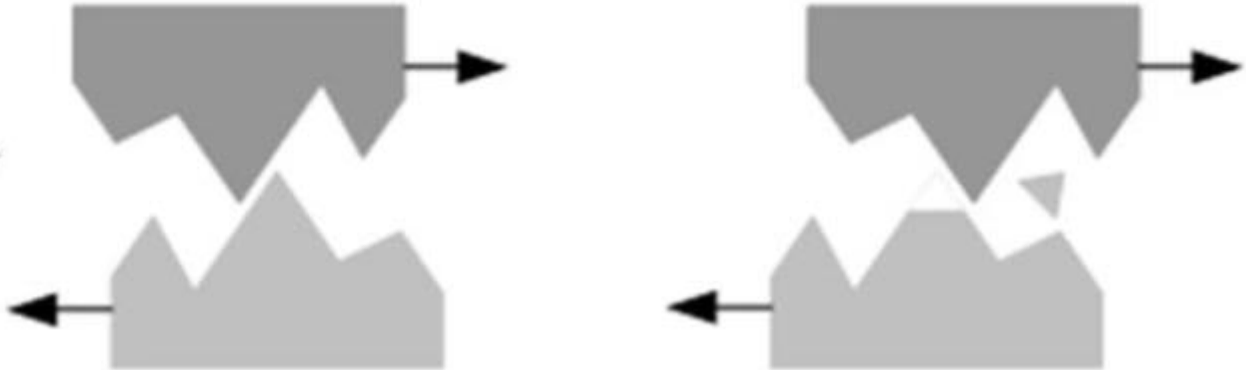
Abrasive Wear. This type of wear is caused by a hard surface or hard particles against a soft surface. The hard material cuts and ploughs the opposing softer surface. It is sometimes confused with adhesive wear if hard particles transfer from one surface to the other and abrade the original surface. This type of wear can be greatly reduced by making the harder surface smooth.



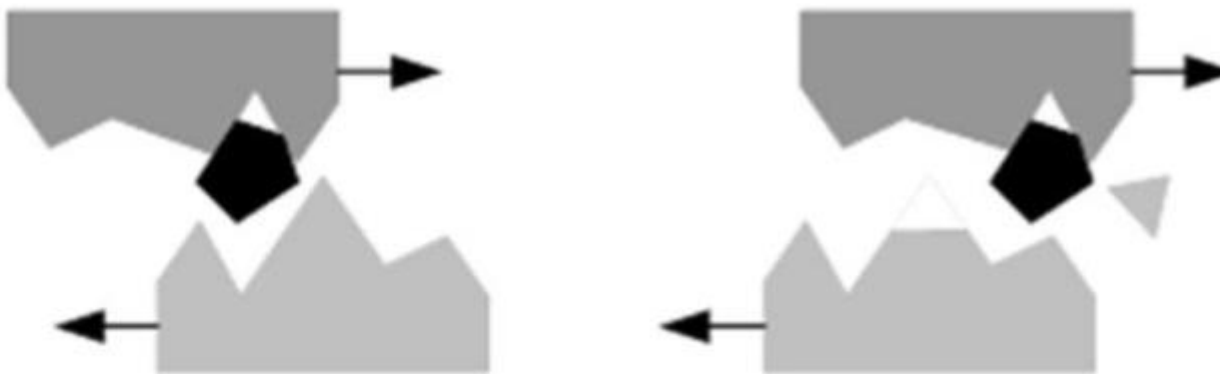
Abrasive wear

Abrasive wear occurs when a harder material is rubbing against a softer material

Two body wear



Three body wear

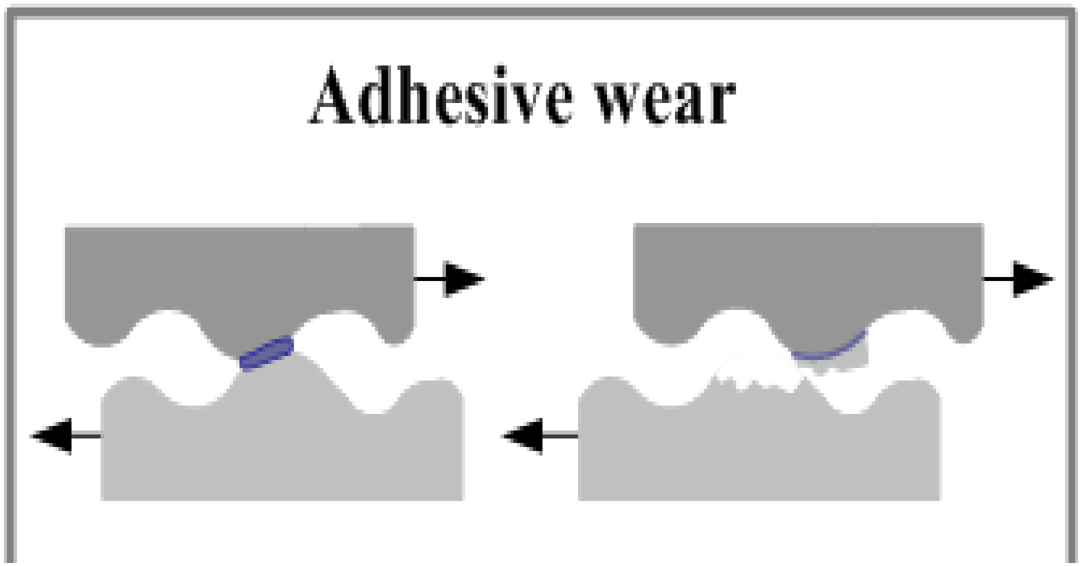


$$V = K\frac{NL}{3\sigma s}$$

Where
V = wear volume, L = sliding velocity
N = applied load, σs = surface strength
K = wear coefficient

Ref.: www.substech.com

Adhesive wear. During sliding fragments will be pulled off one surface and adhere to the other. Strong adhesive forces are required for this type of wear and even then only a small number of asperity junctions result in material transfer. This is the most common and least preventable type of wear.



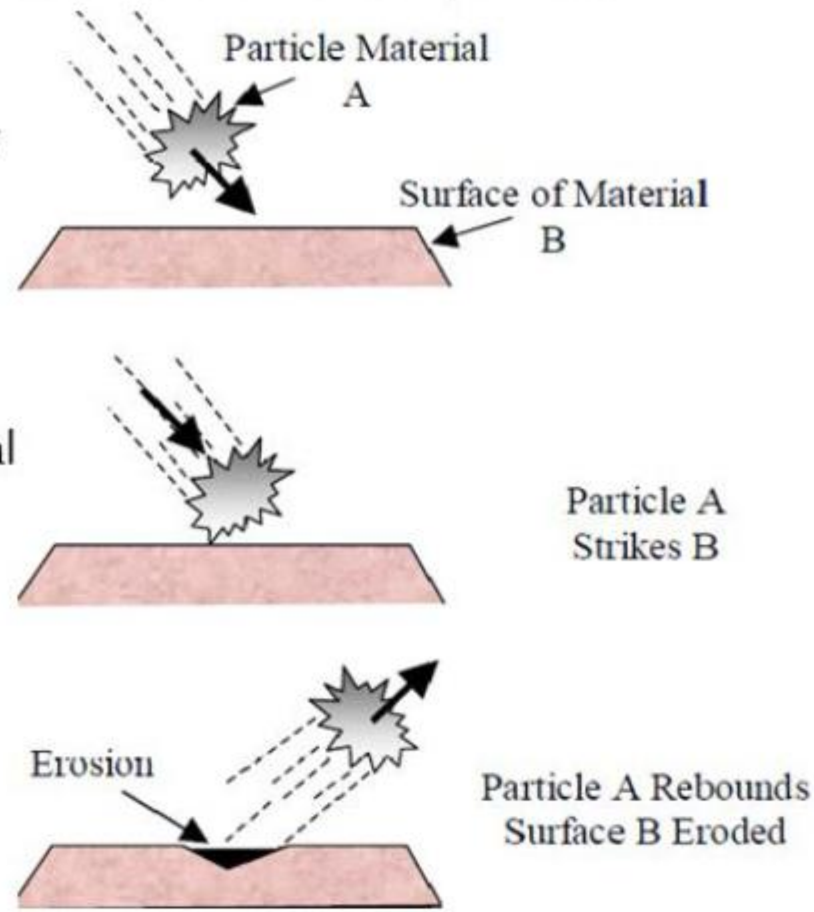
Erosive wear

The impingement of solid particles, or small drops of liquid or gas on the solid surface cause wear what is known as erosion of materials and components.

Pressure generated due to change in velocity

$$P = \Delta V\sqrt{E\rho}$$

P = Impact pressure
E = Modulus of elasticity of impacted material
ρ = Density of the fluid
V = Velocity



Advantages

- Cutting, drilling and polishing of brittle material

Types of erosion

Solid particle erosion
Surface wear by impingement of solid particles carried by a gas or fluid.

e.g. Wear of helicopter blade leading edges in dusty environments.

- **Liquid drop erosion**
  Surface wear by impingement of liquid drops.

e.g. Wear of centrifugal gas compressor blades by condensate droplets.

- **Cavitation erosion**
  Surface wear in a flowing liquid by the generation and implosive collapse of gas bubbles.

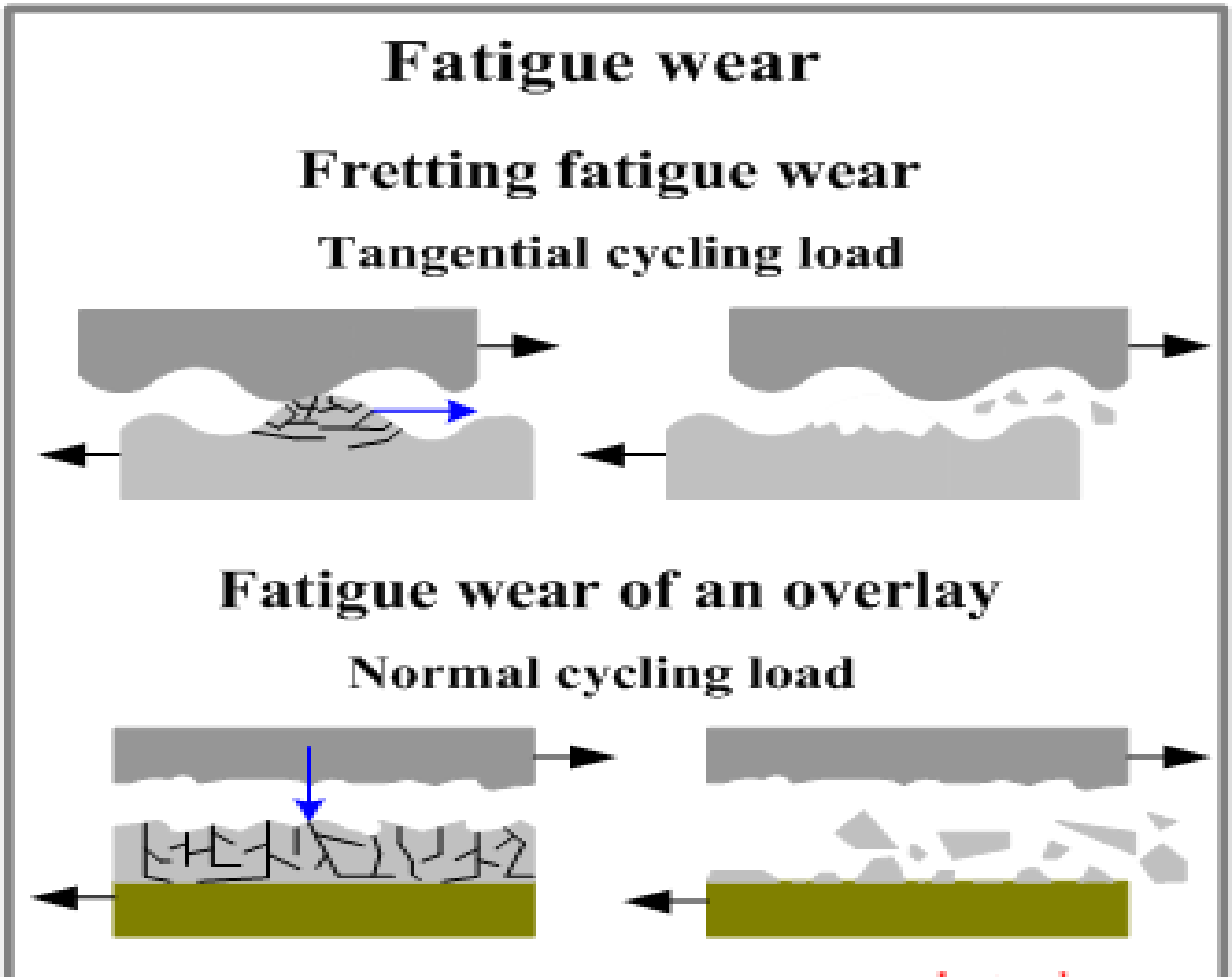
e.g. Fluid-handling machines as marine propellers, dam slipways, gates, and all other hydraulic turbines.

Fatigue wear

Fatigue wear of a material is caused by a cycling loading during friction. Fatigue occurs if the applied load is higher than the fatigue strength of the material.
Fatigue cracks start at the material surface and spread to the subsurface regions. The cracks may connect to each other resulting in separation and delamination of the material pieces.

One of the types of fatigue wear is **fretting wear** caused by cycling sliding of two surfaces across each other with a small amplitude (oscillating). The friction force produces alternating compression-tension stresses, which result in surface fatigue.

Fatigue of overlay of an engine bearing may result in the propagation of the cracks up to the intermediate layer and total removal of the overlay.


Fatigue wear
Fretting fatigue wear
Tangential cycling load
Fatigue wear of an overlay
Normal cycling load

Sliding wear test

- The sliding wear tests in dry lubricating condition was performed for reinforced filled metal alloy composite using a pin-on-disc tribometer (Model TR 20, Ducom, Bangalore, India) as per ASTM G 99 standard.
- A disc that made of EN-31 hardened steel (with hardness 60-70HRC). A fixed wear track of diameter 50 mm was used for all the tests, based on the track diameter the sliding velocity was calculated as 1.024, 2.094, 3.140, 4.188and 5.235 m/sec respectively
- The environment temperature varies from 25^0 C to 45^0 C at an interval of 5^0 C as per our Taguchi design of experiment in this analysis.
- the material loss of composite was measured by a precision electronic balance with an accuracy of ±0.001 g
- The specific wear rate (mm^3/N-m) was calculated through given equation:
- $Ws = \dfrac{\Delta m}{\rho . Vs . t . Fn}$

Where, Ws was specific wear rate in mm^3/N-m, Δm was mass loss of composite during test(gm.),ρ was the density of the composite (g/cm^3), Vs was the sliding velocity (m/s),t was the test duration (s), and Fn was the normal load (N).

Figure A Pin on Disc Tribometer Equipment

 Source MNIT Jaipur

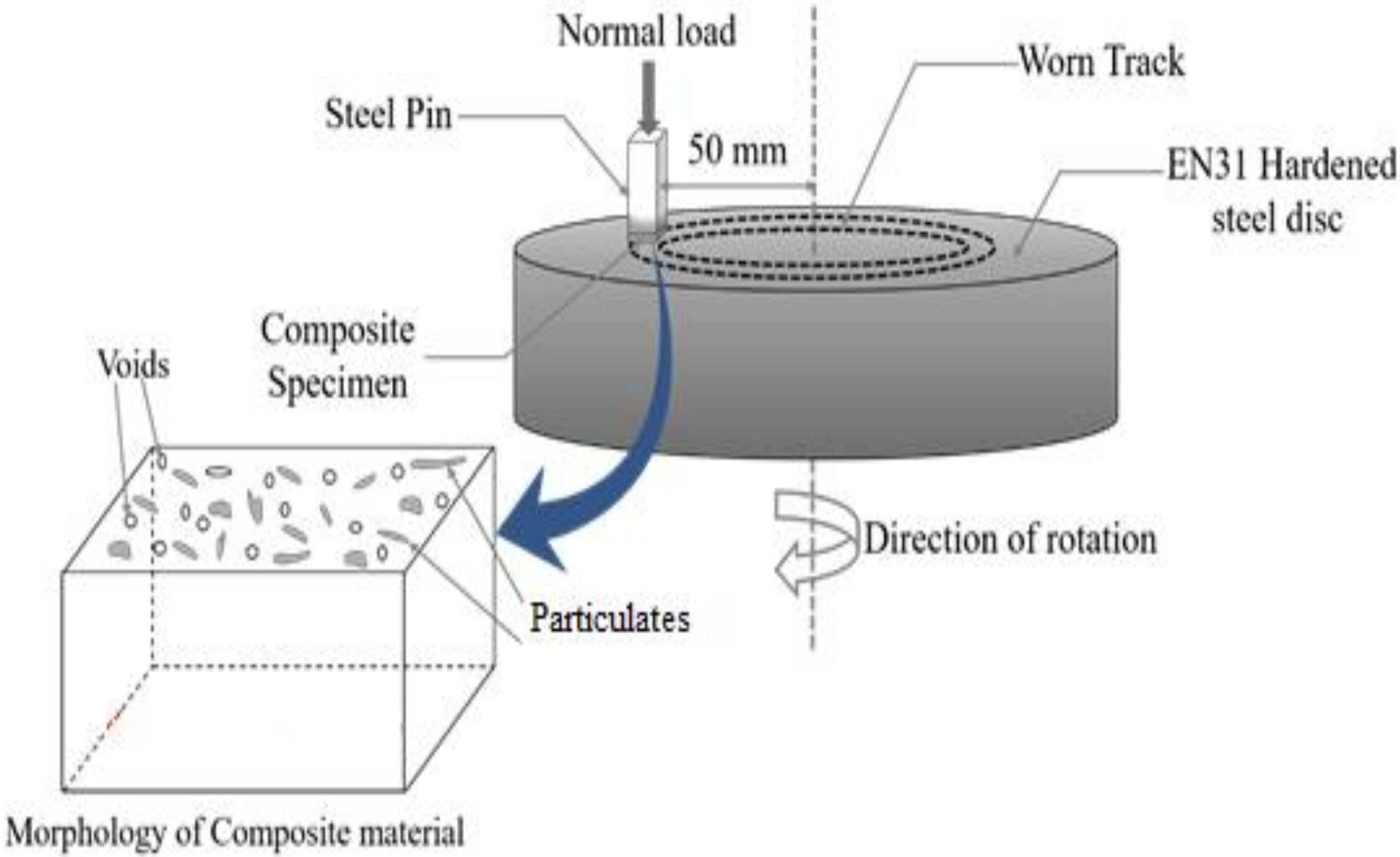


Figure Schematic representations of the pin-on-disc wear test apparatus