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MATERIAL SCIENCE AND ENGINEERING

UNIT 2

STRESS AND STRAIN

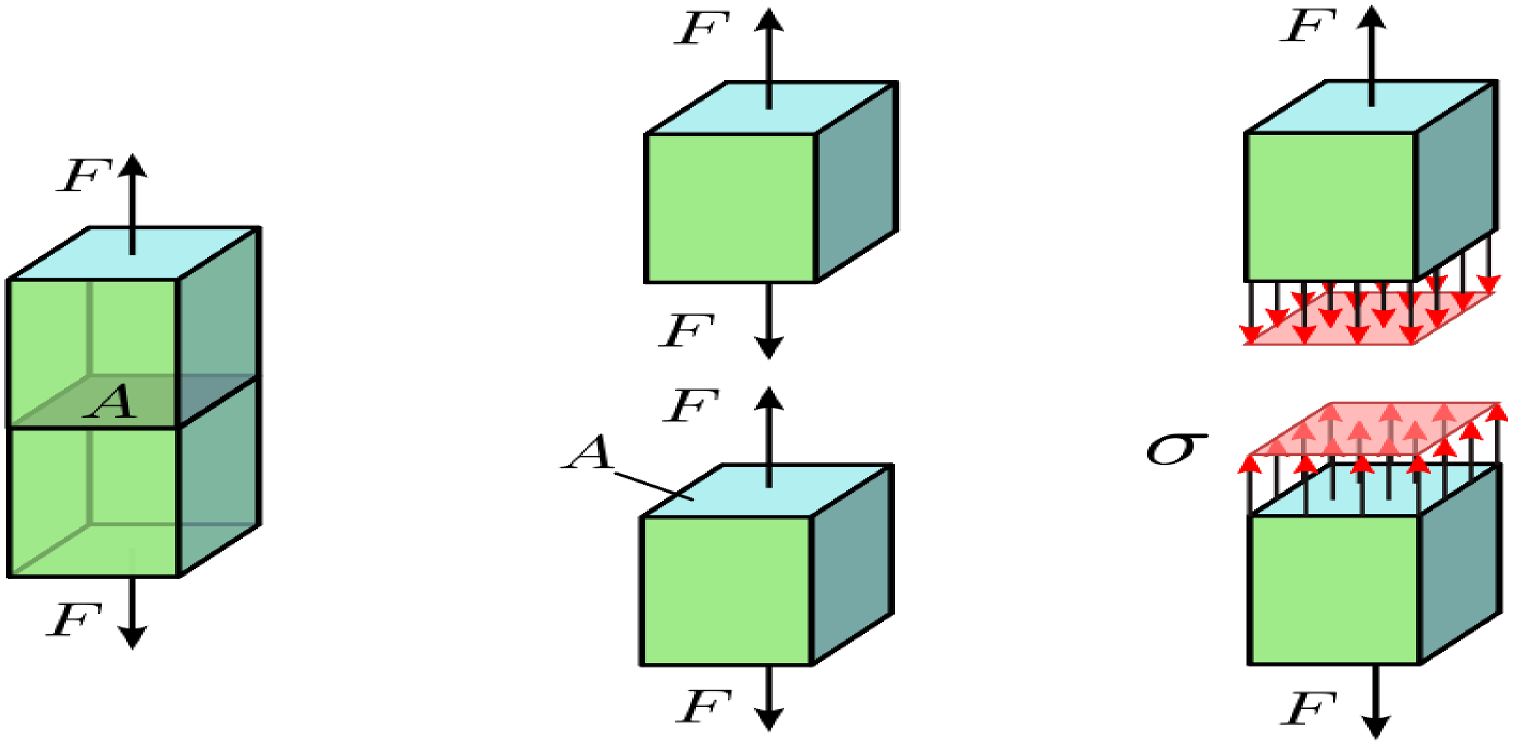
Dr. SWATI GANGWAR

Mr. KAPIL KUMAR

Department Of Mechanical Engineering, MMMUT Gorakhpur

Stress/ Normal Stress/ Simple Stress

A material when subjected to an external force, an internal resisting force induced with in the material, this **internal resistive force is know as stress** or normal stress.



Normal stress

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

σ – Normal Stress

P – Axial Force

A – Cross Sectional Area

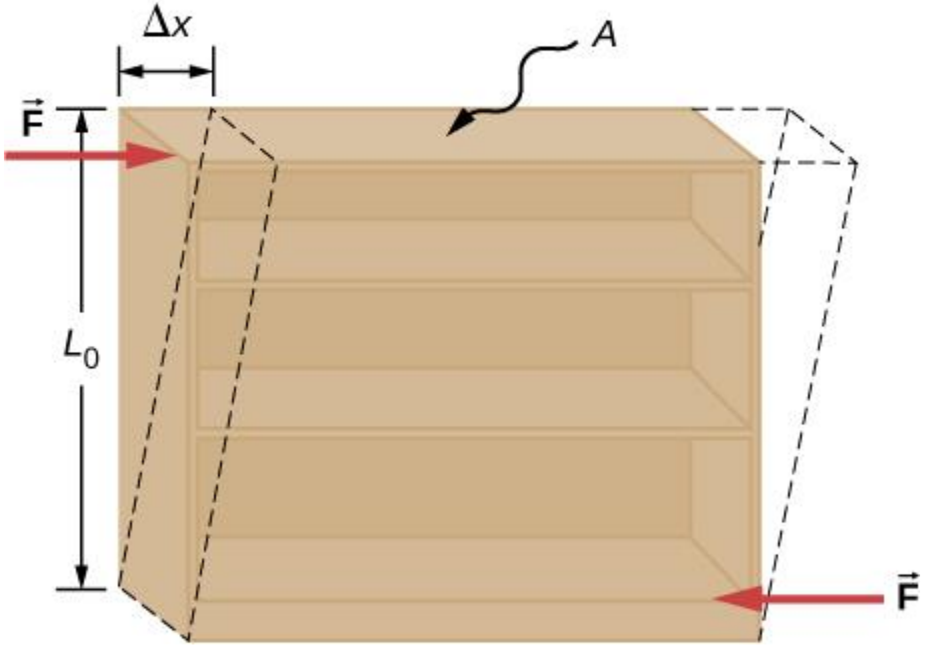
Unit of stress: In S.I.

N/m^2 (Pa)

Other units used in practice are **N/mm^2, kN/mm^2.**

Shear stress

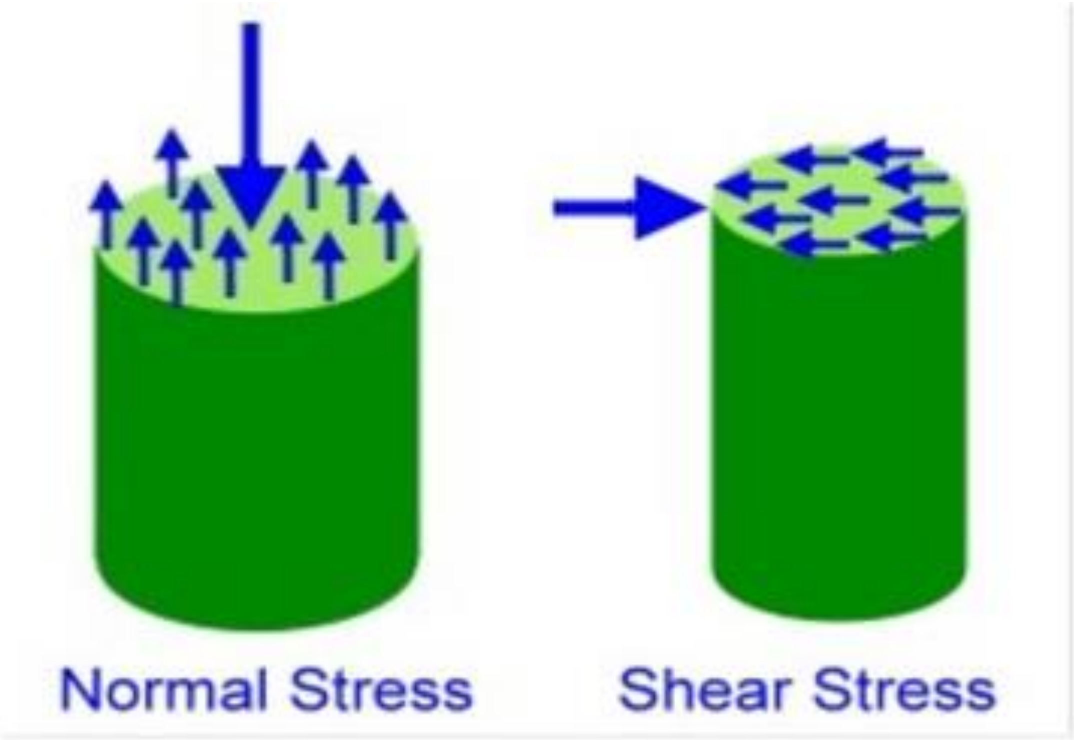
Shear stress is equal to shearing force per unit area.



The shear modulus is the proportionality constant , and is defined by the ratio of stress to strain. It is denoted by symbol S

$$\mathbf{S} = \frac{\textbf{Shear stress}}{\boldsymbol{Shear\ strain}}$$

Difference between Normal stress and Shear stress



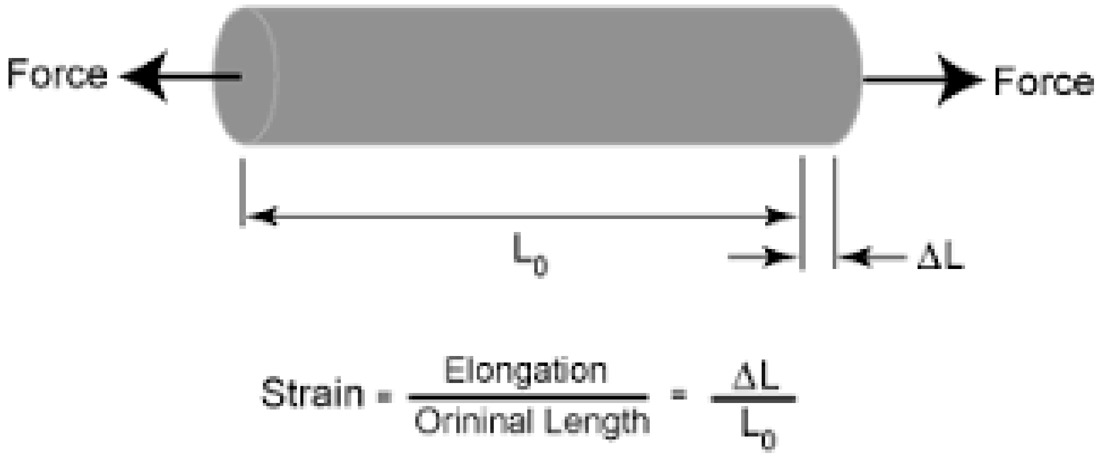
Strain

When an external force applied on a body, there is some change produced in dimensions of the body. ***The ration of change in dimensions of the body to the original dimension is known as strain.***

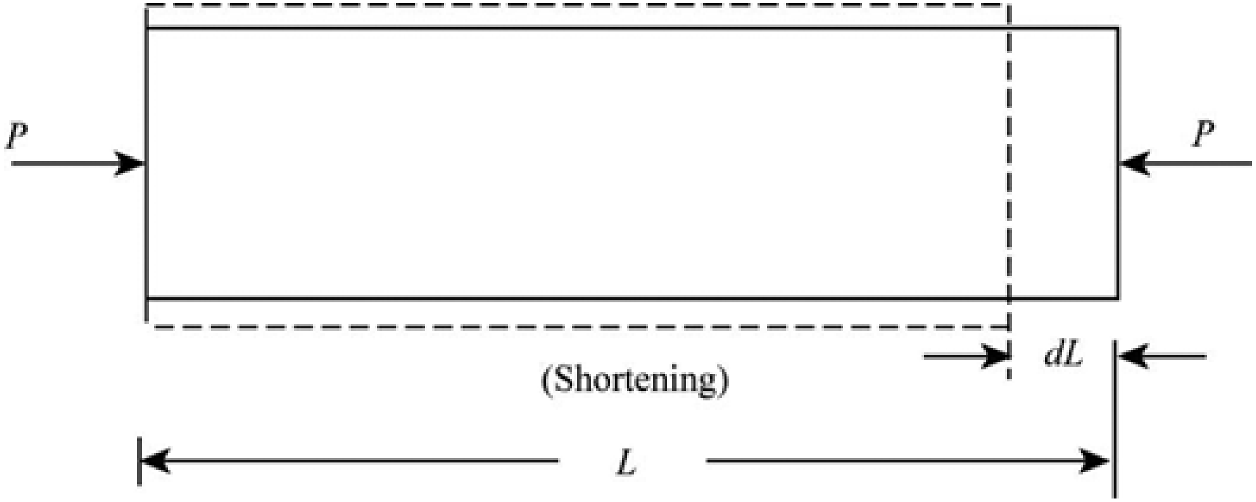
Stain is a **dimensionless quantity**

Types of strain:

- **Tensile strain:** It is the ratio of change in length to the original length of a body when subjected to a tensile force on it.



- **Compressive strain:** It is the ratio of change in length to the original length of a body when subjected to a compressive force on it.



- **Volumetric strain:** It is the ration of change in volume of the body to the original volume.
- **Shear Strain:** Stain induced due to shear stress.

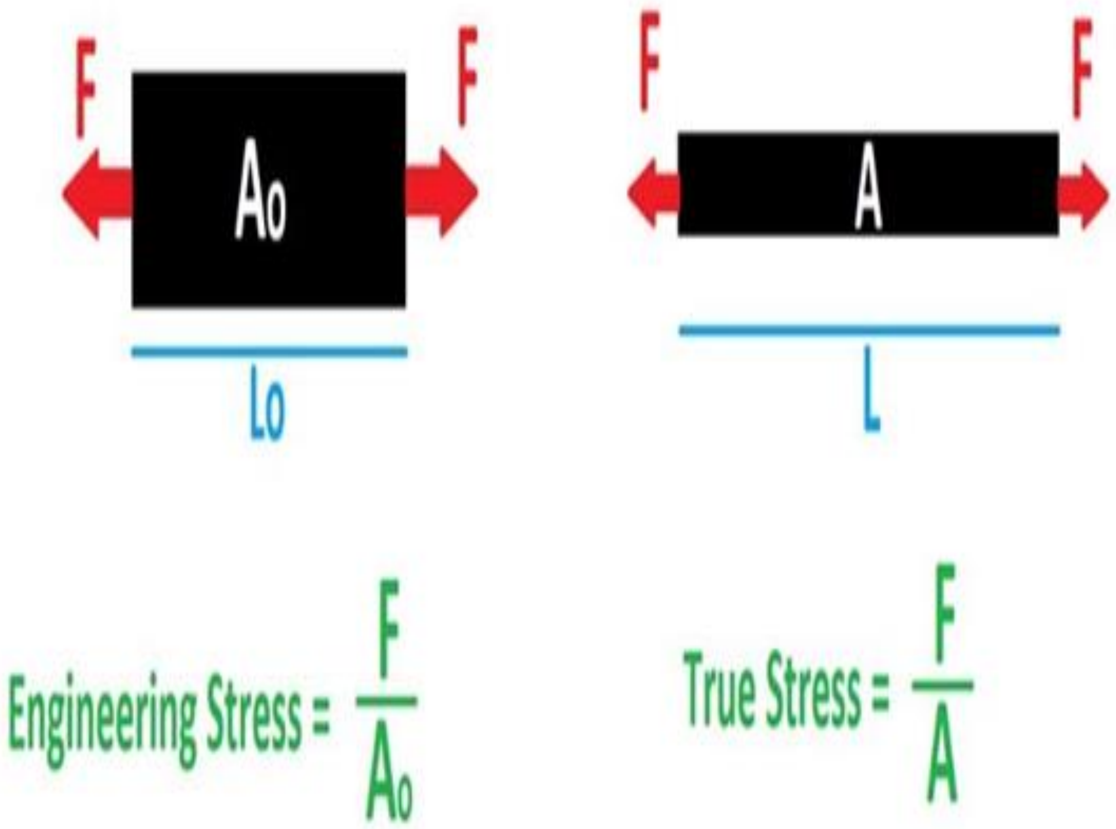
Engineering stress is the applied load divided by the original cross-sectional area of a material.

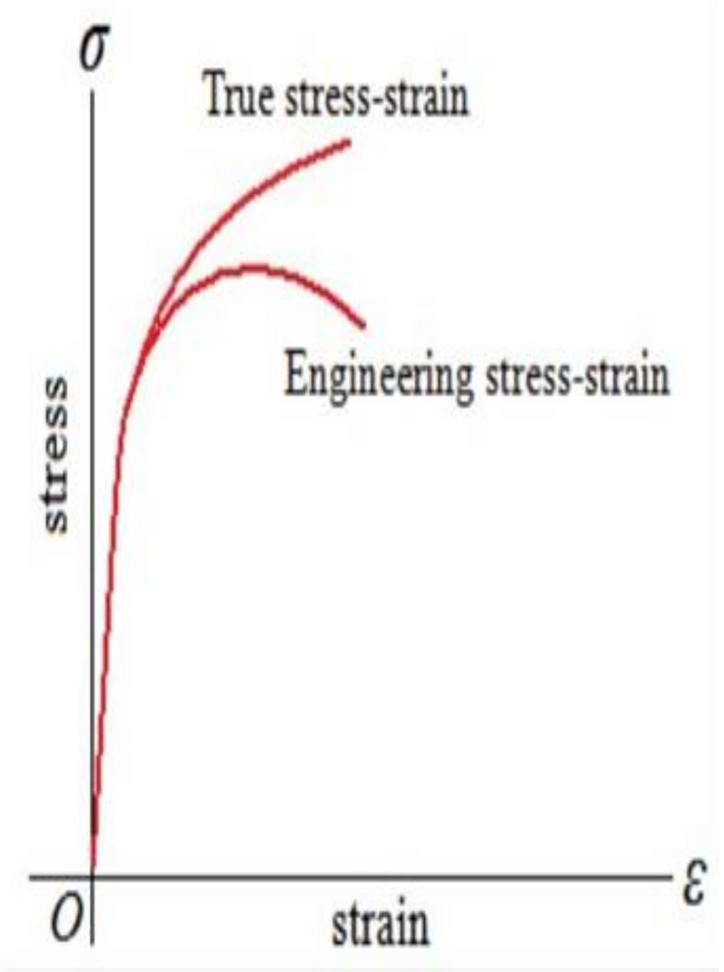
True stress is the applied load divided by the actual cross-sectional area (the changing area with respect to time) of the specimen at that load

Engineering strain is the amount that a material deforms per unit length in a tensile test. Also known as nominal strain.

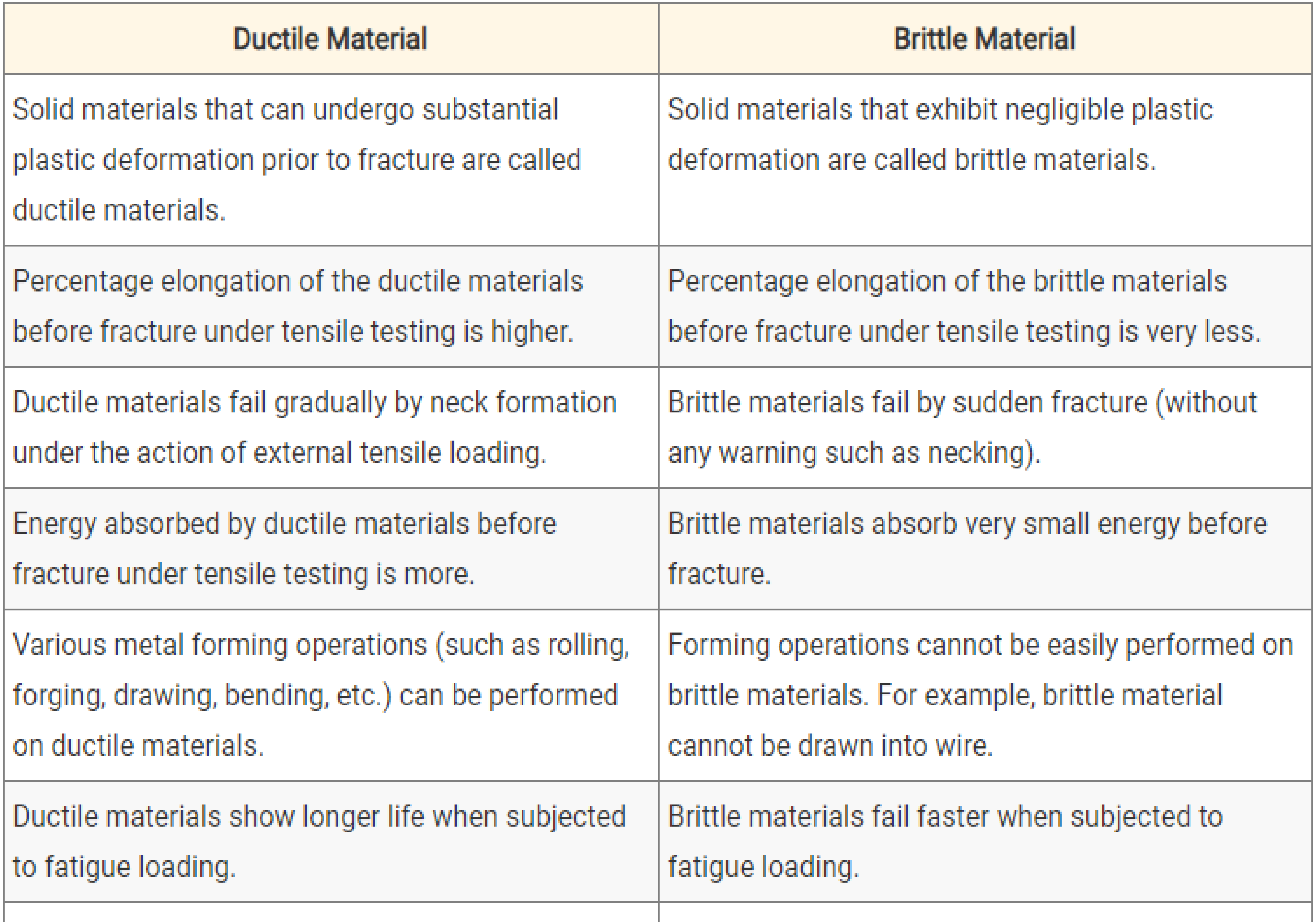
True strain is defined as the instantaneous elongation per unit length of the specimen.

True stress and true strain



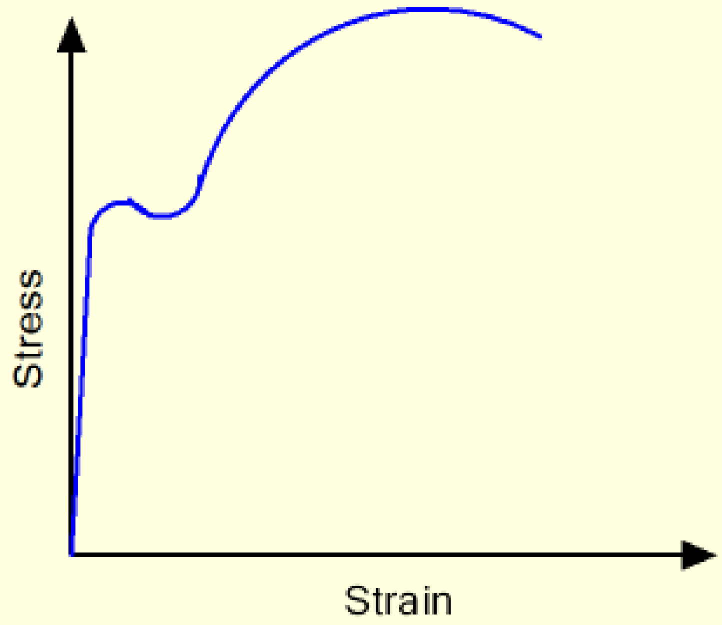


Difference in between Ductile and Brittle materials

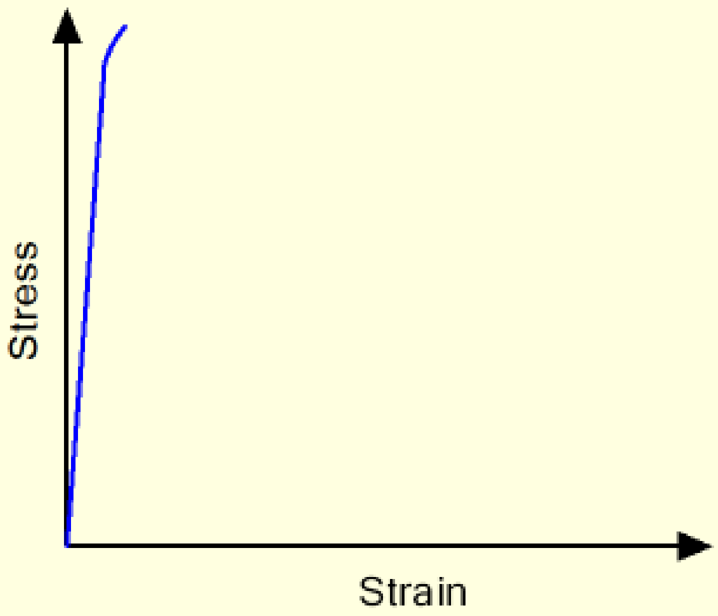


Ductile Material	Brittle Material
Solid materials that can undergo substantial plastic deformation prior to fracture are called ductile materials.	Solid materials that exhibit negligible plastic deformation are called brittle materials.
Percentage elongation of the ductile materials before fracture under tensile testing is higher.	Percentage elongation of the brittle materials before fracture under tensile testing is very less.
Ductile materials fail gradually by neck formation under the action of external tensile loading.	Brittle materials fail by sudden fracture (without any warning such as necking).
Energy absorbed by ductile materials before fracture under tensile testing is more.	Brittle materials absorb very small energy before fracture.
Various metal forming operations (such as rolling, forging, drawing, bending, etc.) can be performed on ductile materials.	Forming operations cannot be easily performed on brittle materials. For example, brittle material cannot be drawn into wire.
Ductile materials show longer life when subjected to fatigue loading.	Brittle materials fail faster when subjected to fatigue loading.

Stress-Strain curve for ductile and brittle materials

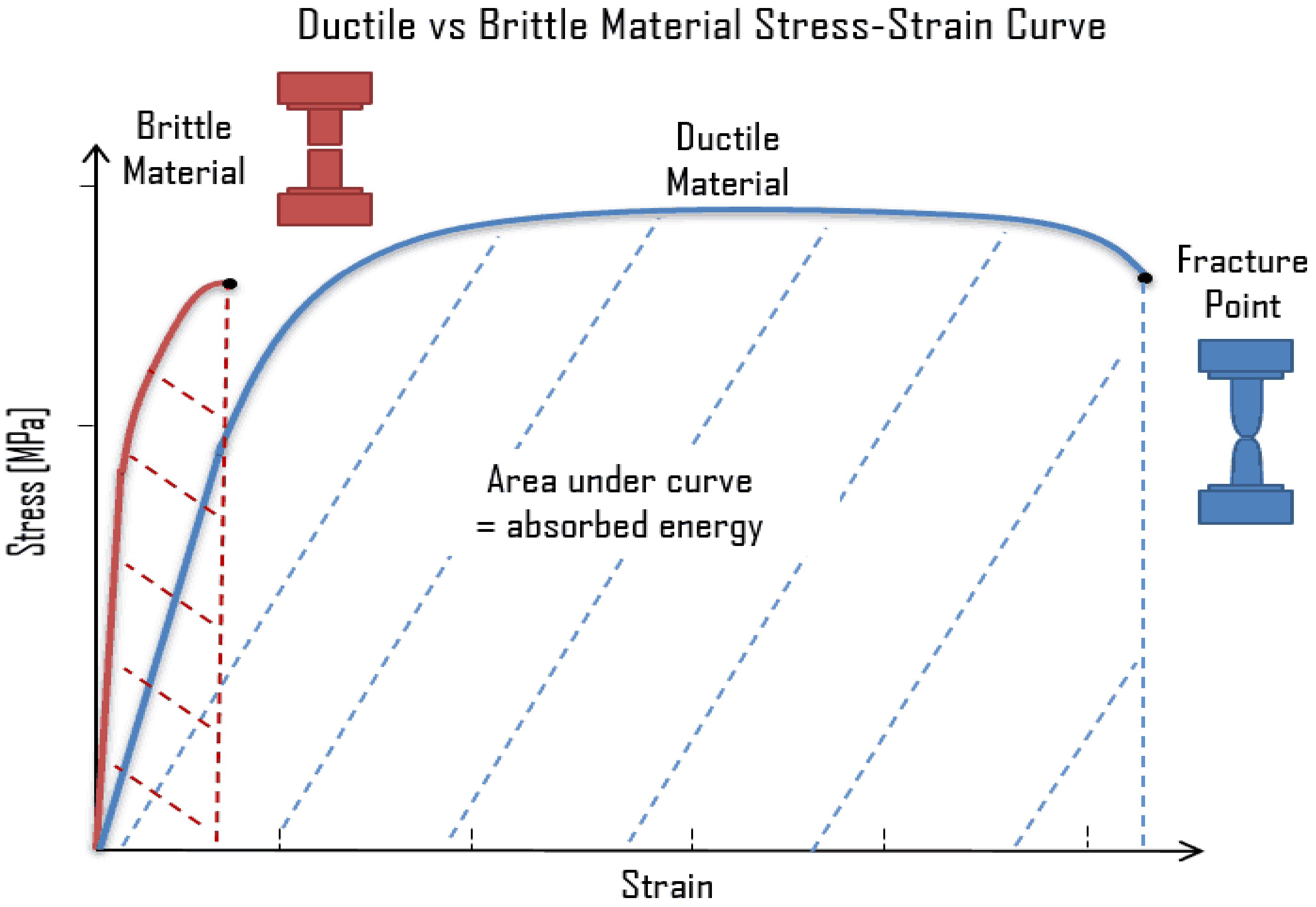


Typical Ductile Material

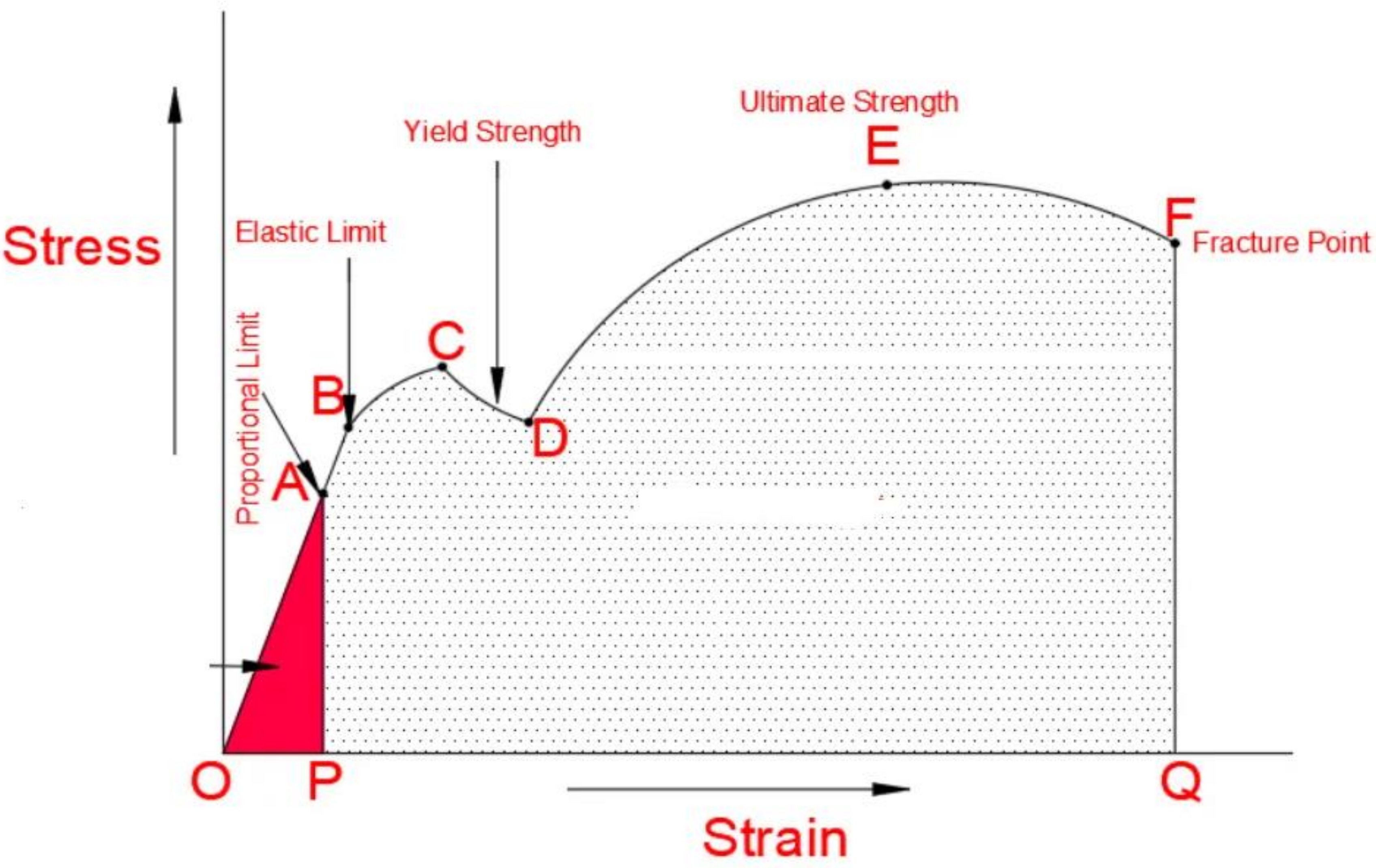


Typical Brittle Material

Stress strain diagram for ductile and brittle materials



Stress strain diagram for mild steel



stress-strain curve for mild steel

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MATERIAL SCIENCE AND ENGINEERING

UNIT 2

IMPACT STRENGTH, FATIGUE FAILURE AND CREEP FAILURE

Dr. SWATI GANGWAR

Mr. KAPIL KUMAR

Department Of Mechanical Engineering, MMMUT Gorakhpur

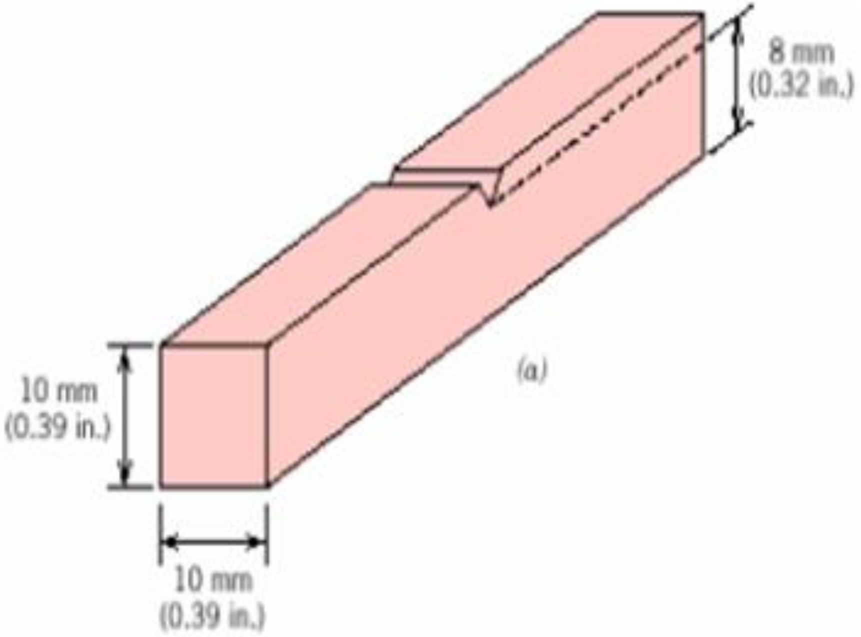
Impact Strength

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

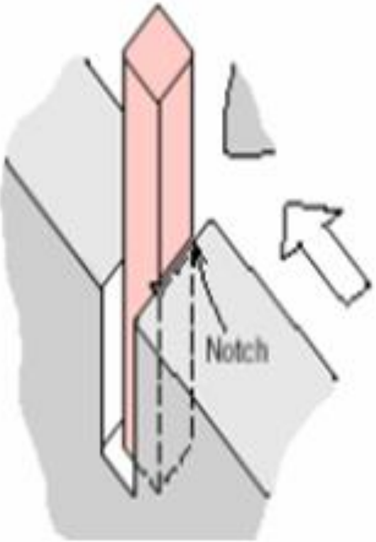
Types of impact test are;

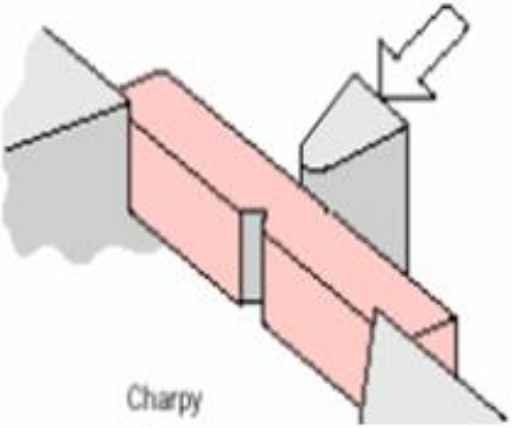
- ➢ Izod impact test
- ➢ Charpy impact test

Impact test



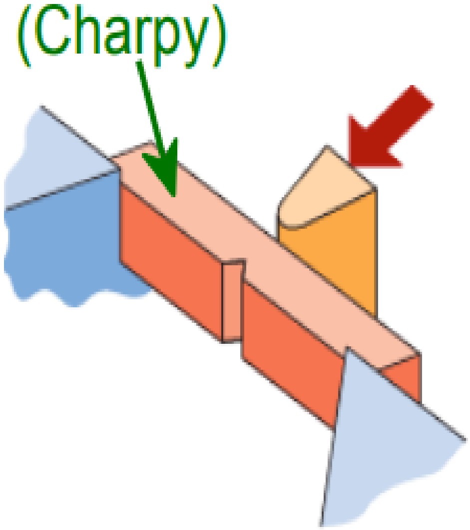
Izod

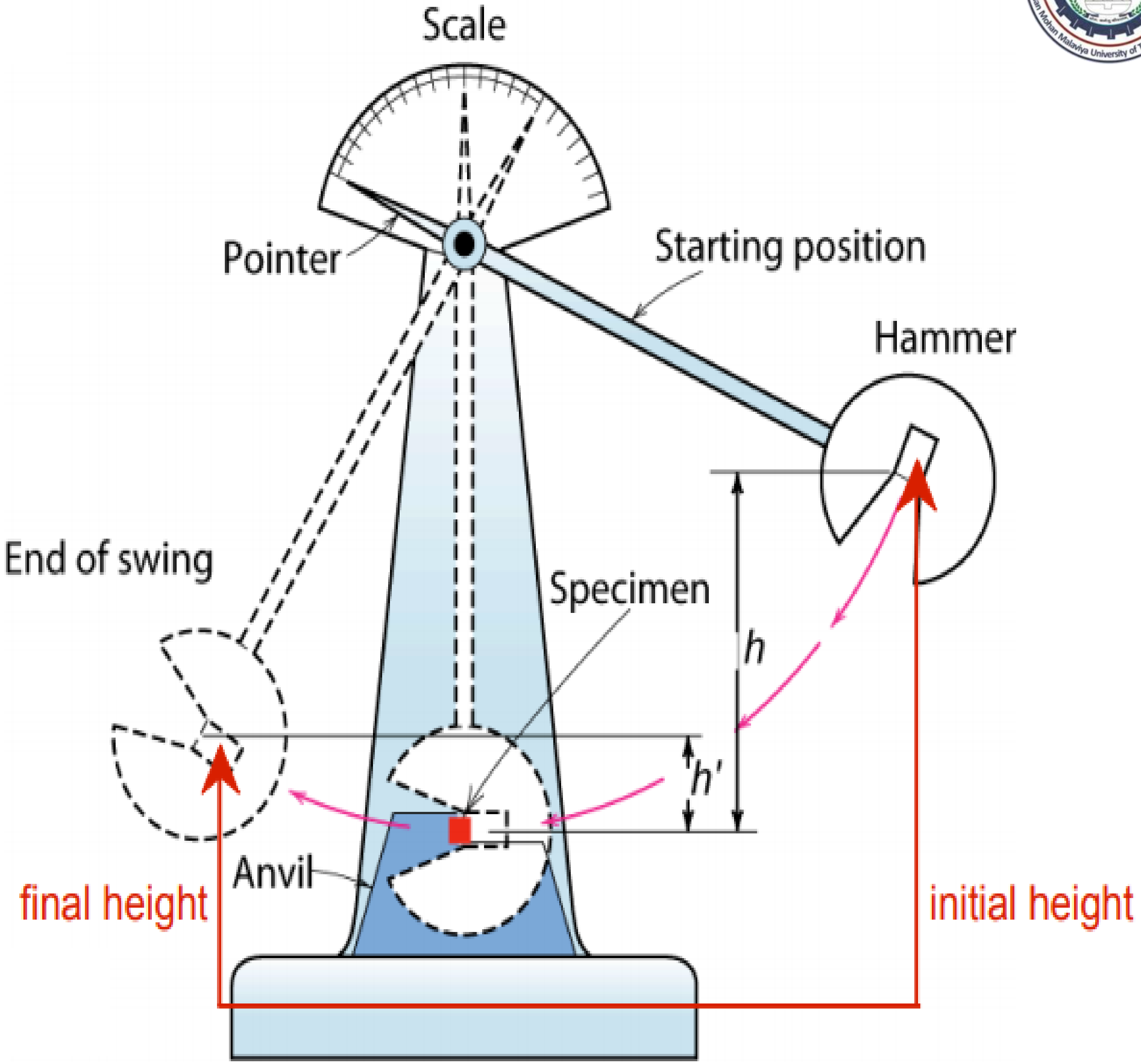




Charpy

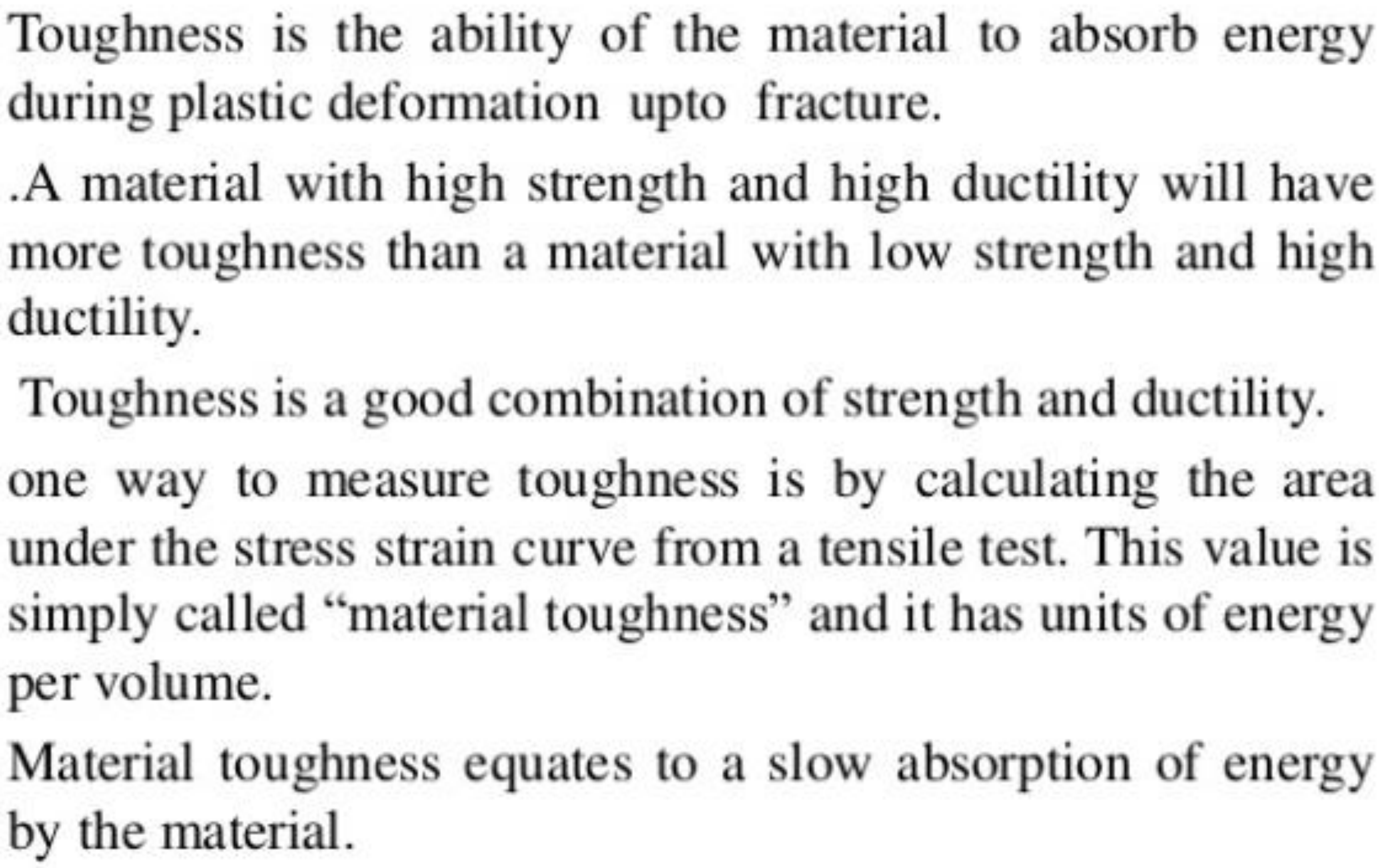
Charpy Impact Test





	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



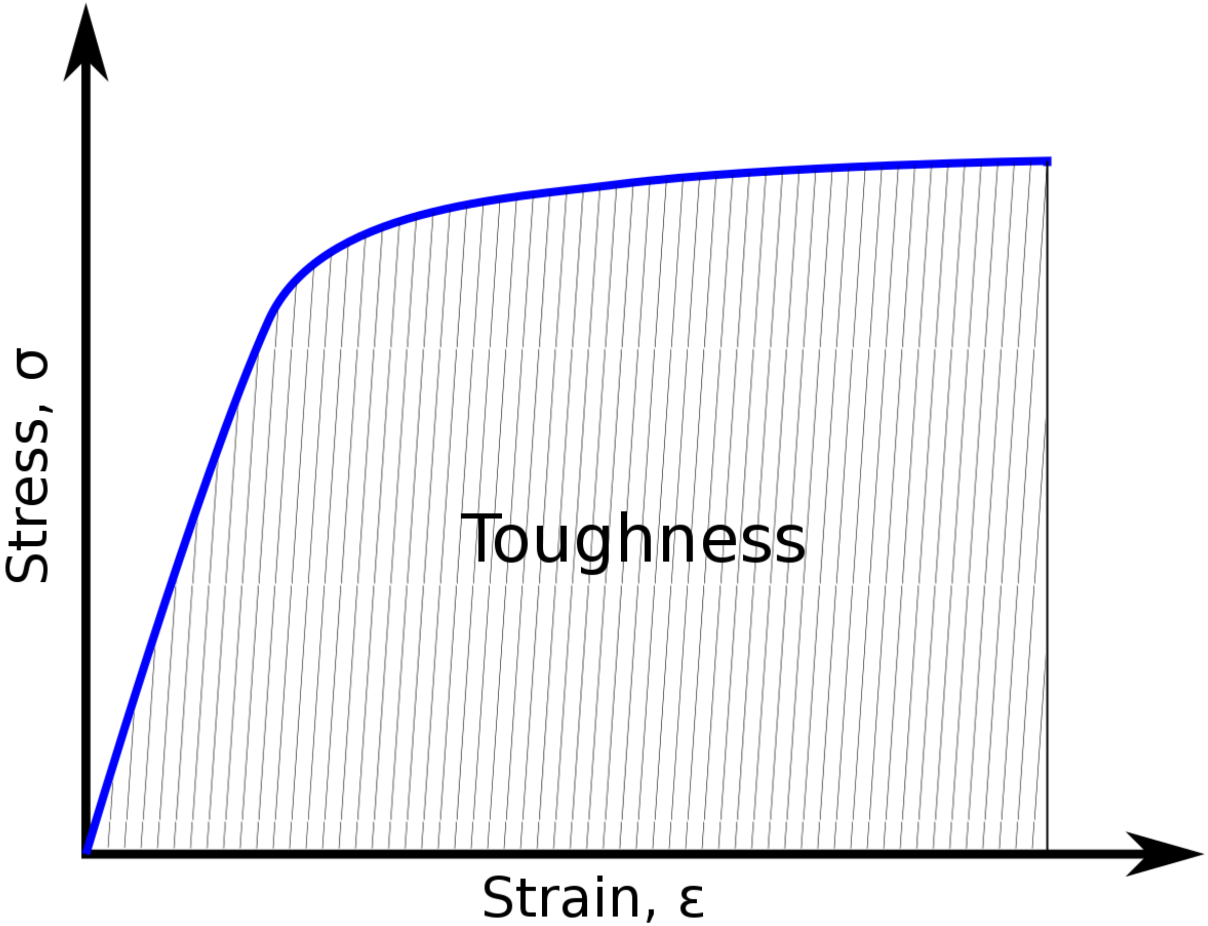
Toughness is the ability of the material to absorb energy during plastic deformation upto fracture.

.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

Fatigue failure

- Failure that occurs **under fluctuating /cyclic loads** called fatigue failure.

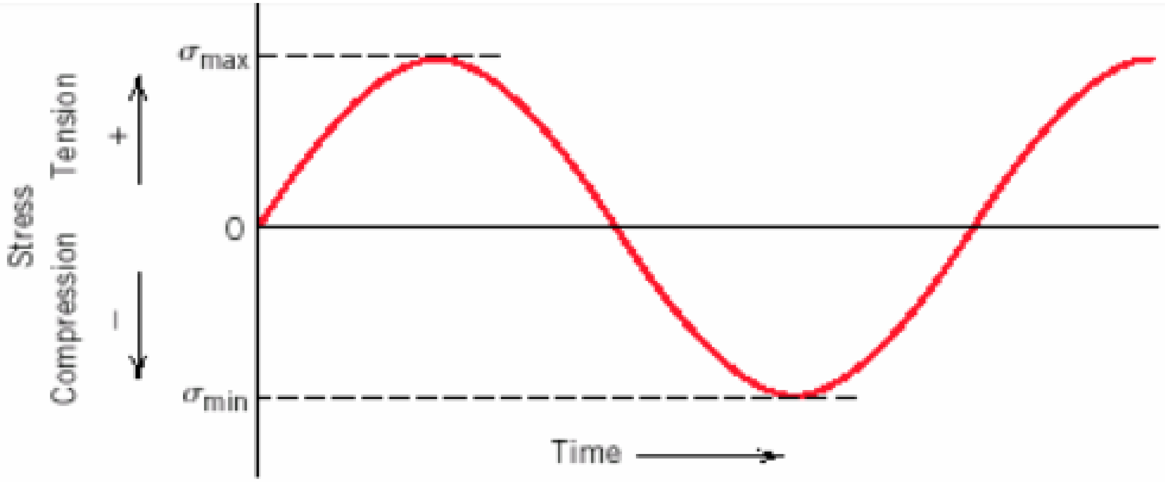
- Fatigue is the process by which ***most materials fails under cyclic loading (Approx. 90%)***

- It occurs when material is subjected to alternative stresses, over a **long period of time**. ***Examples are bridges, turbine blades, bones etc.***

- There are mainly three stress cycles with which loads may applied to the sample.

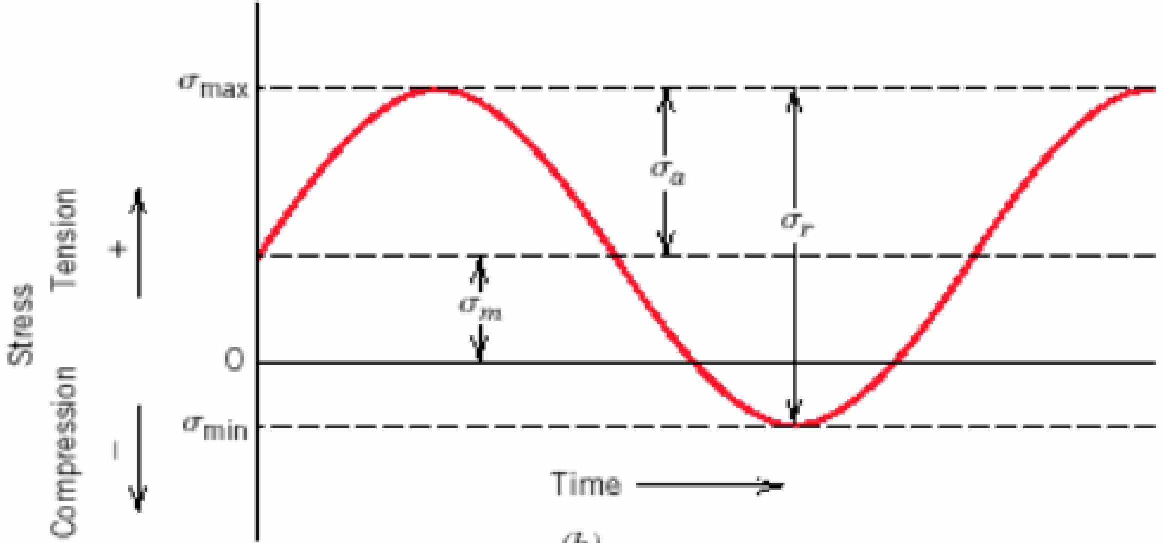
1. **Reversed stress cycle**
2. **Repeated stress cycle**
3. **Random stress cycle**

Fatigue stress cycle



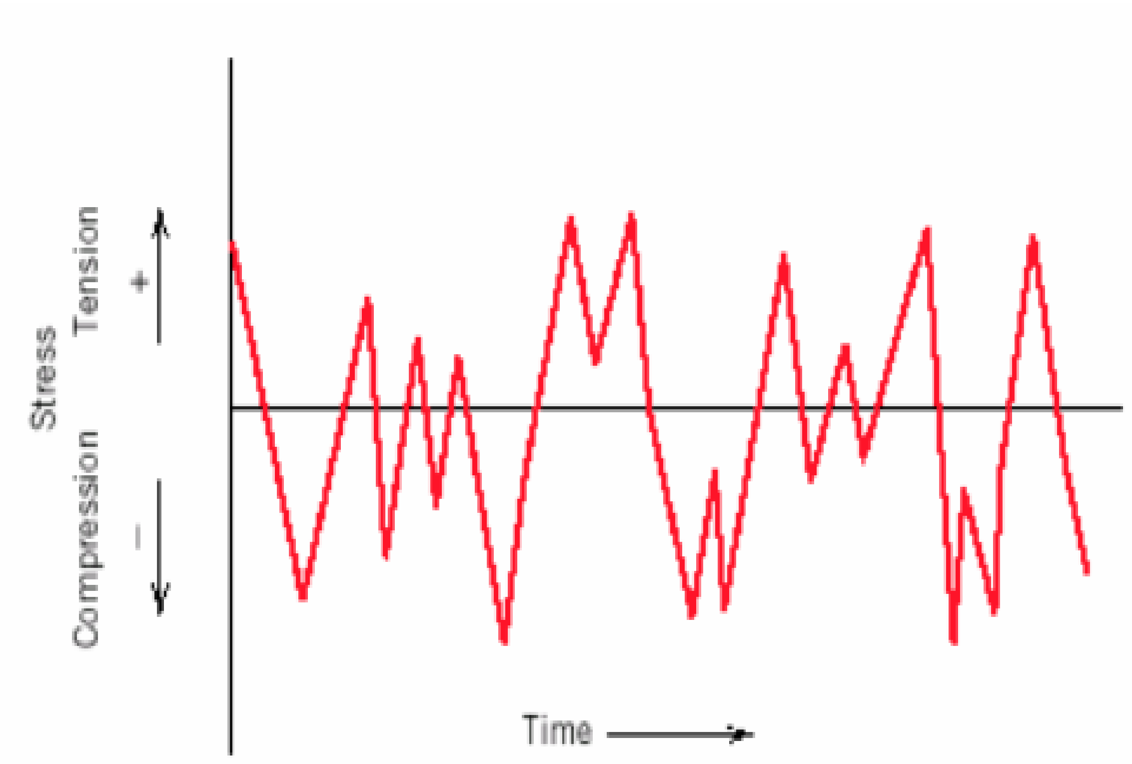
(a)

Periodic and symmetrical about zero stress



(b)

Periodic and asymmetrical about zero stress

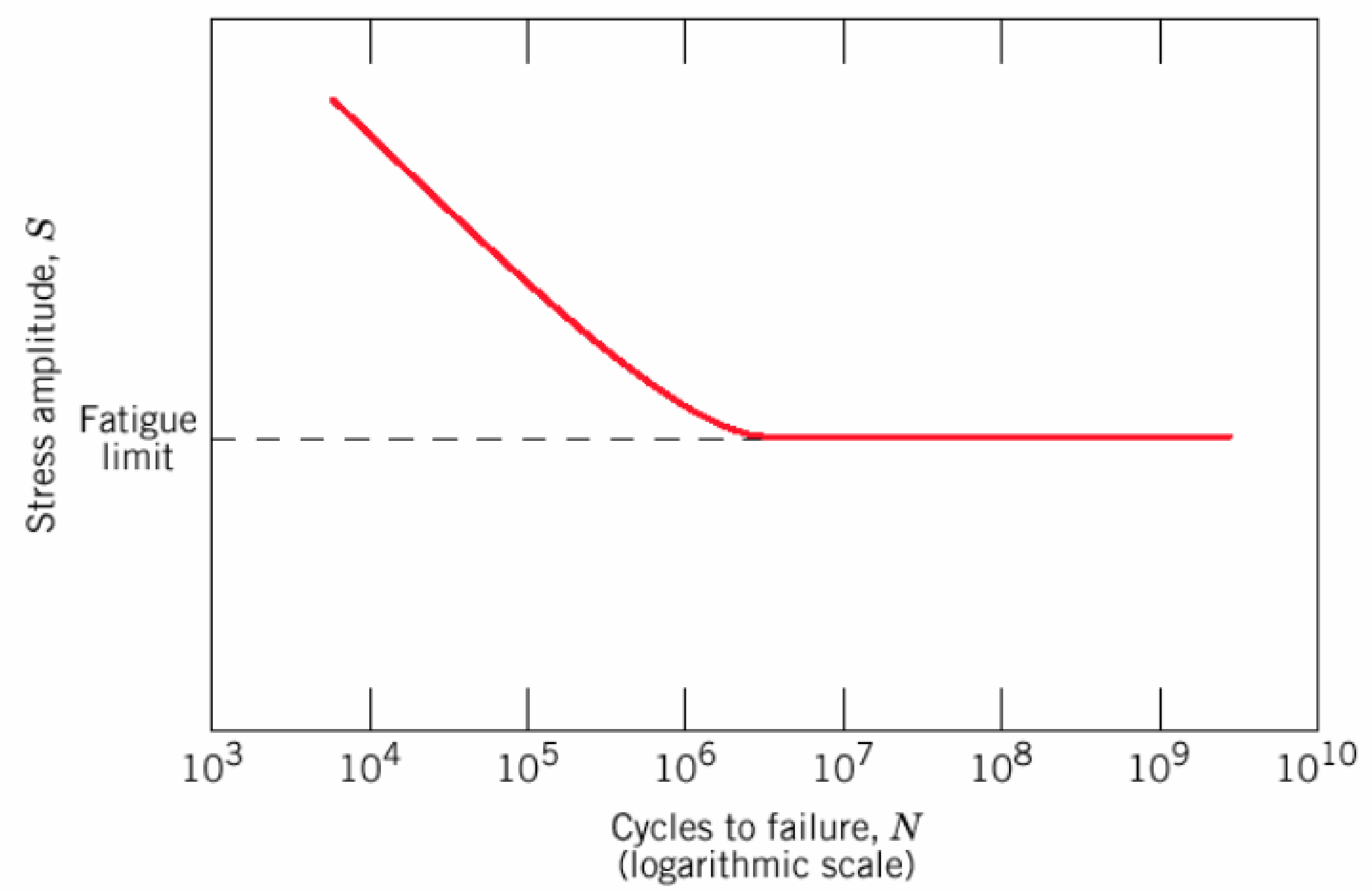


Random stress fluctuations

Stress cycles that can cause fatigue failure are characterized using the following parameters:

Range of stress,	$\sigma_r = \sigma_{max} - \sigma_{min}$
Alternating stress,	$\sigma_a = \sigma_r/2 = (\sigma_{max} - \sigma_{min})/2$
Mean stress,	$\sigma_m = (\sigma_{max} + \sigma_{min})/2$
Stress ratio,	$R = \sigma_{min} / \sigma_{max}$
Amplitude ratio,	$A = \sigma_a / \sigma_m = (1-R) / (1+R)$

S-N Curve


Stress amplitude, S
Fatigue limit
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
Cycles to failure, N
(logarithmic scale)

Factors that affect fatigue life

- Quality of surface (Scratches, voids, etc.)
- Magnitude of stress
- Environmental effects (Thermal fatigue, Corrosion fatigue)

Solutions:

Polishing

Case Hardening

Optimizing geometry

Creep failure

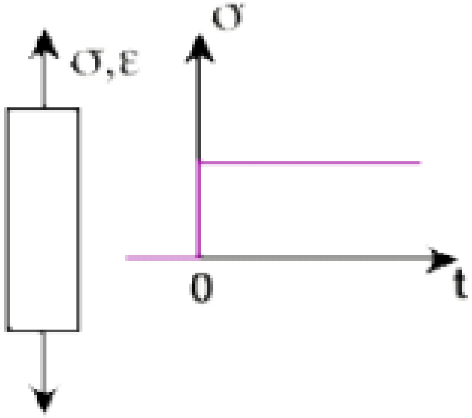
Creep is a **time-dependent and permanent** deformation of materials when subjected to a constant load at a **high temperature** (> 0.4 T_m). Examples: turbine blades, steam generators.

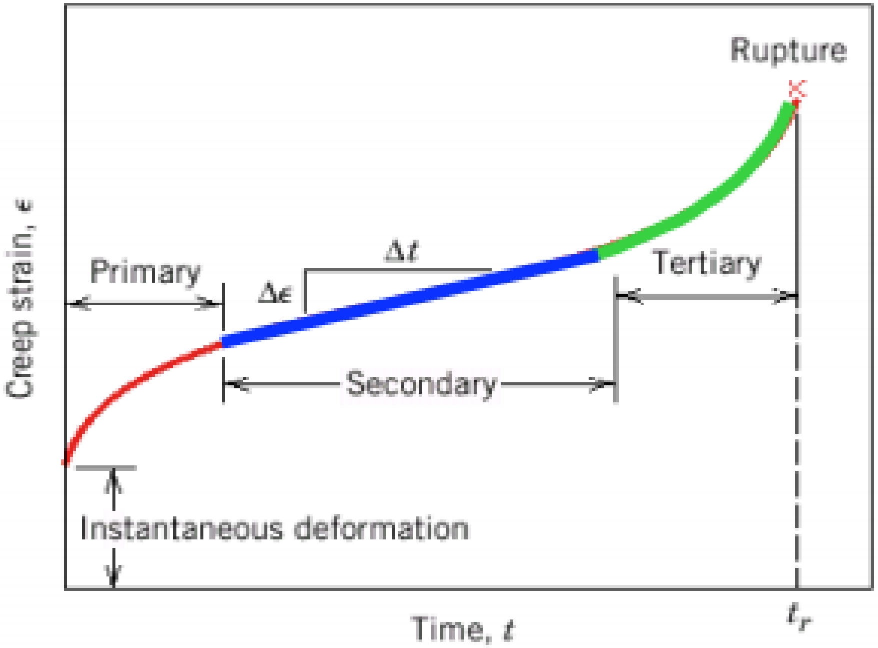
Creep rate – Stress & Temperature effects

- 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.

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Madan Mohan Malaviya University of Technology, Gorakhpur

Mad University of Technology,
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MATERIAL SCIENCE AND ENGINEERING

UNIT 2

HARDNESS

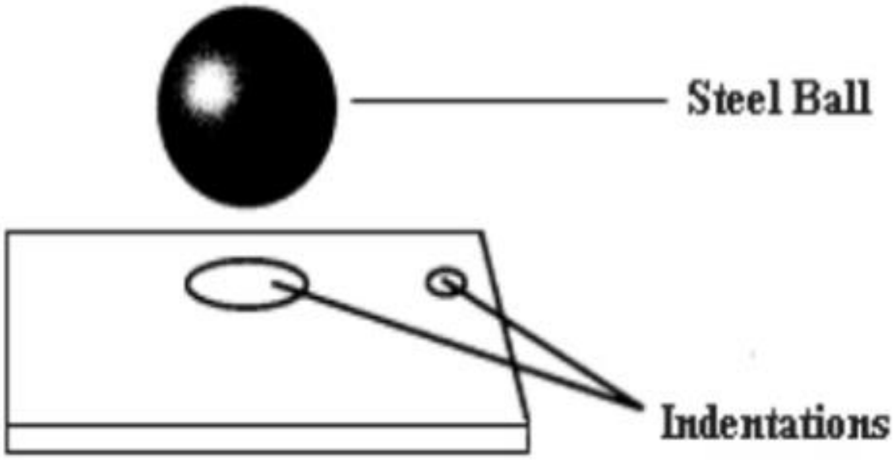
Dr. SWATI GANGWAR
Mr. KAPIL KUMAR

Department Of Mechanical Engineering, MMMUT Gorakhpur

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

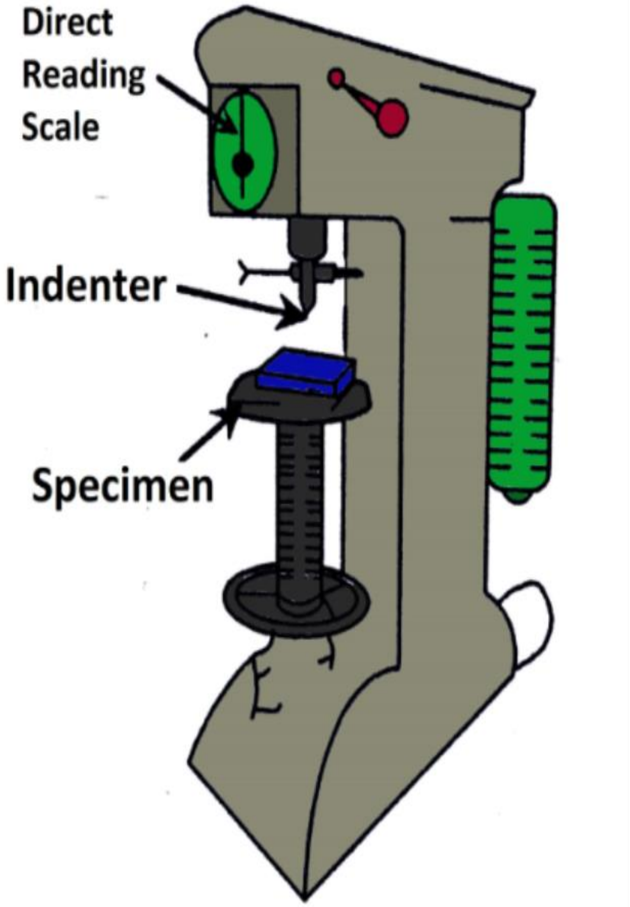
- The Rockwell tests constitute most common method used to measure hardness because they are so **simple to perform and require no special skills.**
- **Several different scales may be utilized from possible combinations of various indenters and different loads**, which permit the testing of all metal 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:

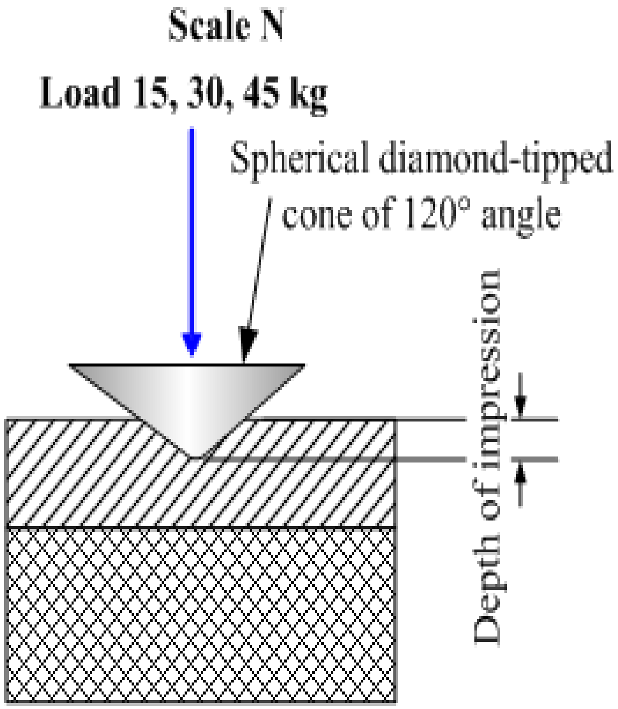
Rockwell (Minor load is 10 kg and major load are 60,100 and 150 kg)

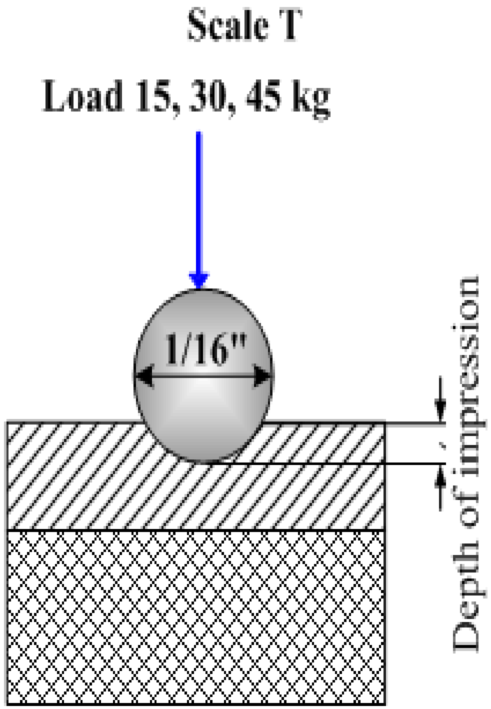
Superficial Rockwell (Minor load is 3 kg and major load are 15, 30 and 45 kg)

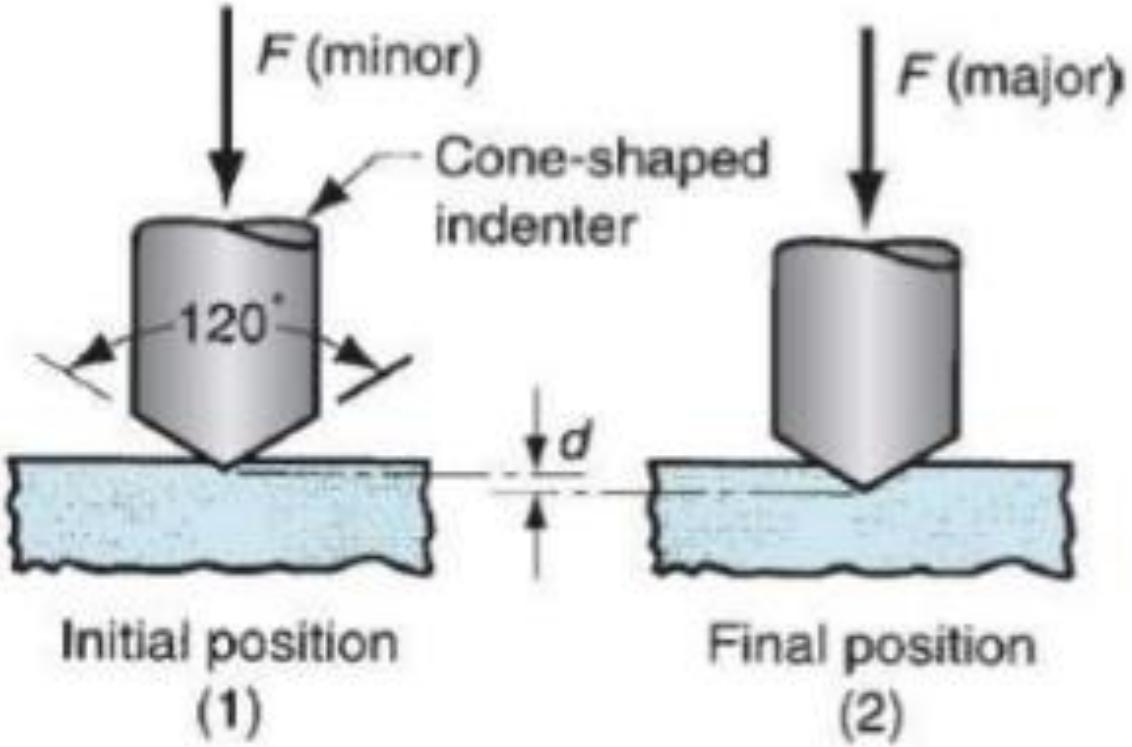
For both the scale designated y the **symbol HR**

Rockwell Superficial Hardness Test



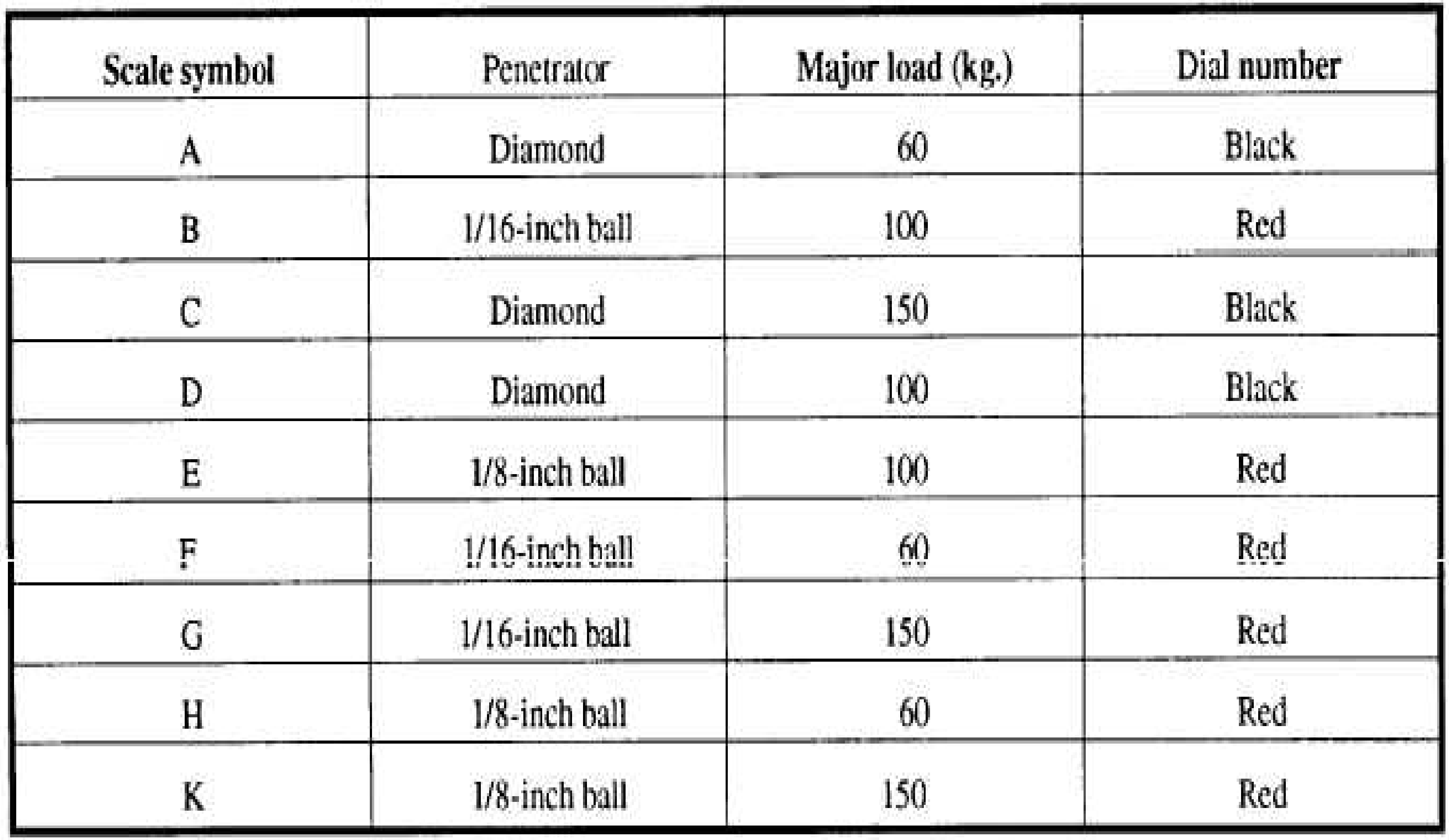





F (minor)
Cone-shaped indenter
120°
d
F (major)
Initial position
(1)
Final position
(2)

Rockwell

Rockwell Hardness Scale



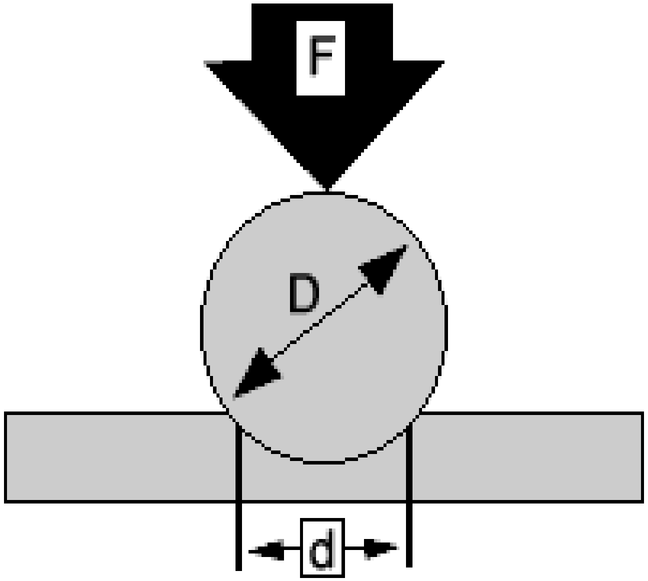
Scale symbol	Penetrator	Major load (kg.)	Dial number
A	Diamond	60	Black
B	1/16-inch ball	100	Red
C	Diamond	150	Black
D	Diamond	100	Black
E	1/8-inch ball	100	Red
F	1/16-inch ball	60	Red
G	1/16-inch ball	150	Red
H	1/8-inch ball	60	Red
K	1/8-inch ball	150	Red

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.

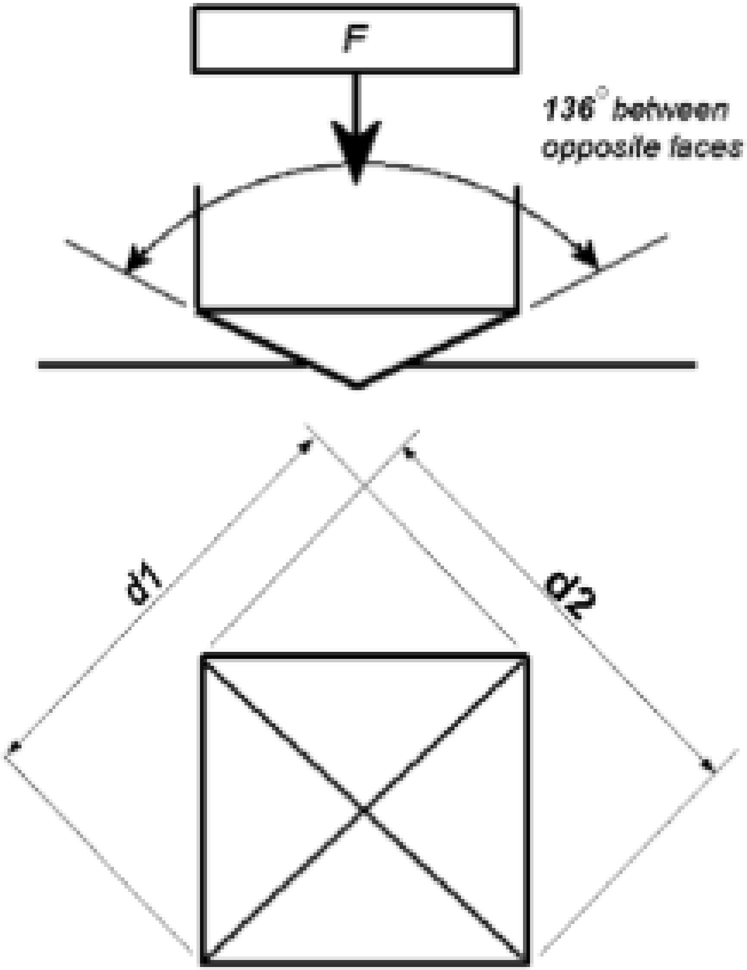


$$HB = \frac{2F}{\pi D\left(D - \sqrt{D^2 - d^2}\right)}$$

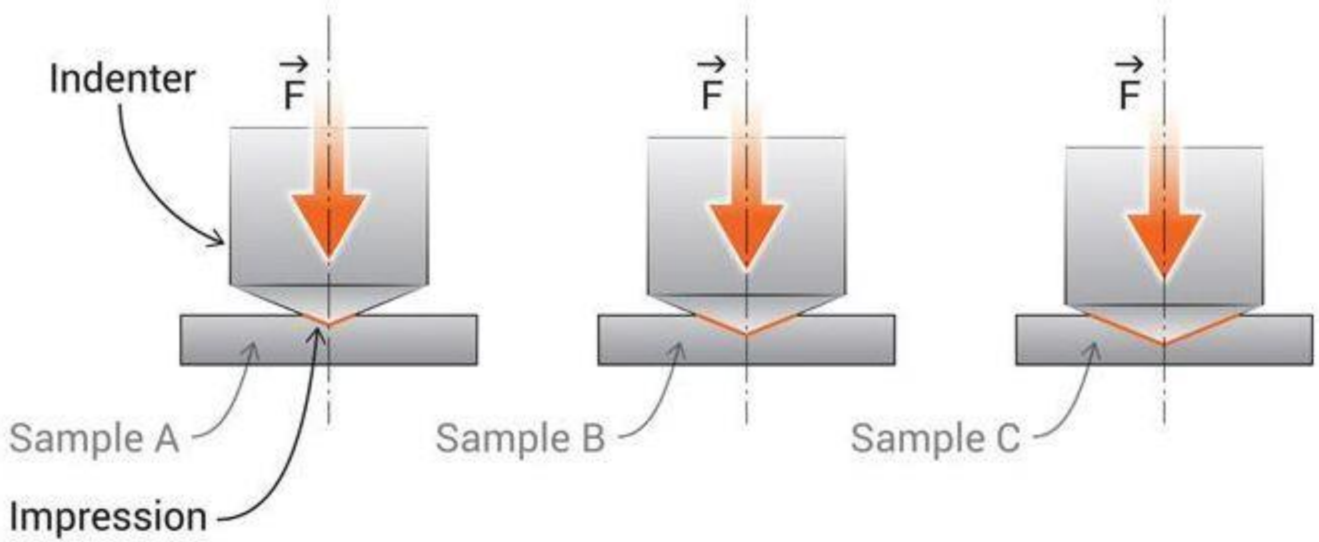
Vickers and Knoop Hardness Tests

- 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.

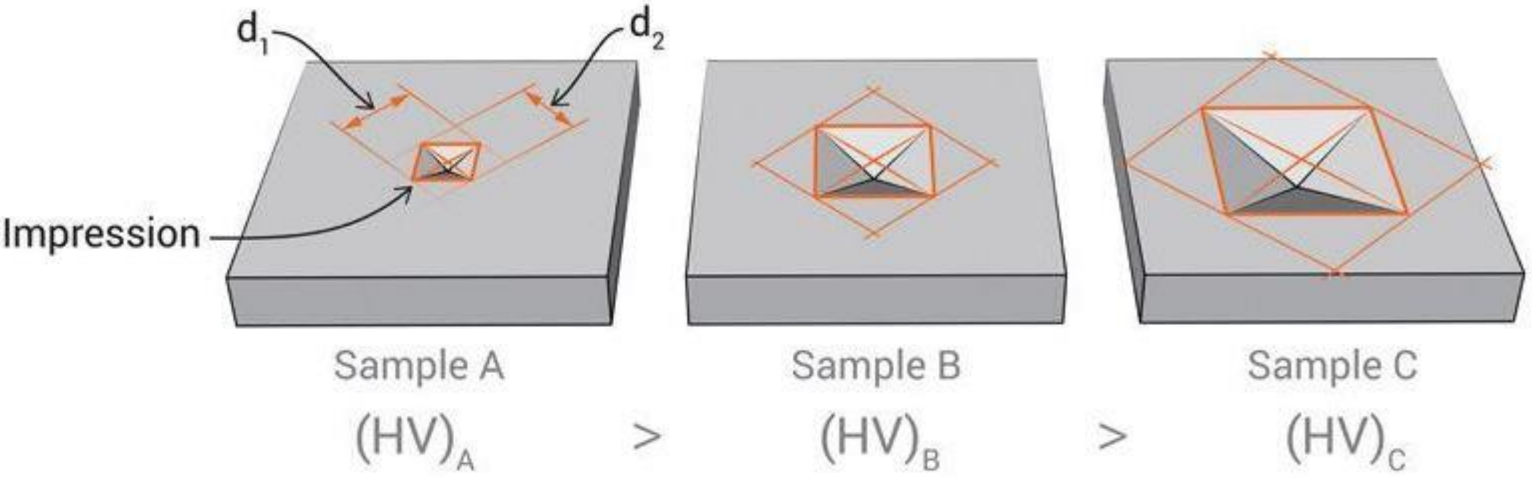
Vicker's Hardness

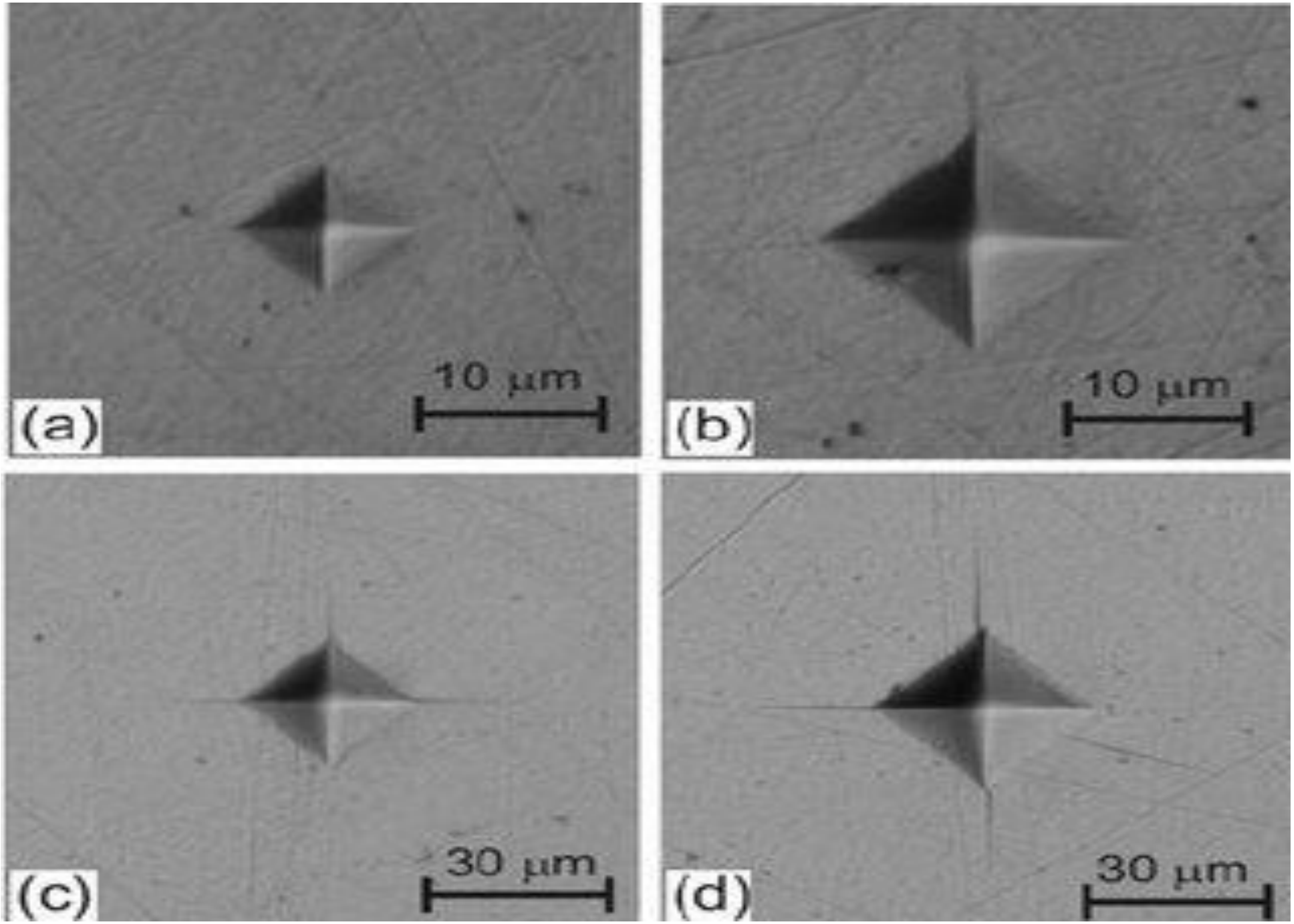


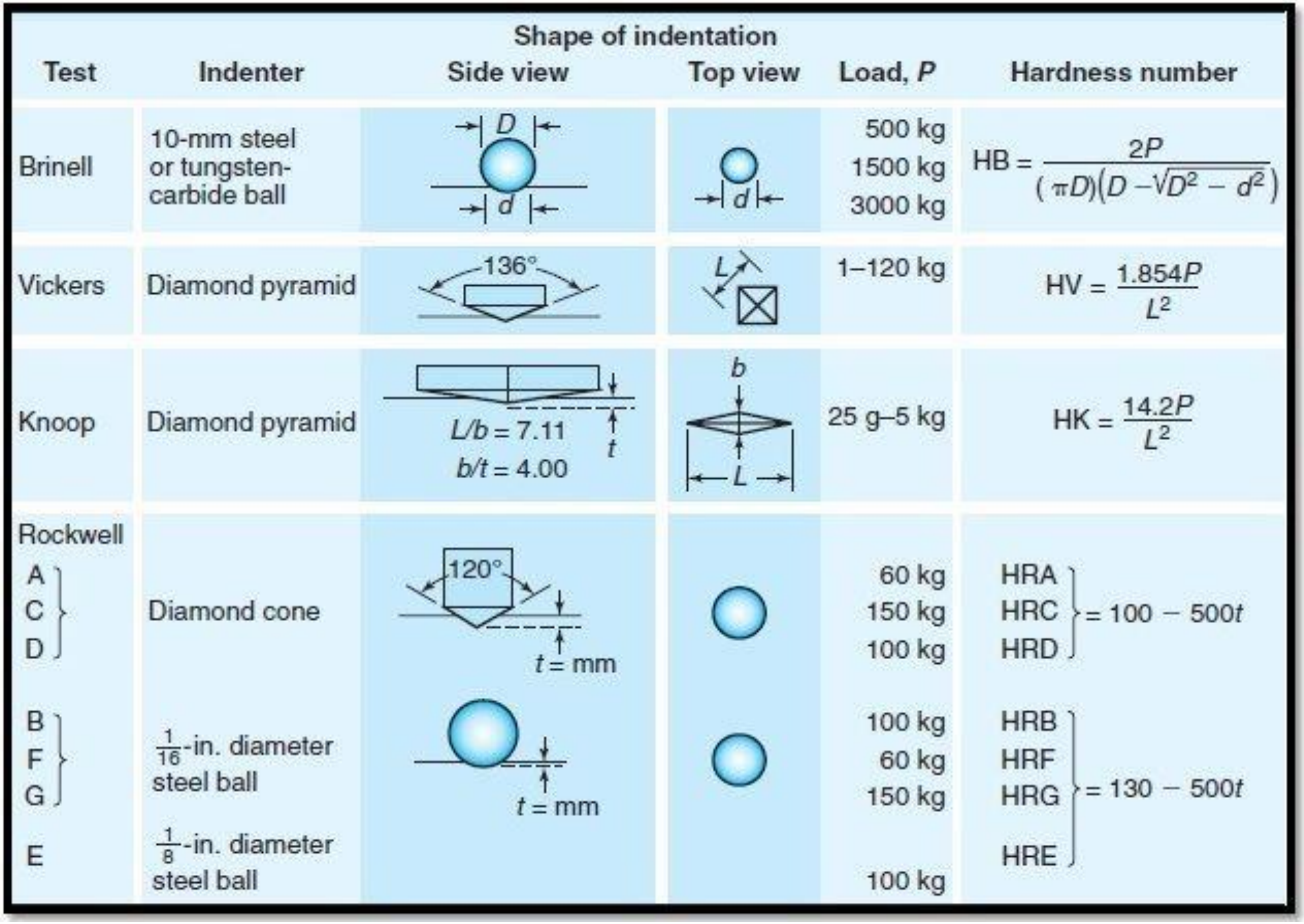
Vicker’s Hardness



Measurement of impression diagonals




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	D d	d	500 kg 1500 kg 3000 kg	$HB = \dfrac{2P}{(\pi D)\left(D - \sqrt{D^2 - d^2}\right)}$
Vickers	Diamond pyramid	136°	L	1–120 kg	$HV = \dfrac{1.854P}{L^2}$
Knoop	Diamond pyramid	$L/b = 7.11$ $b/t = 4.00$ t	b L	25 g–5 kg	$HK = \dfrac{14.2P}{L^2}$
Rockwell					
A	Diamond cone	120° t = mm		60 kg	HRA = $100 - 500t$
C				150 kg	HRC = $100 - 500t$
D				100 kg	HRD = $100 - 500t$
B	$\frac{1}{16}$-in. diameter steel ball	t = mm		100 kg	HRB = $130 - 500t$
F				60 kg	HRF = $130 - 500t$
G				150 kg	HRG = $130 - 500t$
E	$\frac{1}{8}$-in. diameter steel ball			100 kg	HRE = $130 - 500t$

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TOUGHNESS and FRACTURE

Dr. SWATI GANGWAR
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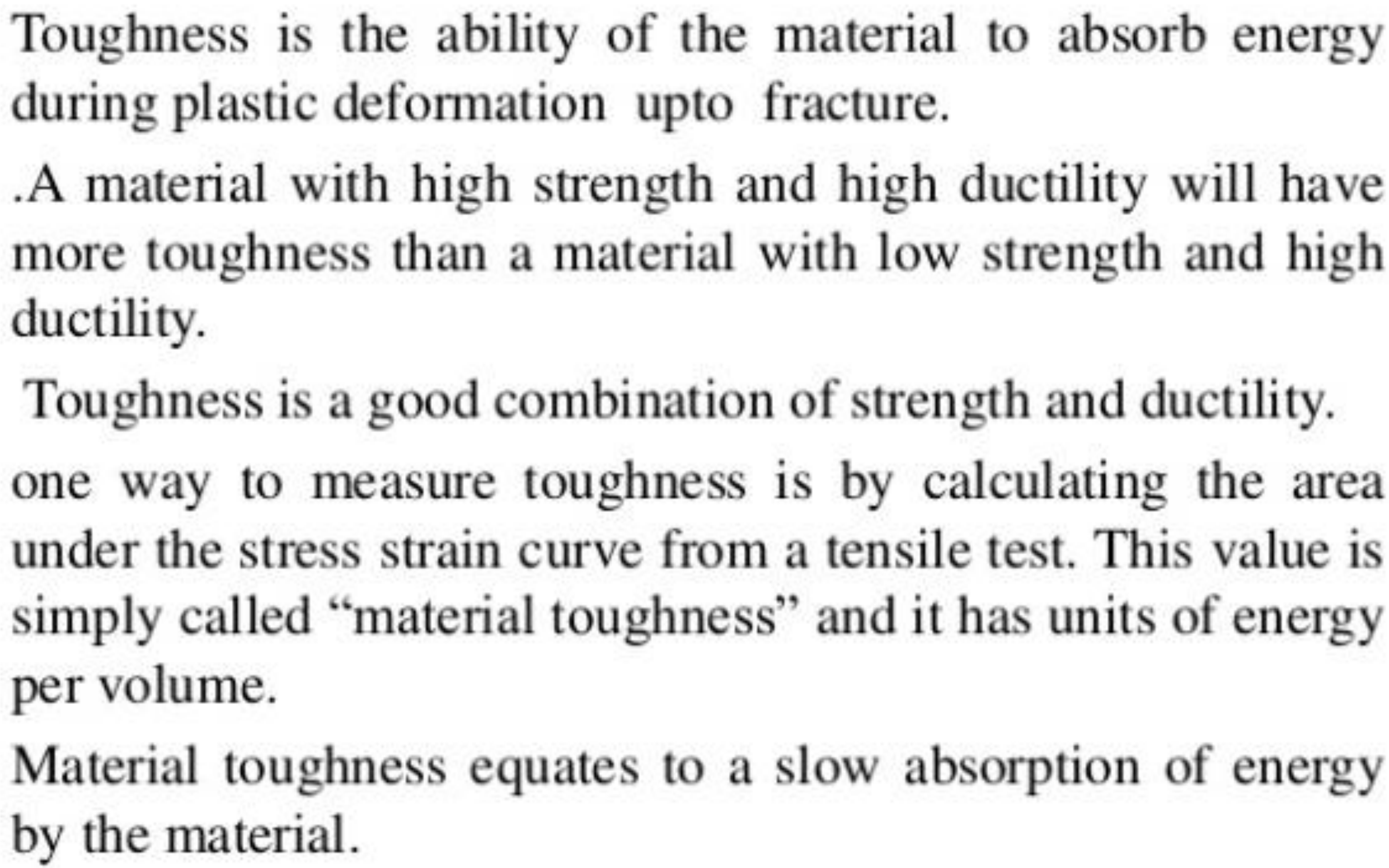
Toughness



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.

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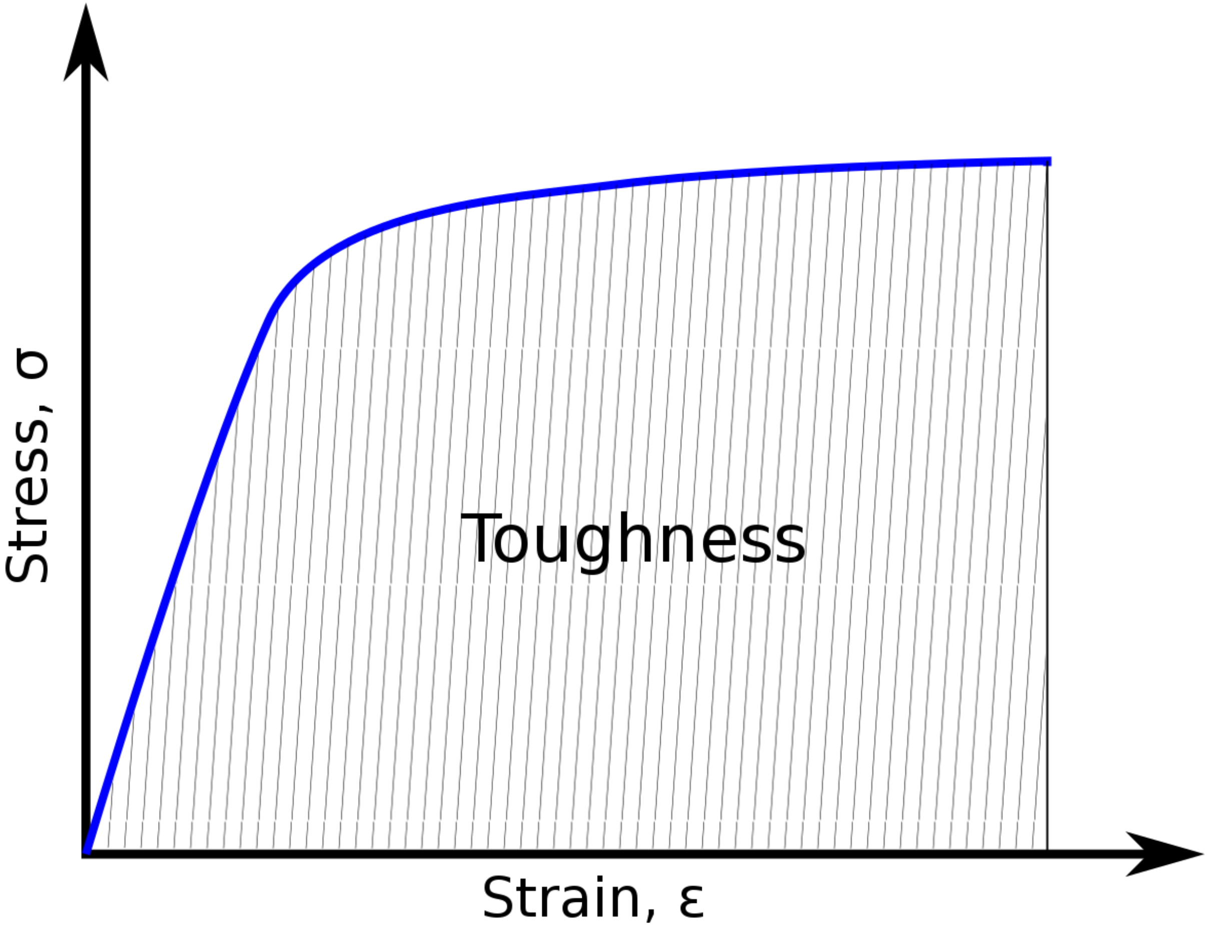

Stress, σ
Toughness
Strain, ε

Fracture

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

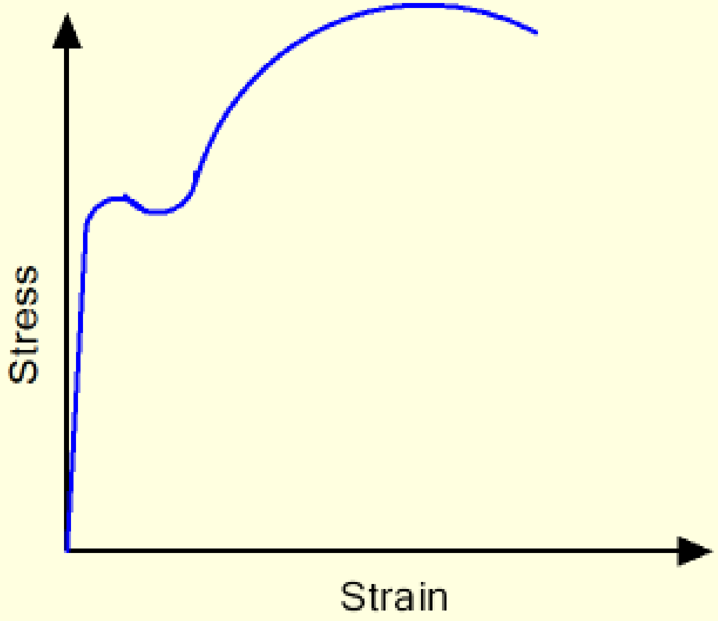
Types of fracture

- Ductile fracture
- Brittle fracture

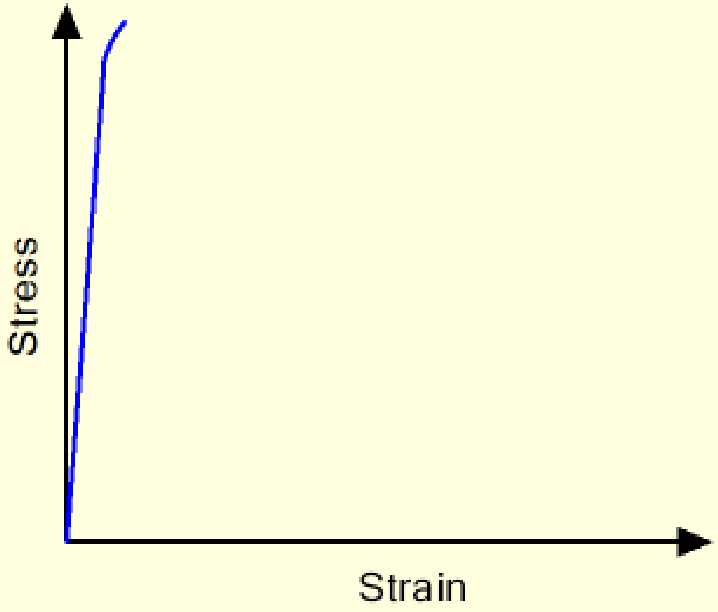
Ductile materials - extensive plastic deformation and energy absorption (“toughness”) before fracture

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

Stress-Strain curve for ductile and brittle materials

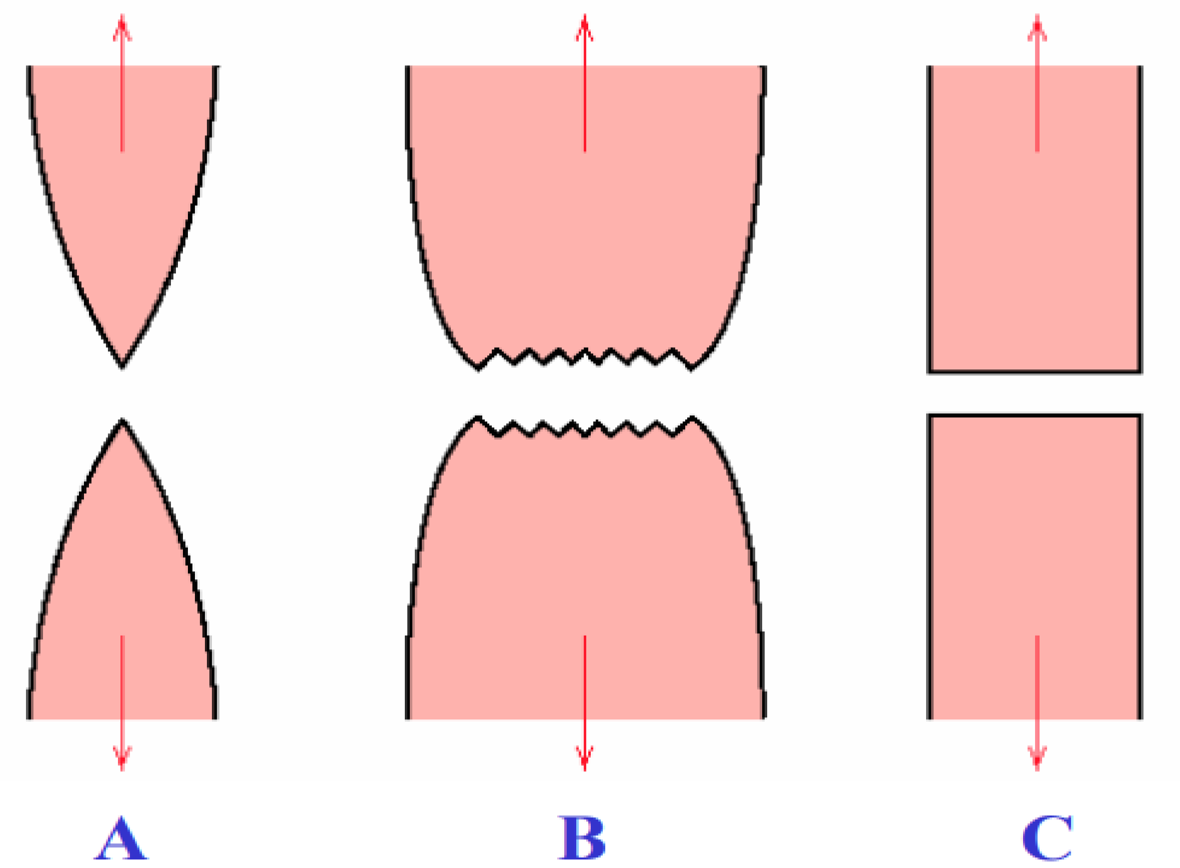


Typical Ductile Material



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

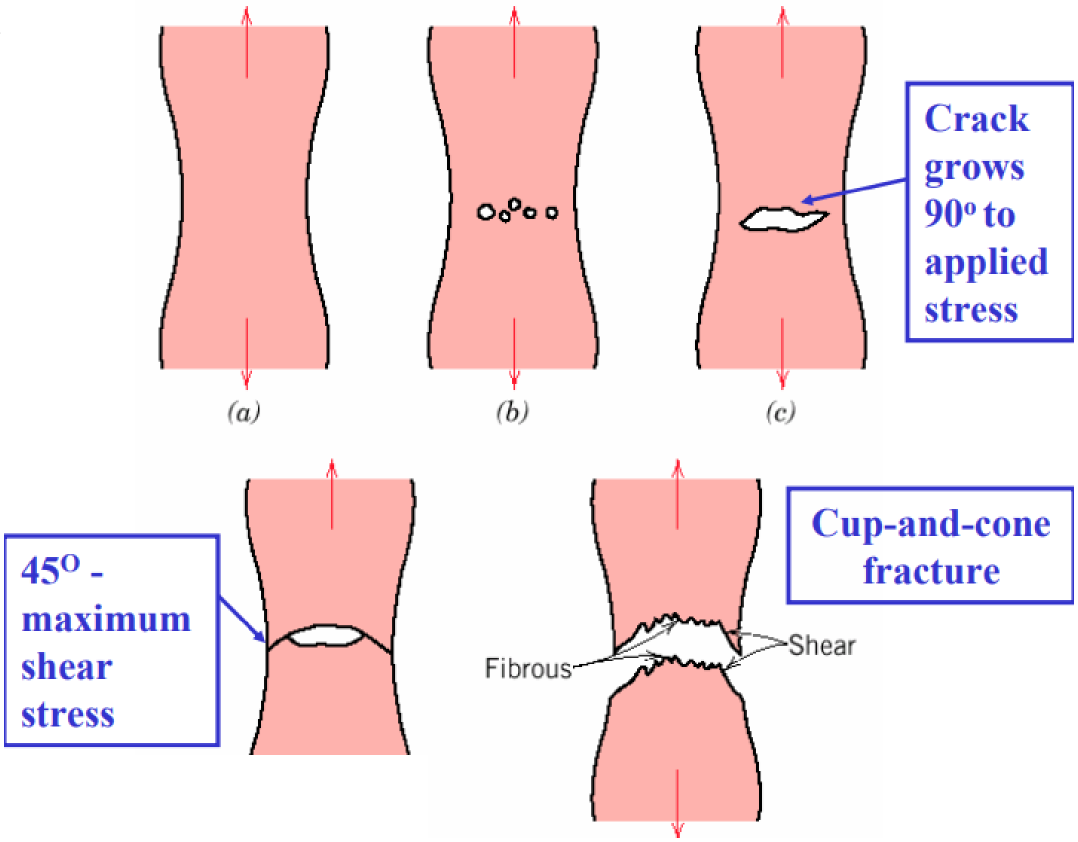
C. **Brittle fracture,** cold metals, ceramics.

Ductile fracture

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


(a)

cup-and-cone fracture



Crack grows 90° to applied stress

45° - maximum shear stress

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).

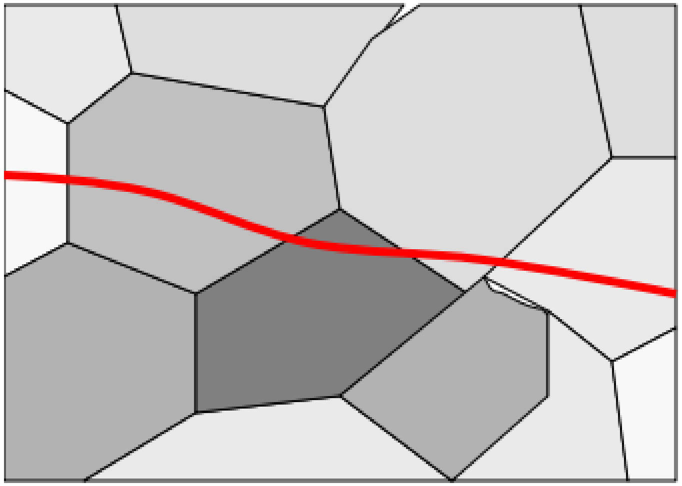
(b)

brittle fracture

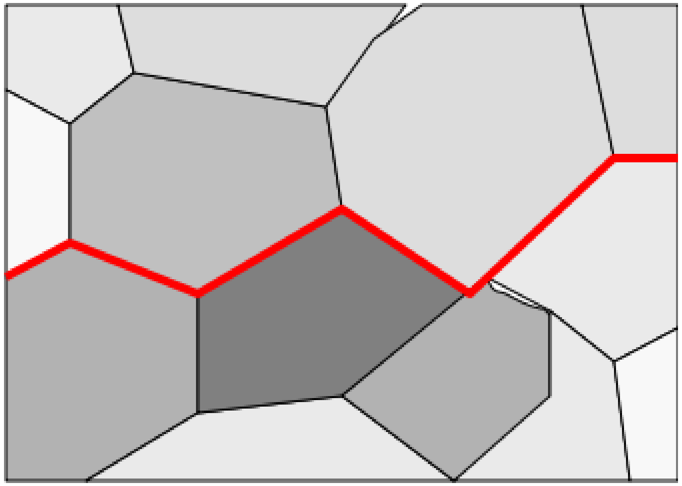
Types of Brittle fracture

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.)

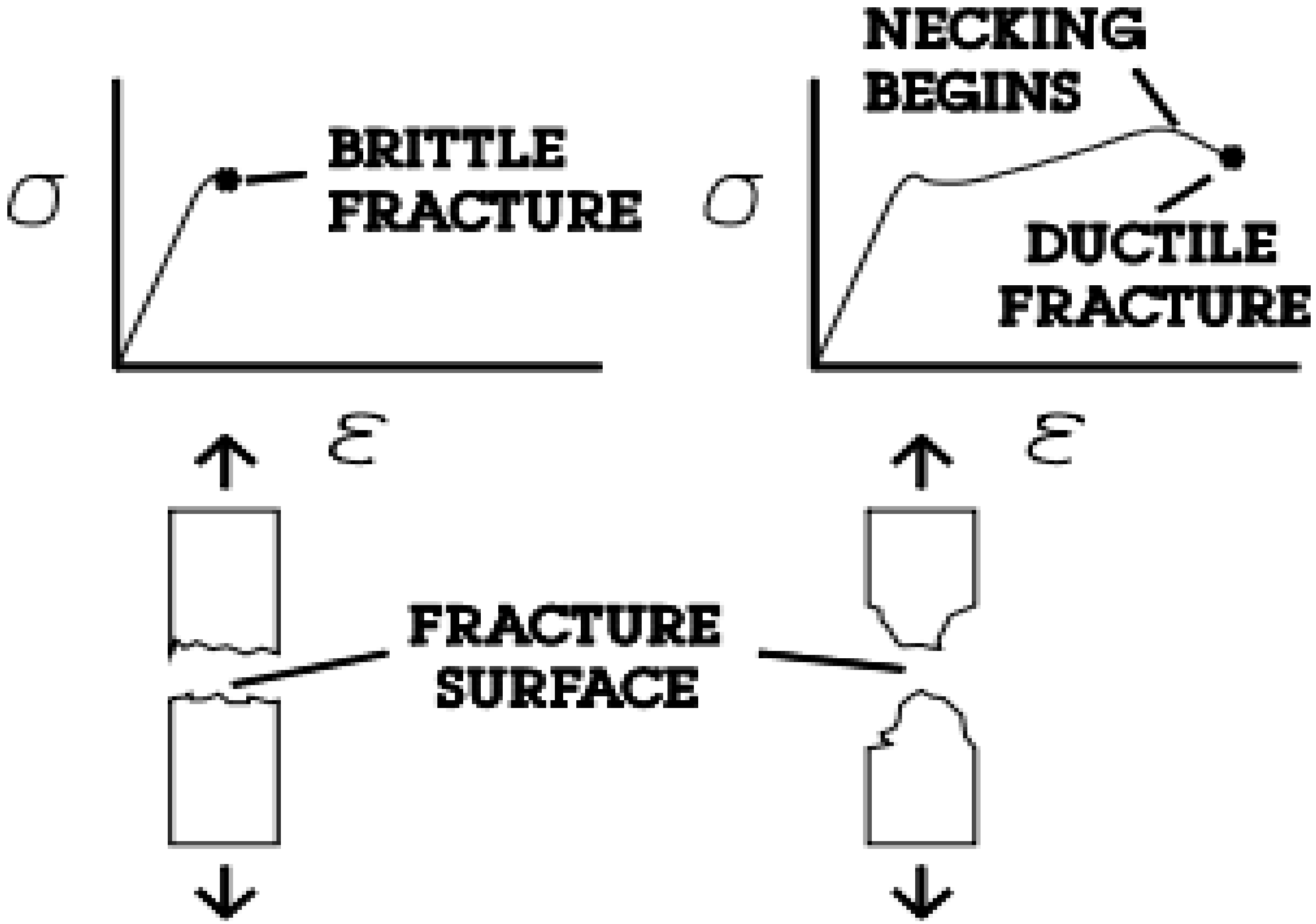


Transgranular fracture



Intergranular fracture

Brittle vs. Ductile fracture



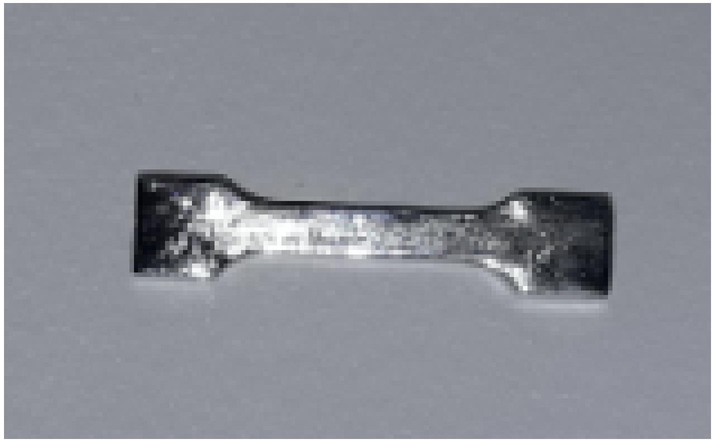
Dog-bone shape specimen

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 30×7×2.5 mm^3 dimension and gauge length 12 mm



MATERIAL SCIENCE AND ENGINEERING

UNIT 2

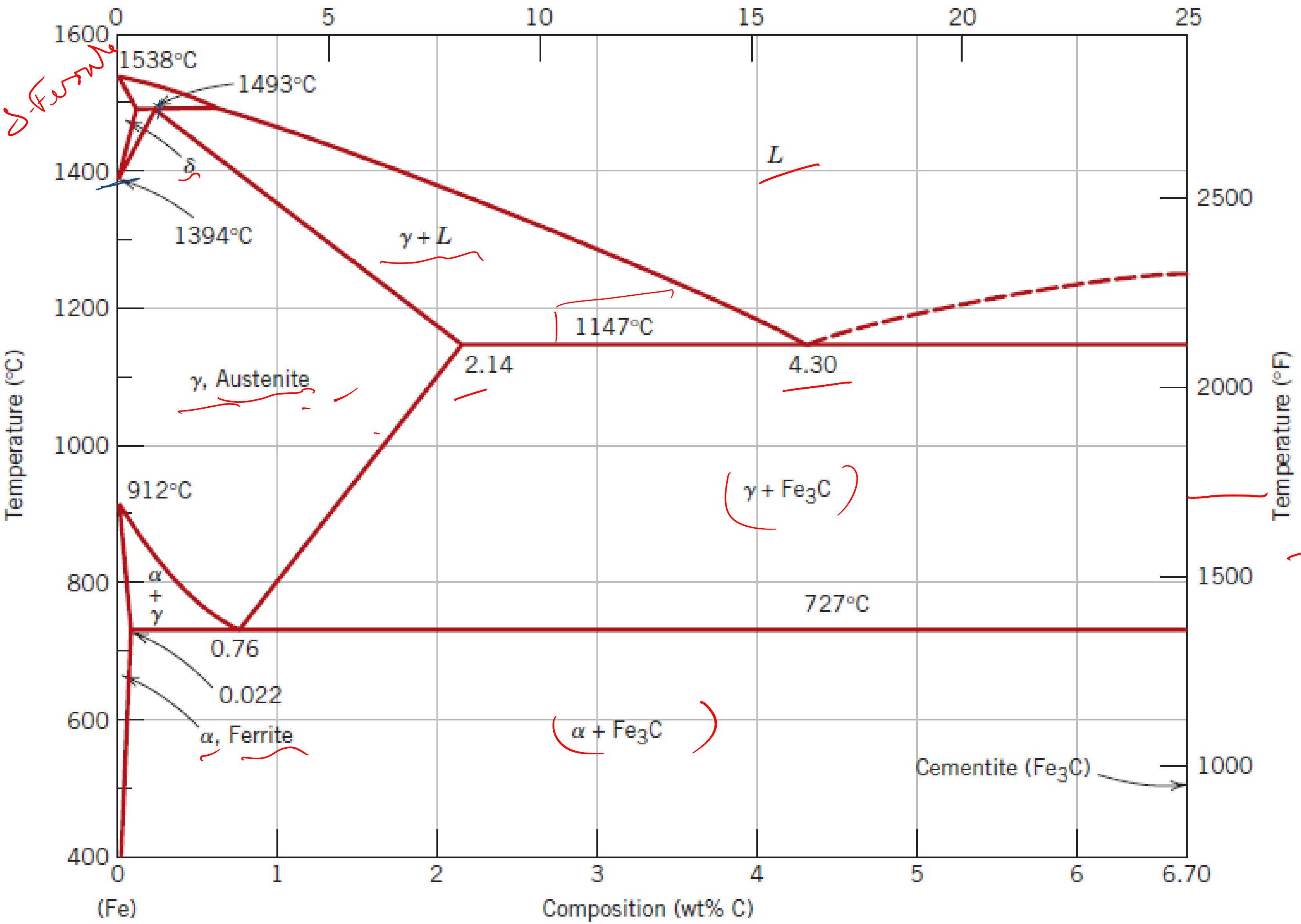
IRON CARBON DIAGRAM

Dr. SWATI GANGWAR

Mr. KAPIL KUMAR

Department Of Mechanical Engineering, MMMUT Gorakhpur

THE IRON–IRON CARBIDE PHASE DIAGRAM (IRON-CARBON PHASE DIAGRAM) (PERITECTIC TYPE)

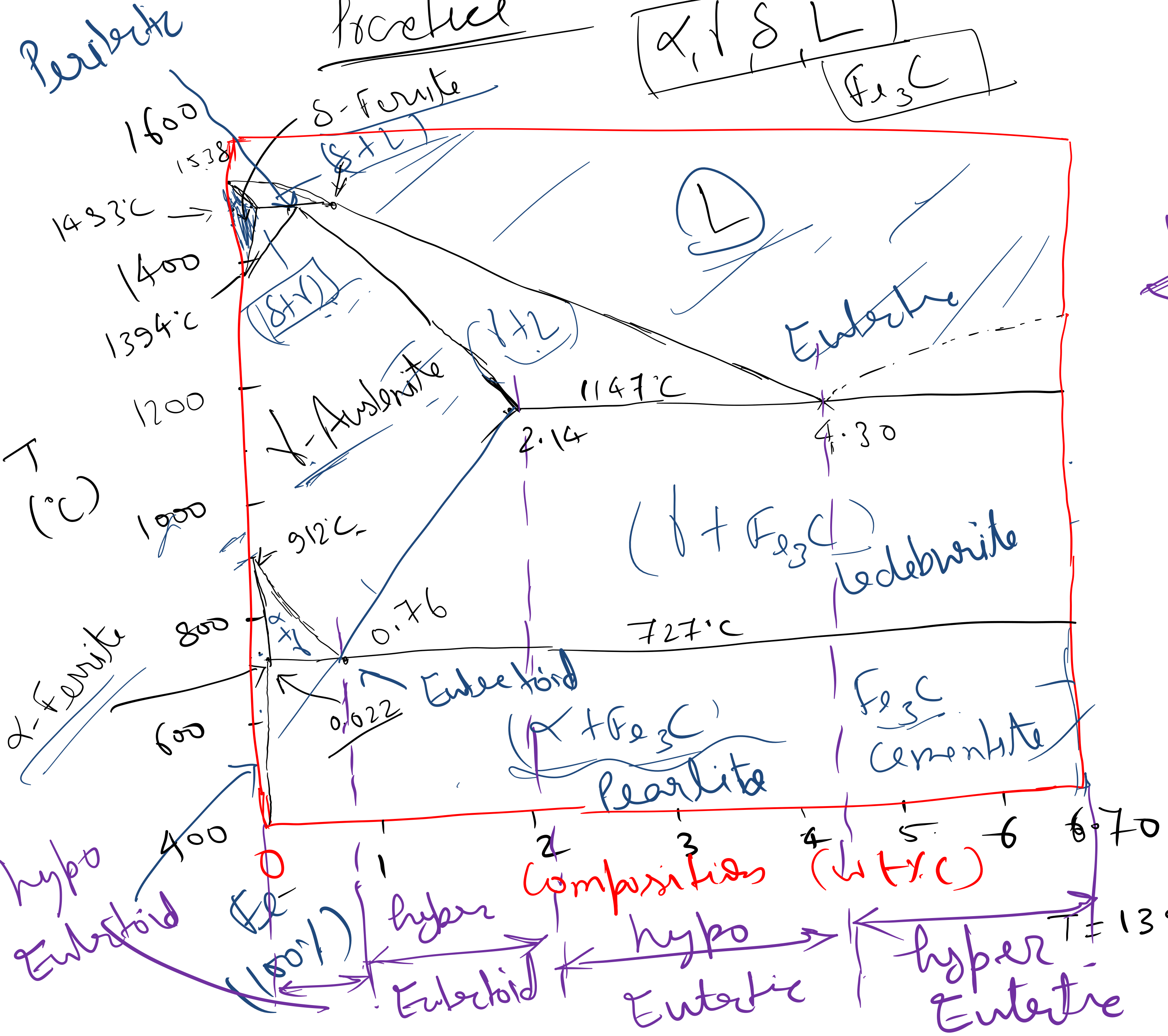


Fe$_3$C

Practice

α, γ, δ, L

Fe_3C



(F)

T - 727°C

C - 0.022%

T - 912°C

C - 0.76%

C - 2.14

T - 1147°C

T = 1394, 1493, 1538

Something about ***pure iron***...

- If we go along the vertical left axis , we will have 100% iron, so concentrate first on the pure iron(where carbon percentage is zero).
- Pure iron, upon heating, experiences two changes in crystal structure before it melts.
- At *room temperature* ,the stable form below 912ºC, called **ferrite,** or **α-iron,** has a **BCC** crystal structure.
- Ferrite experiences a polymorphic transformation to **austenite, or γ-iron,** at 912ºC (1674ºF), which has FCC crystal structure.
- This austenite persists to 1394ºC (2541ºF), at which temperature the FCC austenite reverts back to a ***BCC*** phase known as ***δ-ferrite***, which finally melts at 1538ºC (2800ºF).

Important points about Fe-C diagram

- The composition axis in Figure extends only to 6.70 wt% C; at this concentration the intermediate compound iron carbide, or **cementite (Fe_3C)**, is formed, which is represented by a vertical line on the phase diagram.
- Thus, the iron–carbon system may be divided into two parts: an iron-rich portion, as in Figure and the other (not shown) for compositions between 6.70 and 100 wt% C (pure graphite).

Continue…..

- In practice, all steels and cast irons have carbon contents less than 6.70 wt% C; therefore, we consider only the iron–iron carbide system.
- Carbon is an interstitial impurity in iron and forms a solid solution with each of α- and δ-ferrites, and also with austenite, as indicated by the α, δ, and γ *single phase* fields in Figure.

α-ferrite in Fe-C diagram

- In the BCC α -ferrite, only small concentrations of carbon are soluble; the maximum solubility is 0.022 wt% at 727^{o}C (1341^{o}F). The limited solubility is explained by the shape and size of the BCC interstitial positions, which make it difficult to accommodate the carbon atoms.
- Even though present in relatively low concentrations, carbon significantly influences the mechanical properties of ferrite.
- This particular iron–carbon phase is relatively soft, may be made magnetic at temperatures below 768^{o}C (1414^{o}F), and has a density of 7.88 g/cm3.

Austenite (γ) in Fe-C

- The austenite, or γ *phase of iron, when alloyed with carbon alone, is not stable* below 727°C (1341°F), as indicated in Figure.
- The maximum solubility of carbon in austenite, 2.14 wt%, occurs at 1147°C (2097°F). This solubility is approximately 100 times greater than the maximum for BCC ferrite, because the FCC interstitial positions are larger therefore, the strains imposed on the surrounding iron atoms are much lower.

δ- ferrite in Fe-C

- The α -ferrite is virtually the same as δ-ferrite, except for the range of temperatures over which each exists.
- Because the δ -ferrite is stable only at relatively high temperatures, it is of no technological importance.

Cementite (Fe_3C) in Fe-C

- Cementite forms when the solubility limit of carbon in α -ferrite is exceeded below 727°C (1341°F) (for compositions within the $\alpha+Fe_3C$ *phase region).* see the diagram for percentage of component.
- Cementite will also coexist with the γ *phase between 727°*and 1147°C ($\gamma+Fe_3C$ *phase region*).
- Mechanically, cementite is very hard and brittle; the strength of some steels is greatly enhanced by its presence.
- It is orthorhombic.

Important reactions in Fe-C

- **Eutectic reaction**: when liquid phase changes into two solid phase (γ and cementite) at ***4.30 wt% C and 1147°C***.
- These temperature and composition are known as eutectic temperature and composition.
- It forms the phase mixture known as ledeburite.

$$L \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \gamma + \mathrm{Fe_3C}$$

Important reactions in Fe-C

- **Eutectoid reaction:** when a solid phase changes into two solid phases. eutectoid invariant point exists at a composition of ***0.76 wt% C*** and a temperature of ***727^{o}C***.
- upon cooling, the solid γ *phase is transformed into* α*-iron and cementite.*
- It forms the phase mixture known as **pearlite**.

$$\gamma(0.76\ \text{wt\%}\ \text{C}) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(0.022\ \text{wt\%}\ \text{C}) + \text{Fe}_3\text{C}(6.7\ \text{wt\%}\ \text{C})$$

Important reactions in Fe-C

- **Peritectic Reaction**: This reaction appears at $1493^{o}C$ and at *0.18%C* where a mixture of liquid and solid converts into another solid phase upon cooling .
- This reaction appears in alloys where there is large difference in the melting point.
- Due to the presence of this point it is called peritectic phase diagram.

$$L + \delta \xrightarrow{cooling} \gamma$$

$$L + \delta \xleftarrow{heating} \gamma$$

Pearlite in Fe-C

- Pearlite is the phase mixture of α ferrite and cementite. ***(pearlite is not a phase)***.
- The microstructure for the eutectoid steel (0.76 wt% C) that is slowly cooled through the eutectoid temperature(727°C) consists of alternating layers or lamellae of the two phases(α ferrite and cementite) that form simultaneously during the transformation.

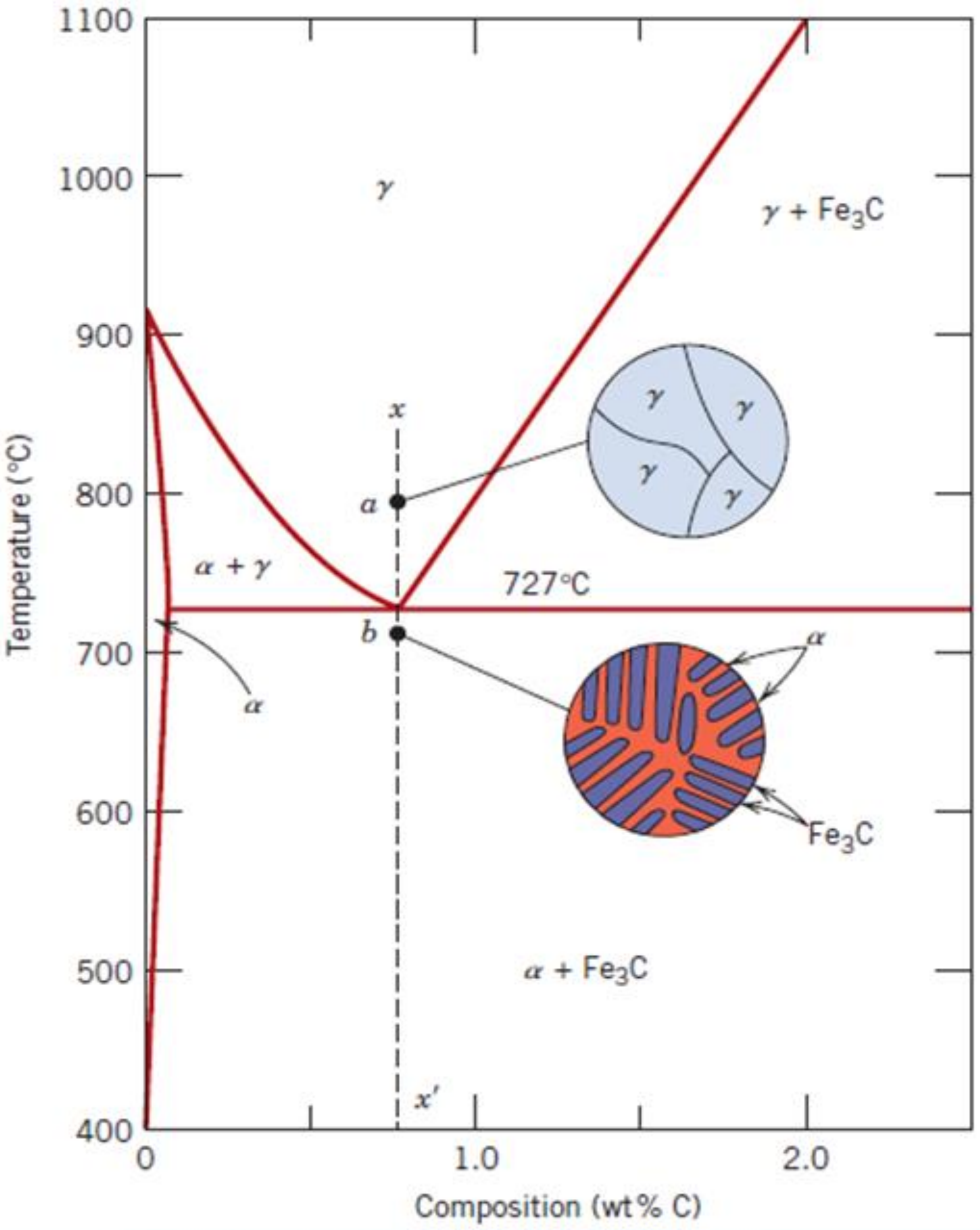


Figure Schematic representations of the microstructures for an iron–carbon alloy of eutectoid composition (0.76 wt% C) above and below the eutectoid temperature.

ledeburite

- It is also a phase mixture , not a phase.
- It is formed when liquid at eutectic composition (4.3%wt of C) is cooled through eutectic temperature(1147°C).
- It is a phase mixture of γ austenite and cementite.

Name of steel	Limit of %wt of C
Hypo- eutectiod	Upto .76
Hyper-eutectoid	.76 to 2.14
Hypo-eutectic	2.14 to 4.3
Hyper-eutectic	4.3 to 6.67

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MATERIAL SCIENCE AND ENGINEERING

UNIT 2

MICROSTRUCTURAL ANALYSIS

Dr. SWATI GANGWAR
Mr. KAPIL KUMAR
Department Of Mechanical Engineering, MMMUT Gorakhpur

Introduction

- **Microstructure:**

  It is the geometric arrangement of grains and the different phases present in a material.

- **Grain Boundaries:**

  It is the interface between two grains in a polycrystalline material where the crystal is disordered due to rapid change in crystallographic directions.

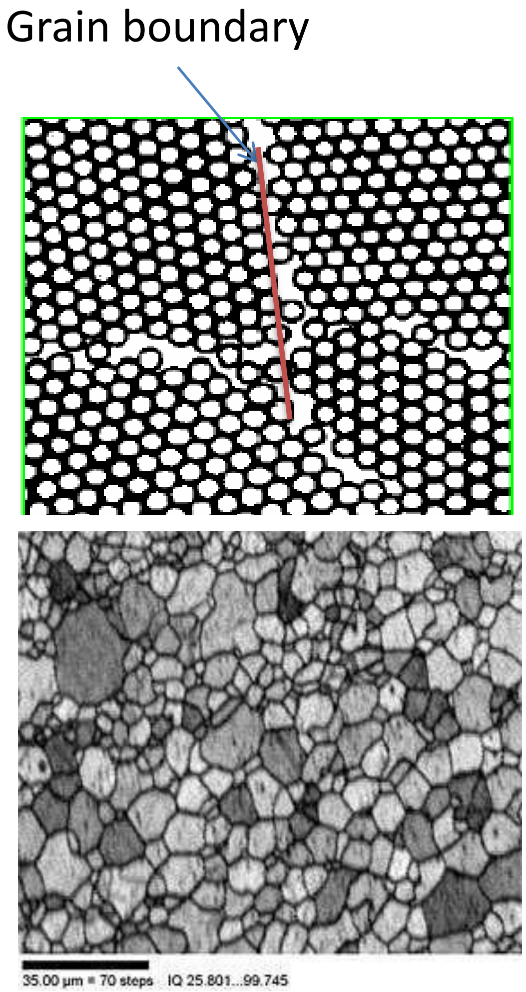
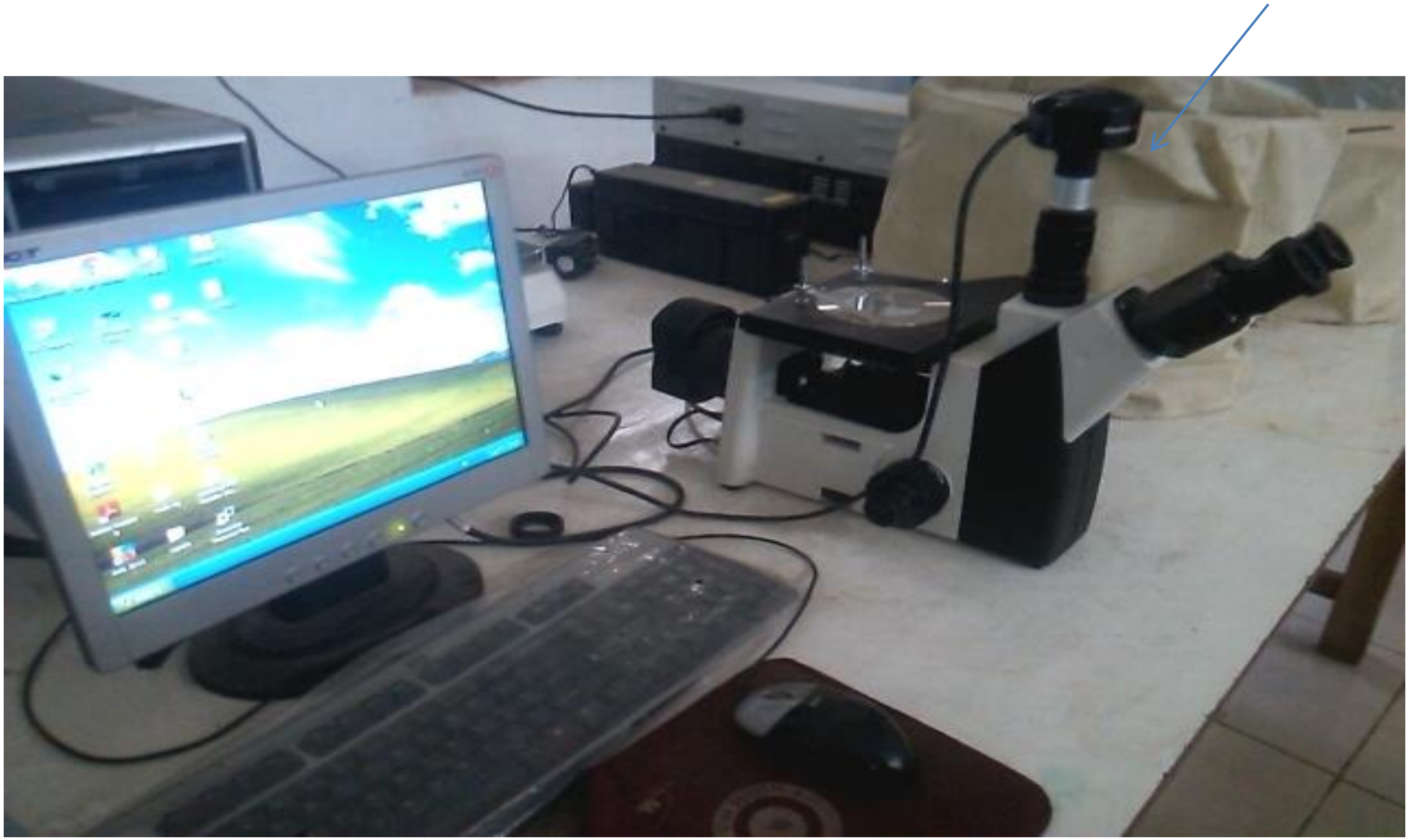


Figure showing the microstructure

Optical Microstructure



Optical microscope with computer attached to obtain the microstructure

Micro-structural Analysis used for?

- Quality Control: Analysis is used to determine whether the structural parameters are within specifications: a criteria for ACCEPTANCE or REJECTION of products

- Failure Analysis: to determine the cause of failure. Failure occur due to several factors (incorrect material selection, improper processing treatment, poor quality control).Failure analysis provides information about the cause of failure

- Research Studies: It is used to determine the
- microstructural changes that occur as a result
- of varying parameters such as composition,
- heat treatment or processing. The research
- studies develop the PROCESSING –
- STRUCTURE - PROPERTIES relationships.

Applications

- Study and characterization of materials.
- Ensure that the associations between properties and structure are properly understood.
- Predict properties of materials.
- Design alloys with new properties.
- Check if the material has been

correctly heat treated.

Safety Instructions

- Optical Metallography involves the use of etchants (standard solutions containing a variety of chemicals such as strong acids and solvents) which can be very corrosive and poisonous.

SPECIMEN PREPARATION

- ❑ Specimen preparation is an important part of metallography (study of microstructure).
- ❑ A specimen must be appropriately prepared to ensure correct observation and interpretation of the microstructure.

Specimen preparation requirements

- *Deformation-free specimen*
- *Flat specimen*
- *No thermal damage*
- *No scratches*

Specimen preparation consists of:

Sample Selection: The number, location orientation of the samples examined are important parameters in selection samples.

- ☐ **SECTIONING**
- ☐ **MOUNTING**
- ☐ **GRINDING**
- ☐ **POLISHING**
- ☐ **ETCHING**

SECTIONING

- Sectioning is the first step in the overall process of sample preparation.
- Sectioning of the test sample is performed carefully to avoid altering the structure of the material.
- Abrasive cutting is the most common cutting method.
- The cutting tool is made of Silicon carbide(Sic) and of diamond particles.
- Use coolant fluid to avoid
- overheating of specimen
- and possible change in material structure.

- **Sawing** is perhaps the oldest method of sectioning that is still used today. It can be accomplished with a hand-held hacksaw, but it can alter the microstructure.

- **Abrasive Wheel Sectioning:** The most popular method of sectioning is with abrasive cut-off wheels. Wheels made of silicon carbide, aluminum oxide, and diamonds are used in the sectioning process. With this type of sectioning, the metallographer has more control over the conditions used.

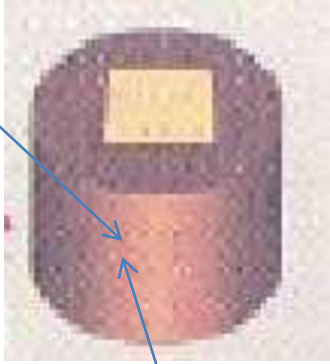
Machines used for sectioning:

Abrasive Cutter

EDM

Mounting

Mounting. Small samples can be difficult to hold safely during grinding and Polishing operations, and their shape may not be suitable for observation on a flat surface. They are therefore mounted inside a polymer block or mount



Mounting Machine

Mounting

Cold mounting:

- It can be done using two components resins (epoxies) which are liquid to start with but which set solid shortly after mixing.
- It requires very simple equipment consisting of a cylindrical ring which serves as a mould and a flat piece which serves as the base of the mould. the sample is placed on the flat piece

within the mould and the mixture

poured in and allowed to set.

Cold mounting takes few hours

to complete.

Mounting

- Hot-mounting

- The sample is surrounded by an organic polymeric powder which melts under the influence of heat (about 200 C).
- Pressure is also applied by a piston, ensuring a high quality mould free of porosity and with intimate contact between the sample and the polymer

Figure showing the mounted specimen.

Grinding

- Grinding is done using rotating discs covered with silicon carbide paper and water.
- There are a number of grades of paper, with 100, 240 400, 800, 1000, 1200, grains of silicon carbide per square inch. 100 grade therefore represents the coarsest particles and this is the grade to begin the grinding operation. *Always use light pressure applied at the centre of the sample.*

Continue….

- Wash the sample in water and move to the next grade, *orienting the scratches from the previous grade normal to the rotation direction*. This makes it easy to see when the coarser scratches have all been removed.
- After the final grinding operation on 1200 paper, wash the sample in water

followed by alcohol and dry

it before moving to the polishers.

Ambry Papers

Polishing

- The polishers consist of rotating discs covered with soft cloth impregnated with a pre-prepared slurry of hard powdery alumina particles (Al2O3, the size ranges from 0.5 to 0.03 µm).
- Begin with the coarse slurry and continue polishing until the grinding scratches have been removed. *It is of vital importance that the sample is thoroughly cleaned using soapy water, followed by alcohol, and dried before moving onto the final stage*. Any contamination of the final polishing disc will make it impossible to achieve a satisfactory polish.
- Examining the specimen in the microscope

after polishing should reveal mirror like surface.

Machine for Grinding and Polishing

Figure showing machine used for grinding and polishing.

Etching

- ❑The purpose of etching is two-fold.

1. Grinding and polishing operations produce a highly deformed, thin layer on the surface which is removed chemically during etching.
2. Attacks the surface with preference for those sites with the highest energy, leading to surface relief which allows different crystal orientations, grain boundaries, precipitates, phases and defects to be distinguished in reflected light microscopy.

Etching

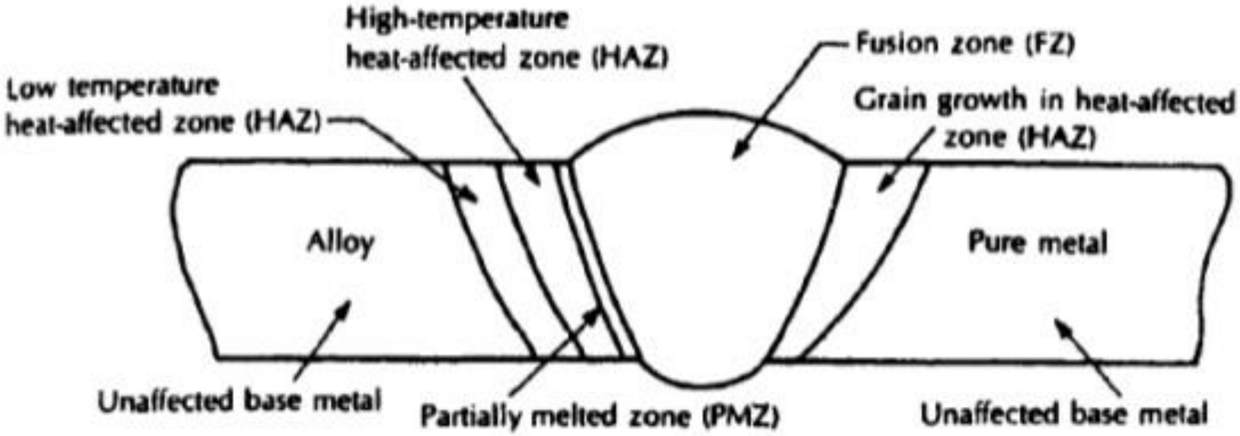
- Etching should always be done in stages, beginning with light attack, an examination in the microscope and further etching only if required.
- If you overetch a sample on the first step then the polishing procedure will have to be repeated.
- The table below gives the etchants for alloys that will be examined in this experiment.

Sample Material	Etchant used
Al alloys	Keller's (2 ml HF +3 ml HCL + 5 ml NO3+ 190 ml water)
Cu-Zn alloy (brass)	10 ml HNO3+90 ml water
Steel and cast irons	Nital (2% HNO3 + 98% ethanol)

Samples prepared for Vickers Hardness test.

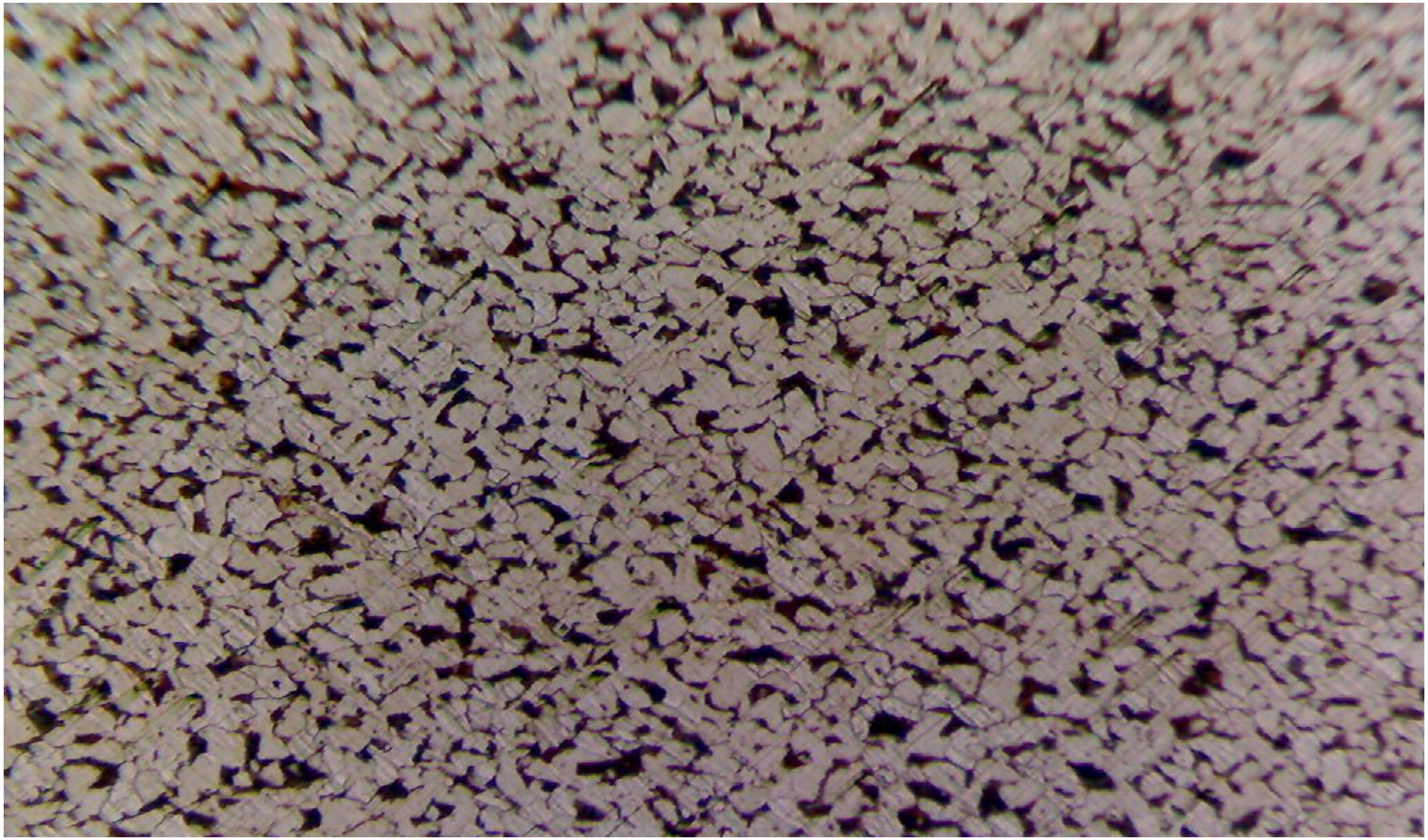
Different Zones in Welding

Micro-structural zones in Fusion welding

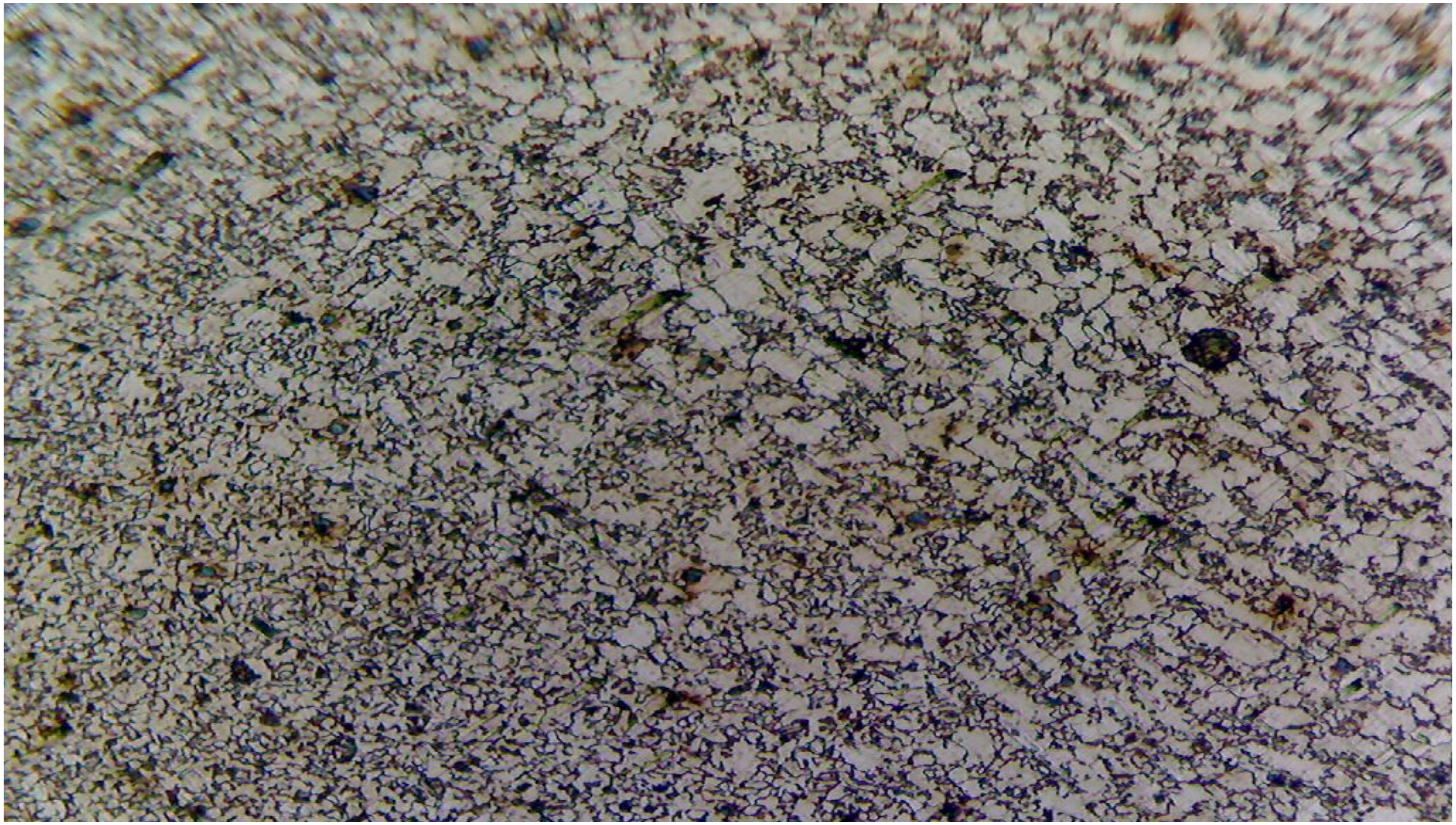


1) Fusion zone 2) Weld interface/partially melted zone
3) Heat affected zone 4) Unaffected base metal

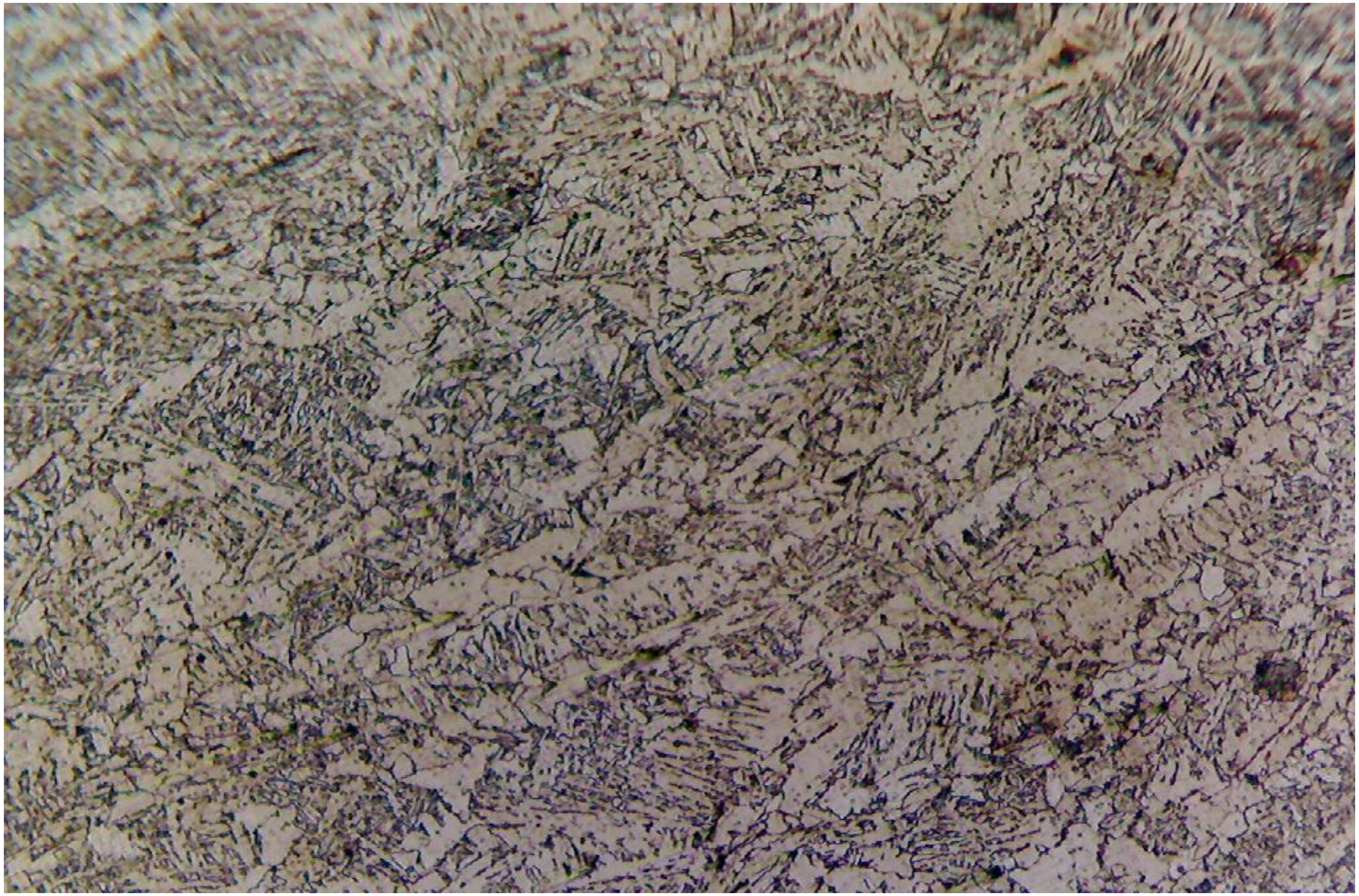
Microstructure of Mild steel base plate at 100× magnifications



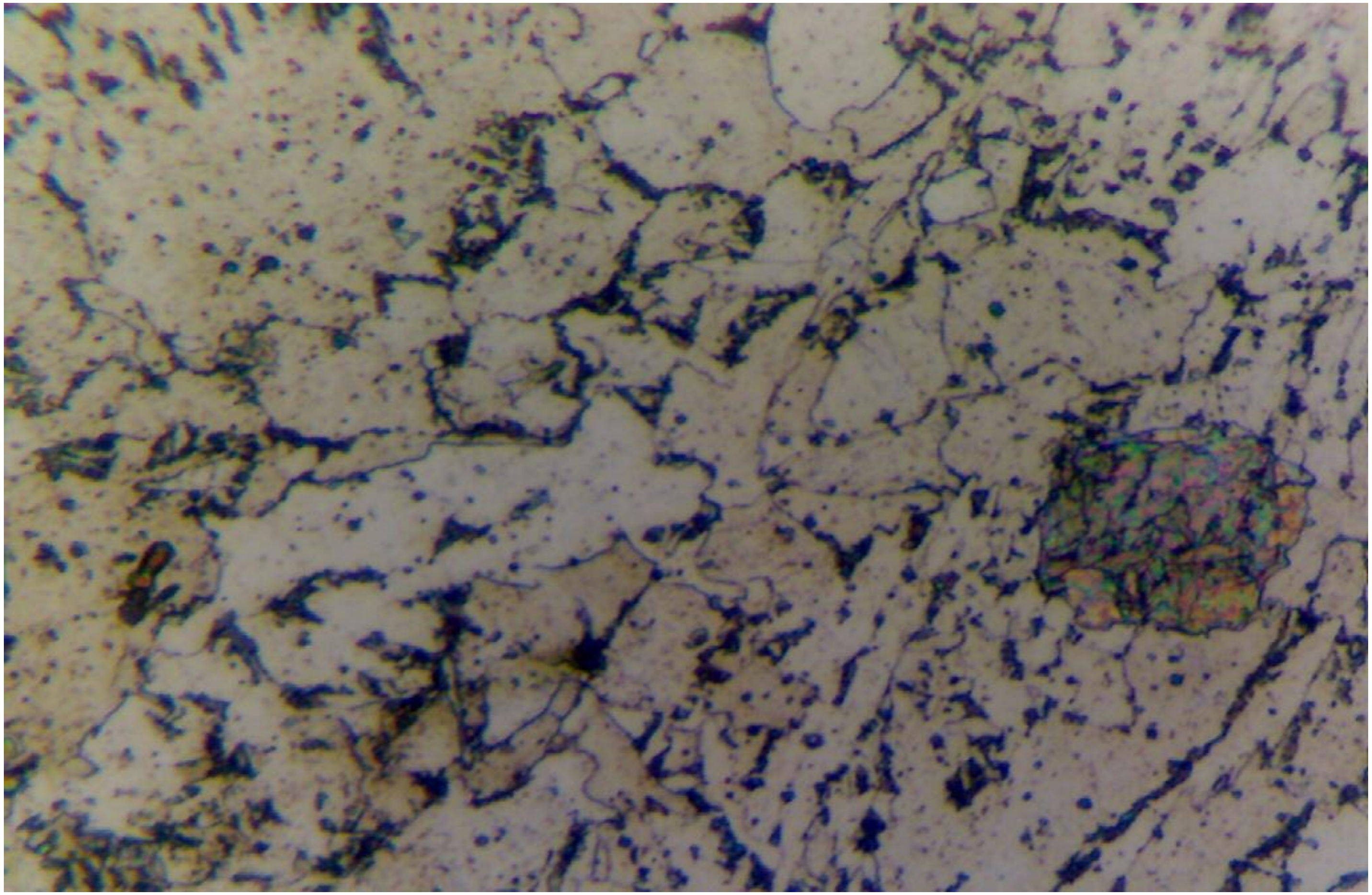
Microstructure of HAZ region at 100× magnifications.



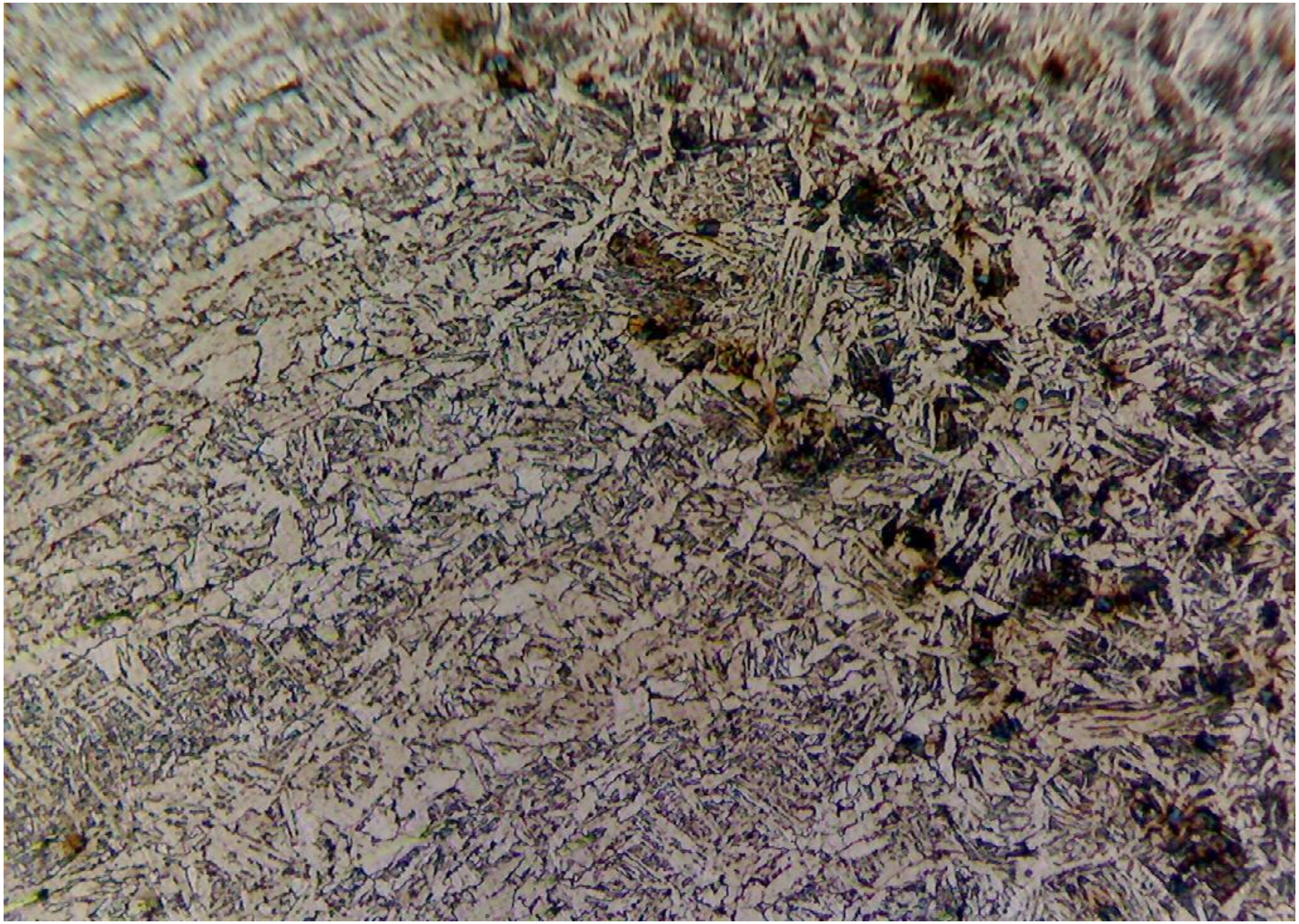
Microstructure of weld metal at 100× magnifications.



Microstructure of weld metal at 500× magnifications.



coarse grain and weld metal fusion boundary at 100× magnifications



Conclusion

- The microstructure of materials is an essential feature for the design of engineering structures with improved performances.
- In these last decades, a huge effort has been made in the direction of conceiving new materials with specific microstructures for the sake of producing exotic mechanical behaviors both in the static and the dynamic regime.
- Such man-made artifacts, usually called metamaterials, indeed show peculiar material properties that cannot be found in natural materials and that can have multiple engineering applications

Mad University of Technology,
pur(U.P)
NDIA

मदन मोहन मालवीय प्रौद्योगिकी विश्वविद्यालय, गोरखपुर

Madan Mohan Malaviya University of Technology, Gorakhpur

योगः कर्मसु कौशलम्

MATERIAL SCIENCE AND ENGINEERING

UNIT 2

PHASE DIAGRAMS

Dr. SWATI GANGWAR
Mr. KAPIL KUMAR

Department Of Mechanical Engineering, MMMUT Gorakhpur

Solubility Limit

For many alloy systems and at some specific temperature, there is a maximum concentration of solute atoms that may dissolve in the solvent to form a solid solution; this is called a **solubility limit.**

Phases

- A phase may be defined as a homogeneous portion of a system that has uniform physical and chemical characteristics.

- Sometimes, a single-phase system is termed *homogeneous.*

- *Systems composed* of two or more phases are termed *mixtures or heterogeneous systems.*

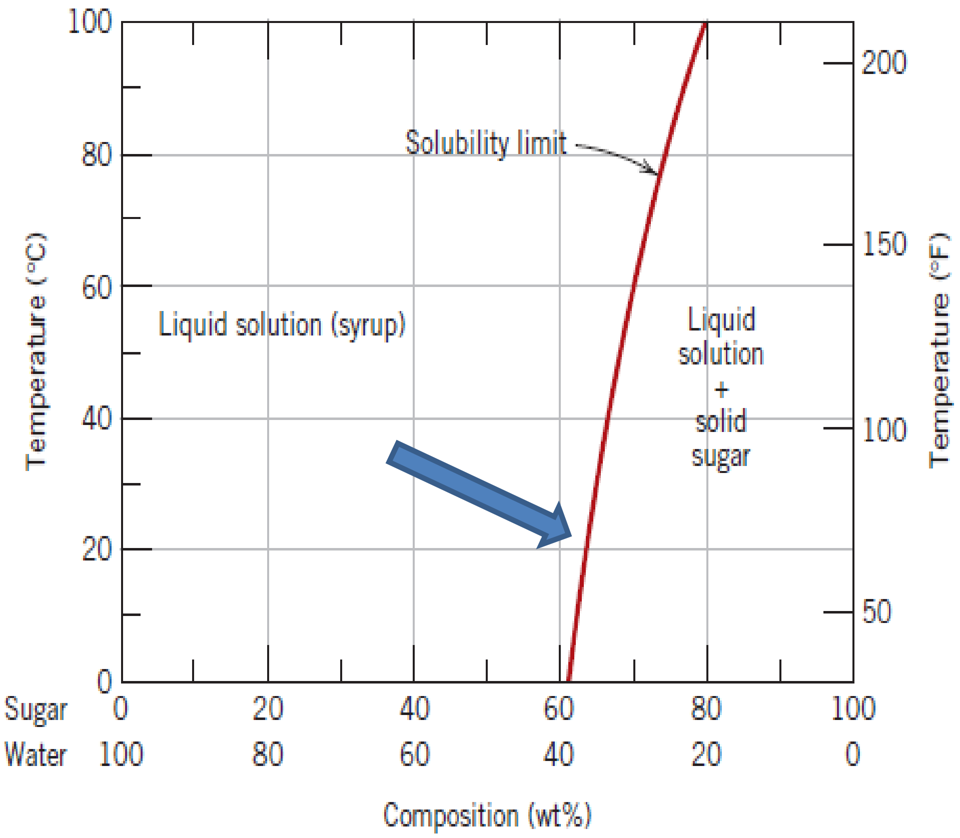
Equilibrium

- Equilibrium is another essential concept that is best described in terms of a thermodynamic quantity called the **free energy.**
- free energy is a function of the internal energy of a system, and also the randomness or disorder of the atoms or molecules (or entropy).
- A system is at equilibrium if its free energy is at a minimum under some specified combination of temperature, pressure, and composition.
- The (macroscopic) characteristics of the system do not change with time — the system is stable.
- A change in T, P or C for the system will result in an increase in the free energy and possible changes to another state whereby the free energy is lowered.

Phase equilibrium

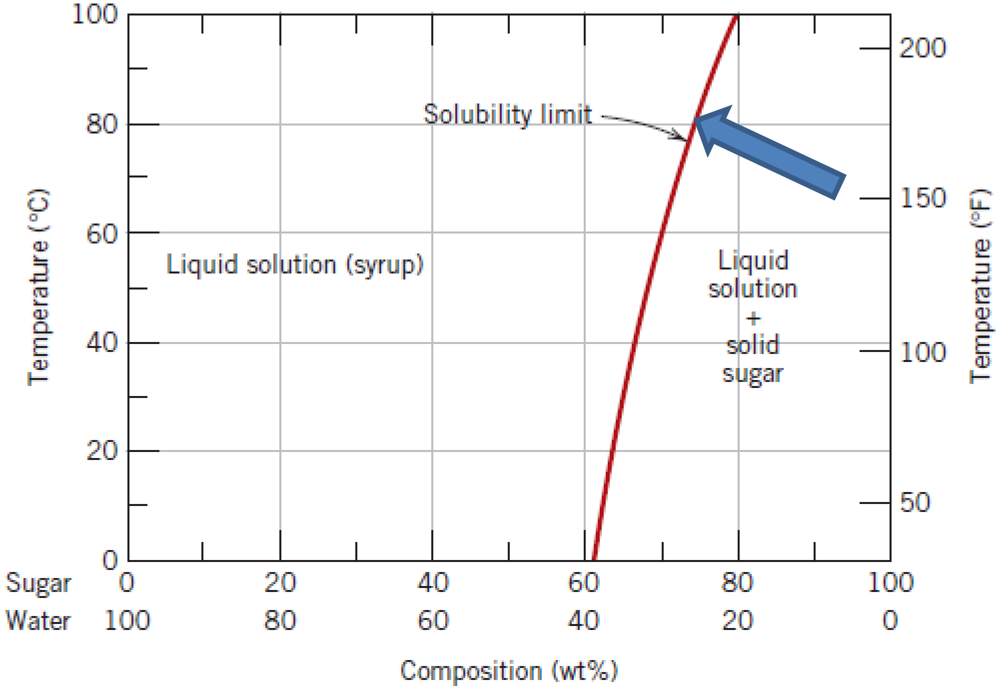
- Refers to equilibrium as it applies to systems (more than one matter, like Fe-C system) in which more than one phase may exist.
- Phase equilibrium is reflected by a constancy with time in the phase characteristics of a system.
- Much of the information about the control of the phase structure of a particular system is conveniently and concisely displayed in what is called a **phase diagram,** also often termed an *equilibrium diagram.*
- Now, there are three externally controllable parameters that will affect phase structure—*temperature*, *pressure,* and *composition* and phase diagrams are constructed when various combinations of these parameters are plotted against one another.

Example of phase equilibrium



Suppose that a sugar–water syrup is contained in a closed vessel and the solution is in contact with solid sugar at 20ºC. If the system is at equilibrium, the composition of the syrup is 65 wt% sugar 35wt% water, and the amounts and compositions of the syrup and solid sugar will remain constant with time.

- If the temperature of the system is suddenly raised—say, to 100^{o}C—this equilibrium or balance is temporarily upset in that the solubility limit has been increased to 80 wt% sugar . Thus, some of the solid sugar will go into solution in the syrup. This will continue until the new equilibrium syrup concentration is established at the higher temperature.



Gibbs Phase Rule

Phase diagrams and phase equilibrium are subject to the laws of thermodynamics.

Gibbs phase rule is a criterion that determines how many phases can coexist within a system at equilibrium.

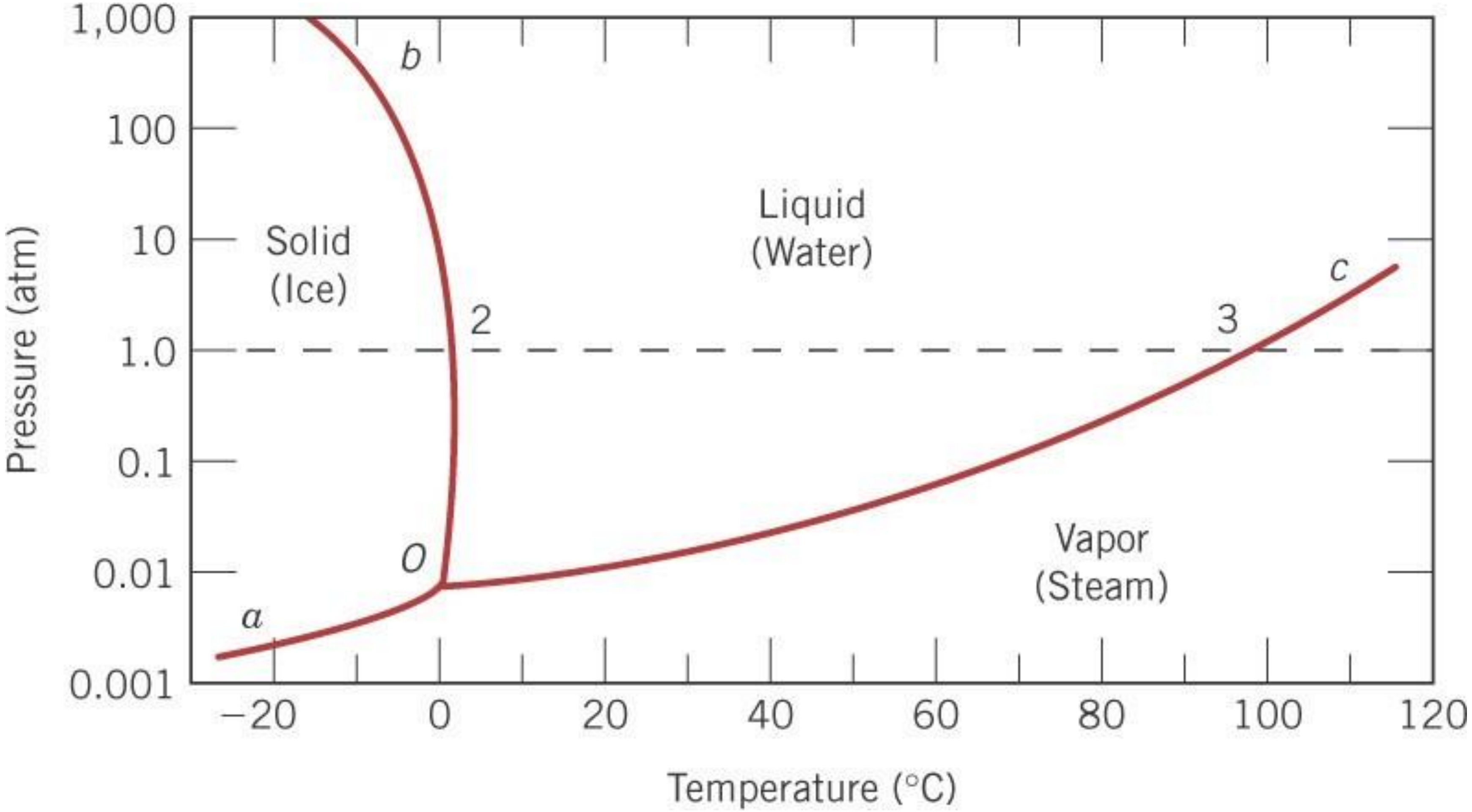
$$P + F = C + N$$

- P: No. of phases present
- F:degrees of freedom (temperature, Pressure, Composition)
- C: components or compounds
- N: non-compositional variables

ONE-COMPONENT (OR UNARY) PHASE DIAGRAMS

- Perhaps the simplest and easiest type of phase diagram to understand is that for a one-component system, in which ***composition is held constant*** (i.e., the phase diagram is for a pure substance).
- This means that ***pressure*** and ***temperature*** are the variables.
- Sometimes also called a *pressure -temperature (or P–T) diagram.*

Example of One Component Phase Diagram (water)



Binary Phase Diagrams

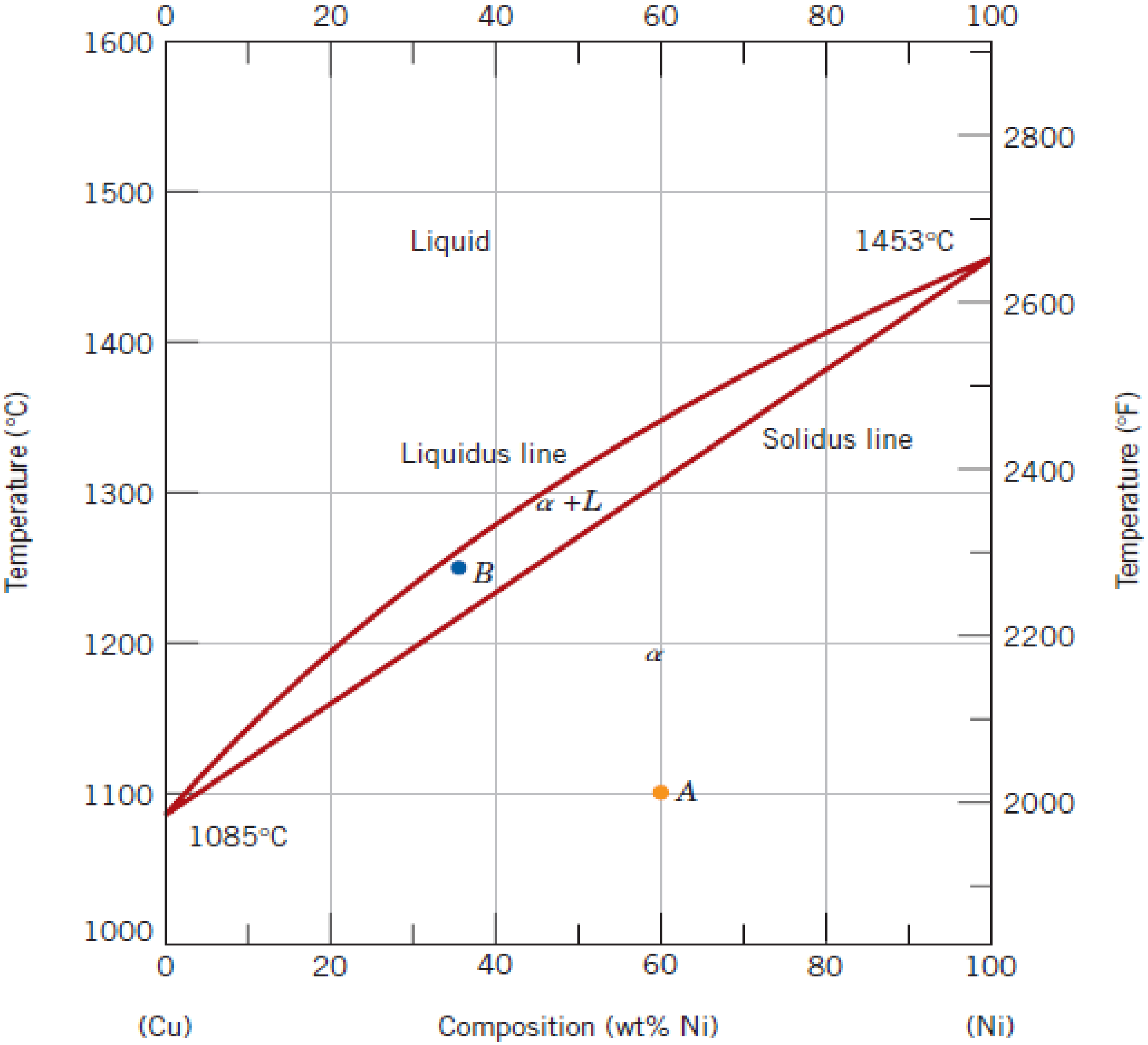
- Another type of extremely common phase diagram is one in which **temperature** and **composition** are variable parameters, and pressure is held constant—normally 1 atm.
- There are various type of binary phase diagram

1. **Solid solution type** (components are complete soluble in solid and liquid state for all proportion)
2. **Eutectic type** (components are complete soluble in liquid phase in all proportion and partially soluble in solid state(for very less proportion of component it is completely soluble and most of the proportion it makes phase mixture.))
3. **Peritectic type** (it also has eutectic point but it has named on peritectic point)

Continue…

- The copper–nickel system en example of *Solid solution type* binary phase diagram which is termed ***isomorphous*** because of this complete liquid and solid solubility of the two components at any composition.

Example of Binary Phase Diagram (Cu-Ni system)



- Three different phase regions, or fields, appear on the diagram, an alpha (α) field, a liquid (*L) field, and a two-phase* α+ *L* field which is known as *mushy zone.*
- The liquid *L is a homogeneous liquid solution composed of both copper and* nickel.
- The *phase α is a substitutional solid solution consisting of both Cu and Ni* atoms, and having an FCC crystal structure.
- There are 2 important line , liquidus and solidus line which are shown in figure.
- the line separating the *L* and *α+ L phase fields is termed the liquidus line.*
- the line separating the *α* and *α+ L phase fields is termed the solidus line.*

INTERPRETATION OF PHASE DIAGRAMS

For a binary system of known composition and temperature that is at equilibrium, at least three kinds of information are available:

(1)the phases that are present,
(2)the compositions of these phases,
(3) the percentages or fractions of the phases.

Point (1) is very simple to compute, One just locates the temperature–composition point on the diagram and notes the phase(s) with which the corresponding phase field is labeled. Go to the figure and consider the point A, you will notice that point A lies in the α phase and you can get the corresponding percentage of the composition.

Continue….

- For an alloy having composition and temperature located in a two-phase region, the situation is more complicated. In all two-phase regions $\alpha+ L$ (and in two-phase regions only), one may imagine a series of horizontal lines, one at every temperature; each of these is known as a **tie line**, or sometimes as an **isotherm.**
- **These tie** lines extend across the two-phase region and terminate at the phase boundary lines on either side.

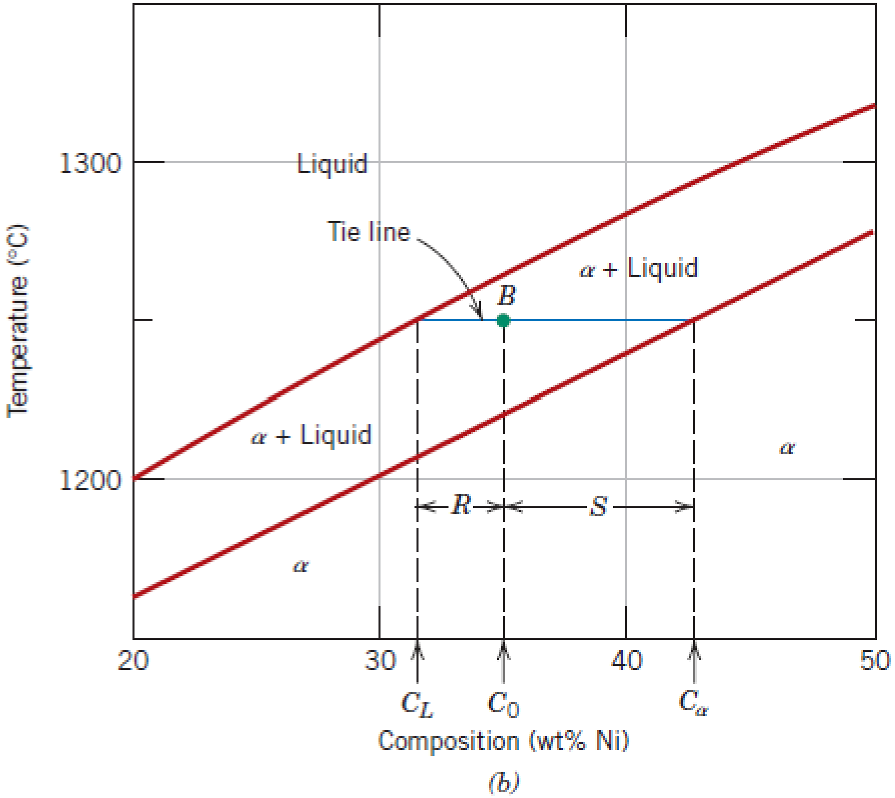
Lever rule

If the composition and temperature position is located within a two-phase region, things are more complex. The tie line must be utilized in conjunction with a procedure that is often called the **lever rule (or the *inverse lever rule), which is applied*** as follows:

1. The tie line is constructed across the two-phase region at the temperature of the alloy.
2. The overall alloy composition is located on the tie line.
3. The fraction of one phase is computed by taking the length of tie line from the overall alloy composition to the phase boundary for the *other phase, and* dividing by the total tie line length.
4. The fraction of the other phase is determined in the same manner.
5. If phase percentages are desired, each phase fraction is multiplied by 100

Example

- Consider the figure shown below, *in which at 1250^{o}C both α (solid)* and *L (liquid)* phases are present for a 35 wt% Ni–65 wt% Cu alloy. The problem is to compute the fraction of each of the *α and liquid phases.*



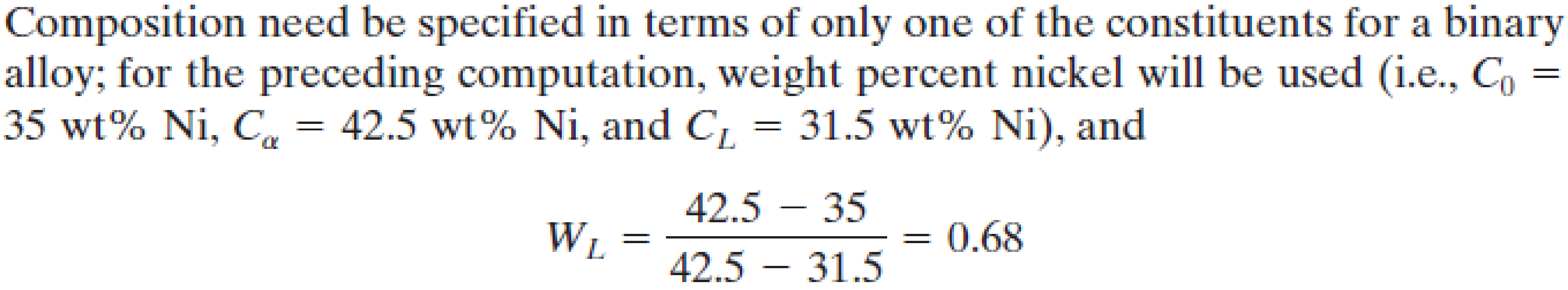
The tie line has been constructed that was used for the determination of α *and L phase compositions.*

Let the overall alloy composition be located along the tie line and denoted as C_o

mass fractions be represented by W_α *and* W_L *for the* α *and L phases.*

From the lever rule, W_L *may be computed according to*

$$W_L = \frac{C_\alpha - C_0}{C_\alpha - C_L}$$



Composition need be specified in terms of only one of the constituents for a binary alloy; for the preceding computation, weight percent nickel will be used (i.e., C_0 = 35 wt% Ni, C_α = 42.5 wt% Ni, and C_L = 31.5 wt% Ni), and

$$W_L = \frac{42.5 - 35}{42.5 - 31.5} = 0.68$$

Similarly, for α the phase,

$$W_\alpha = \frac{C_0 - C_L}{C_\alpha - C_L}$$

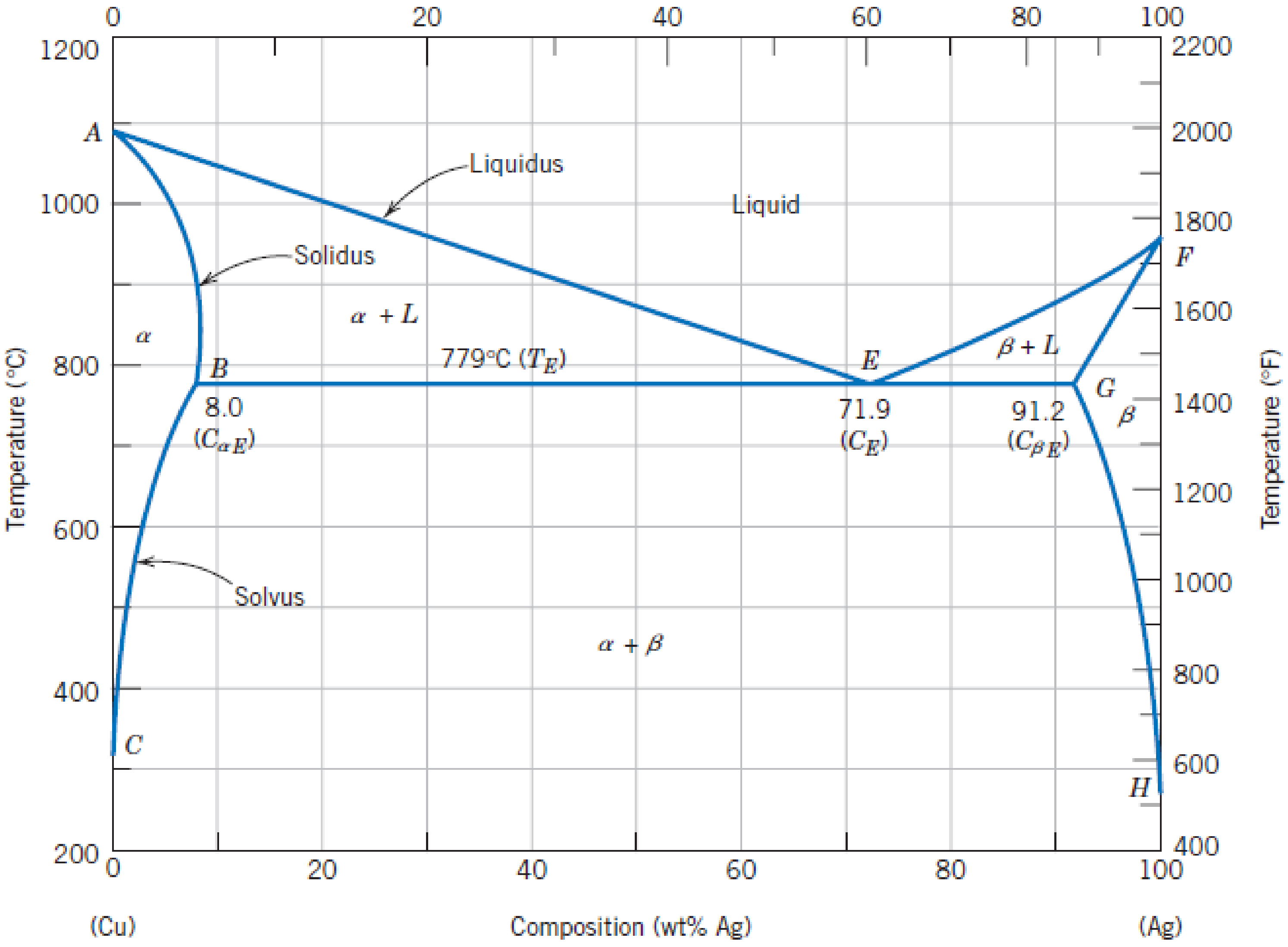
$$= \frac{35 - 31.5}{42.5 - 31.5} = 0.32$$

Of course, identical answers are obtained if compositions are expressed in weight percent copper instead of nickel.

Thus, the lever rule may be employed to determine the relative amounts or fractions of phases in any two-phase region for a binary alloy if the temperature and composition are known and if equilibrium has been established.

BINARY EUTECTIC SYSTEMS

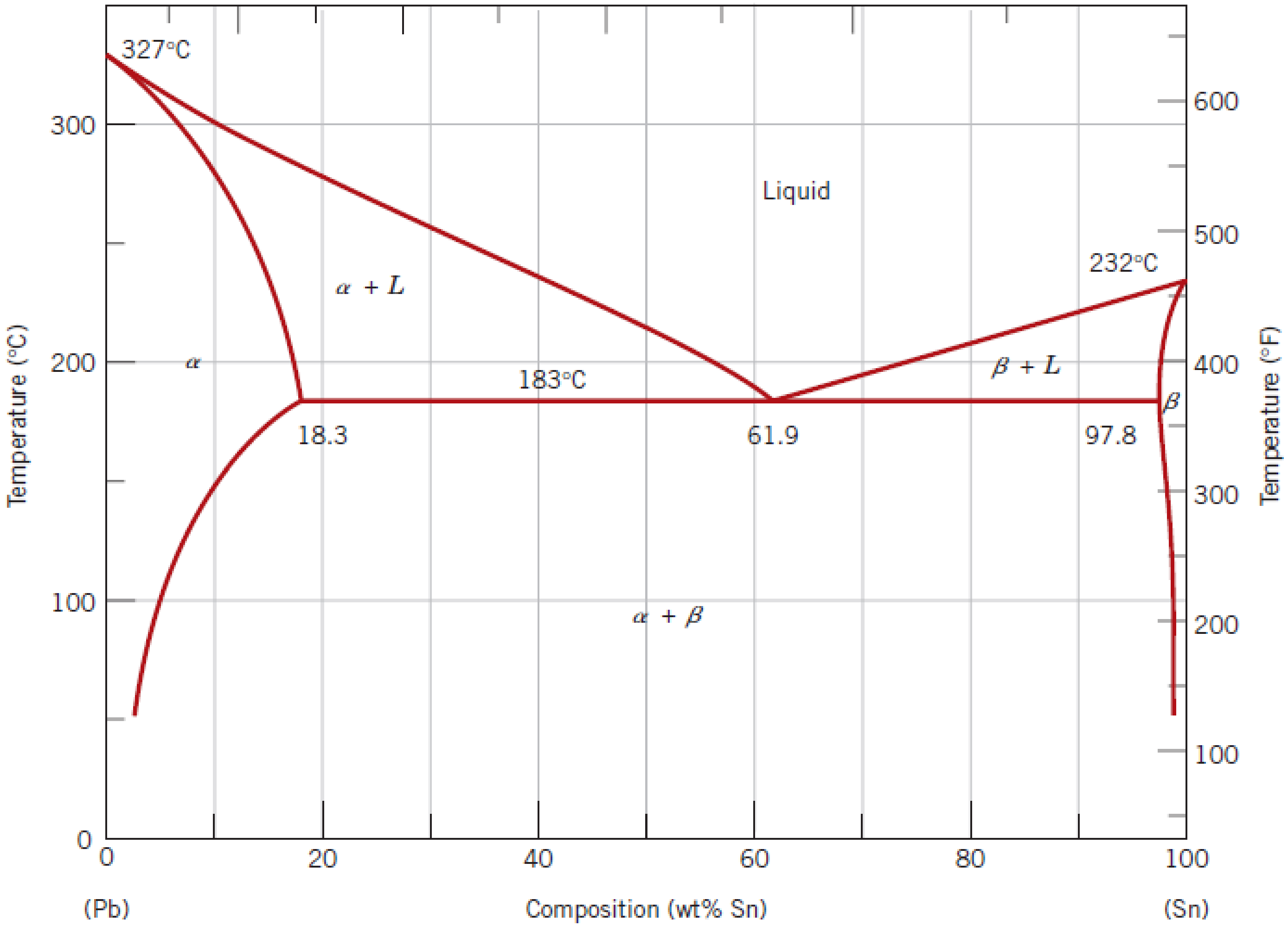
- Another type of common and relatively simple phase diagram found for binary alloys is shown in Figure below for the copper–silver system.
- Three single-phase regions are found on the diagram:α , β , and liquid.
- The α *phase is a solid solution rich in copper,* it has silver as the solute component and an FCC crystal structure.
- The β -phase solid solution also has an FCC structure, but copper is the solute.
- Pure copper and pure silver are also considered to be α *and* β *phases, respectively.*


0
20
40
60
80
100
1200
1000
800
600
400
200
2200
2000
1800
1600
1400
1200
1000
800
600
400
A
Liquidus
Liquid
Solidus
F
$\alpha + L$
α
$\beta + L$
B
779°C (T_E)
E
G
8.0
($C_{\alpha E}$)
71.9
(C_E)
91.2
($C_{\beta E}$)
β
Solvus
$\alpha + \beta$
C
H
Temperature (°C)
Temperature (°F)
0
20
40
60
80
100
(Cu)
Composition (wt% Ag)
(Ag)

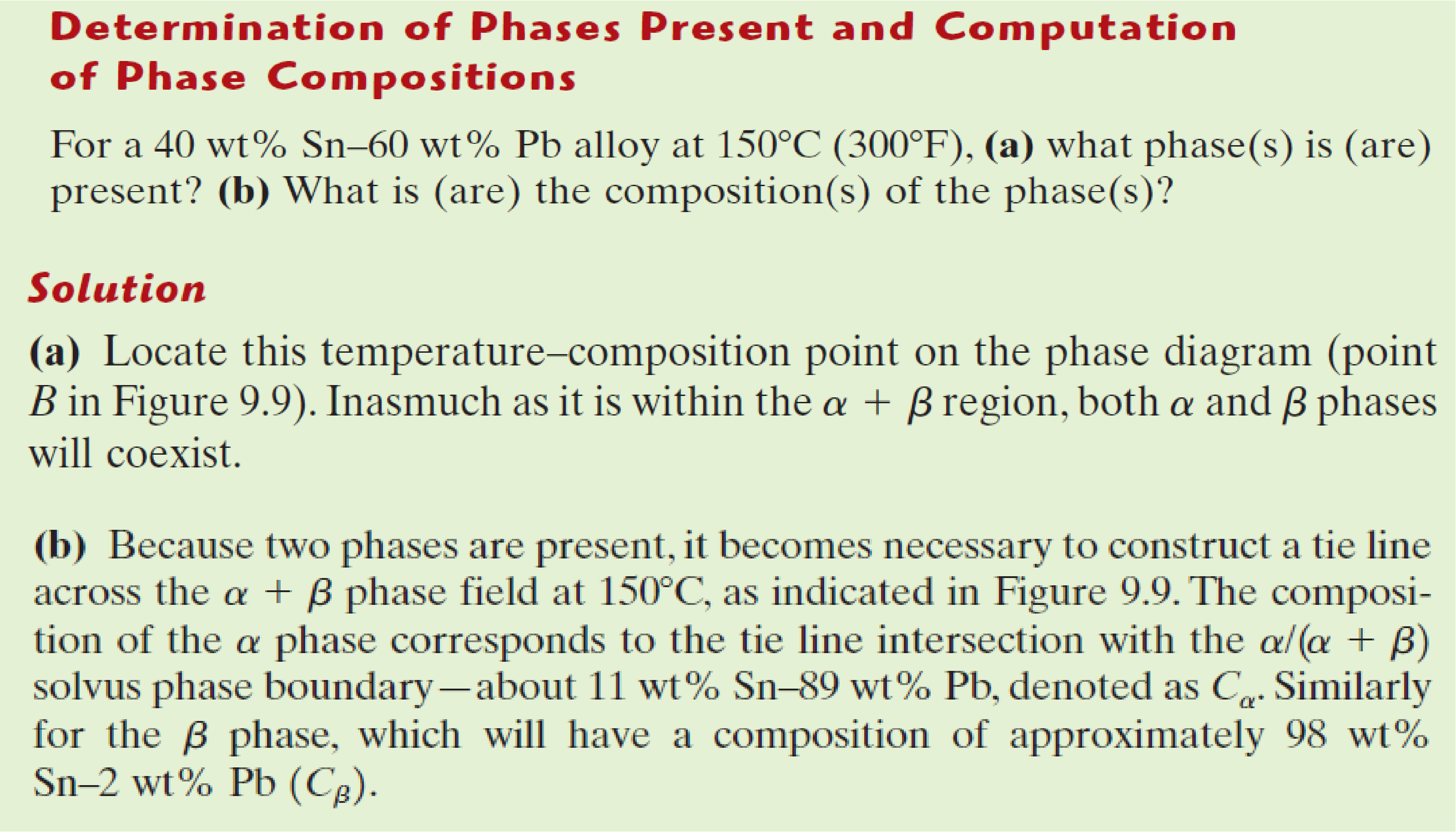
- The solid solubility limit line separating the α *and* α+ β *phase regions is termed a* ***solvus line.*** Similarly boundary GH is also a solvus line (α+ β and β).
- The boundary AB *between the* α *and* α+ *L fields is the* ***solidus line.*** Similarly boundary GF is also the solidus line (β + *L and* β).
- ***liquidus line*** separates α+ *L and L for AE and* β + *L and* β for *EF.*
- liquidus lines meet at the point *E on the phase diagram, through which also* passes the horizontal isotherm line *BEG. Point E is called an* **invariant point ,** which has ***zero degree of freedom.***
- *An important reaction takes place at point E, which is called* **eutectic reaction** *(eutectic means easy melting) (C shows composition.)*

$$L(C_E) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(C_{\alpha E}) + \beta(C_{\beta E})$$

Sn-Pb system (eutectic type)



Example



Determination of Phases Present and Computation of Phase Compositions

For a 40 wt% Sn–60 wt% Pb alloy at 150°C (300°F), **(a)** what phase(s) is (are) present? **(b)** What is (are) the composition(s) of the phase(s)?

Solution

(a) Locate this temperature–composition point on the phase diagram (point *B* in Figure 9.9). Inasmuch as it is within the $\alpha + \beta$ region, both α and β phases will coexist.

(b) Because two phases are present, it becomes necessary to construct a tie line across the $\alpha + \beta$ phase field at 150°C, as indicated in Figure 9.9. The composition of the α phase corresponds to the tie line intersection with the $\alpha/(\alpha + \beta)$ solvus phase boundary—about 11 wt% Sn–89 wt% Pb, denoted as C_α. Similarly for the β phase, which will have a composition of approximately 98 wt% Sn–2 wt% Pb (C_β).

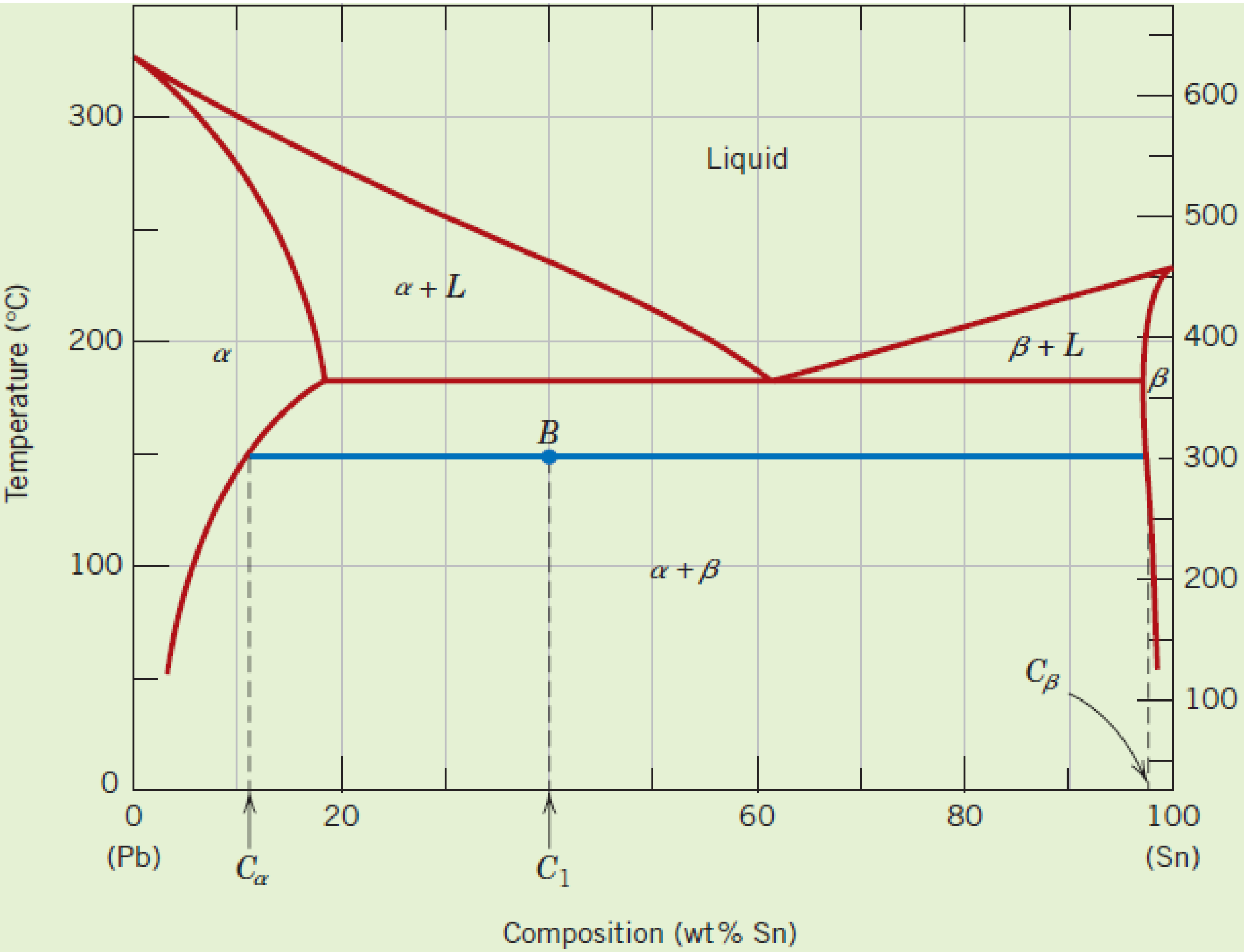


Figure 9.9 The lead–tin phase diagram. For a 40 wt% Sn–60 wt% Pb alloy at 150°C (point *B*), phase compositions and relative amounts are computed in Example Problems 9.2 and 9.3.

EXAMPLE PROBLEM 9.3

Relative Phase Amount Determinations—Mass and Volume Fractions

For the lead–tin alloy in Example Problem 9.2, calculate the relative amount of each phase present in terms of **(a)** mass fraction and **(b)** volume fraction. At 150°C take the densities of Pb and Sn to be 11.23 and 7.24 g/cm^3, respectively.

Solution

(a) Because the alloy consists of two phases, it is necessary to employ the lever rule. If C_1 denotes the overall alloy composition, mass fractions may be computed by subtracting compositions, in terms of weight percent tin, as follows:

$$W_\alpha = \frac{C_\beta - C_1}{C_\beta - C_\alpha} = \frac{98 - 40}{98 - 11} = 0.67$$

$$W_\beta = \frac{C_1 - C_\alpha}{C_\beta - C_\alpha} = \frac{40 - 11}{98 - 11} = 0.33$$

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MATERIAL SCIENCE AND ENGINEERING

UNIT 2

NON DESTRUCTIVE TESTING

Dr. SWATI GANGWAR
Mr. KAPIL KUMAR

Department Of Mechanical Engineering, MMMUT Gorakhpur

Non-Destructive Testing

Non-destructive testing is the testing of materials, for ***surface or internal flaws or metallurgical condition,*** without interfering in any way with the integrity of the material or its suitability for service.

Types of NDT Tests

1. Radiography
2. Magnetic Particle Crack Detection
3. Dye Penetrant Testing
4. Ultrasonic Flaw Detection
5. Eddy Current and Electro-magnetic Testing

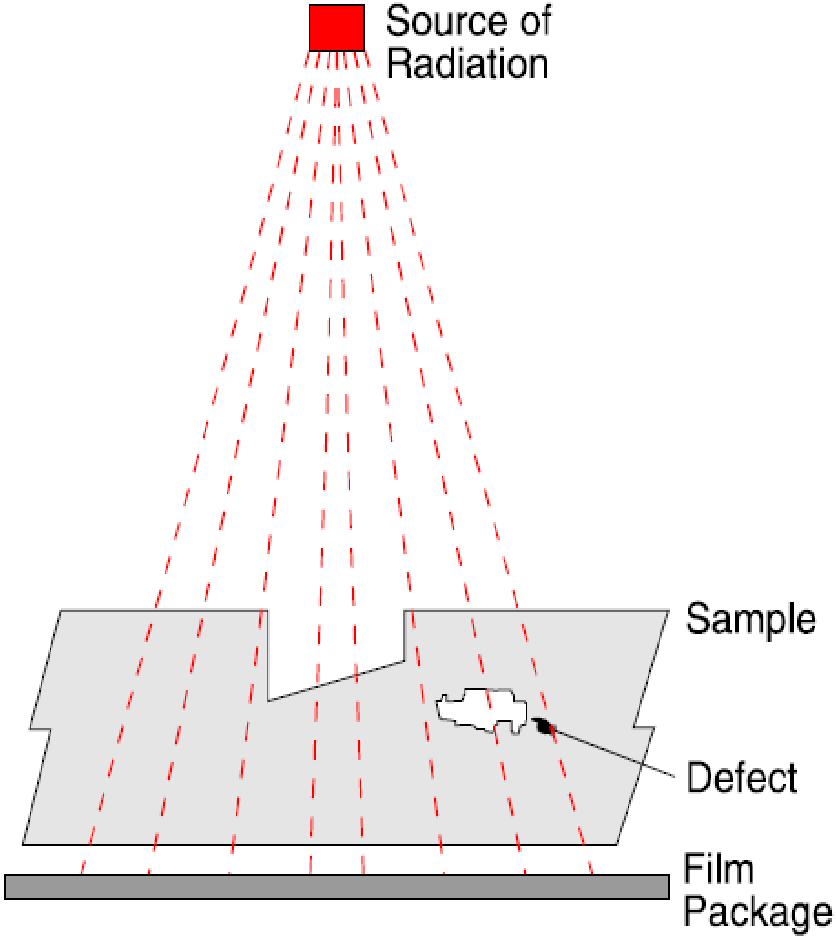
Radiography

- This technique is suitable for the detection of internal defects in ferrous and nonferrous metals and other materials.
- X-rays, generated electrically, and Gamma rays emitted from radio-active isotopes, are penetrating radiation which is differentially absorbed by the material through which it passes; the greater the thickness, the greater the absorbtion. Furthermore, the denser the material the greater the absorbtion.

Method

- Material with internal voids is tested by placing the subject between the source of radiation and the film. The voids show as darkened areas.
- In X-radiography the penetrating power is determined by the number of volts applied to the X-Ray tube - in steel approximately 1000 volts per inch thickness is necessary.
- In Gamma radiography the isotope governs the penetrating power and is unalterable in each isotope. Thus Iridium 192 is used for 1/2" to 1" steel and Caesium 134 is used for 3/4" to 21/2" steel.

Process



Schematic illustration of a typical exposure arrangement for radiography. The source of radiation can be either an X-ray tube or a radioactive isotope.

The resultant radiograph shows the subject as seen from the source.

Advantages of Radiography

- ❑Information is presented pictorially.
- ❑A permanent record is provided which may be viewed at a time and place distant from the test.
- ❑Useful for thin sections.
- ❑Sensitivity declared on each film.
- ❑Suitable for any material.

Disadvantages of Radiography

- ☐ Generally an inability to cope with thick sections.
- ☐ Possible health hazard.
- ☐ Need to direct the beam accurately for two-dimensional defects.
- ☐ Film processing and viewing facilities are necessary, as is an exposure compound.
- ☐ Not suitable for automation, unless the system incorporates fluoroscopy with an image intensifier or other electronic aids.
- ☐ Not suitable for surface defects.
- ☐ No indication of depth of a defect below the surface

Magnetic Particle Crack Detection

- This method is suitable for the detection of surface and near surface discontinuities in magnetic material, mainly ferritic steel and iron.

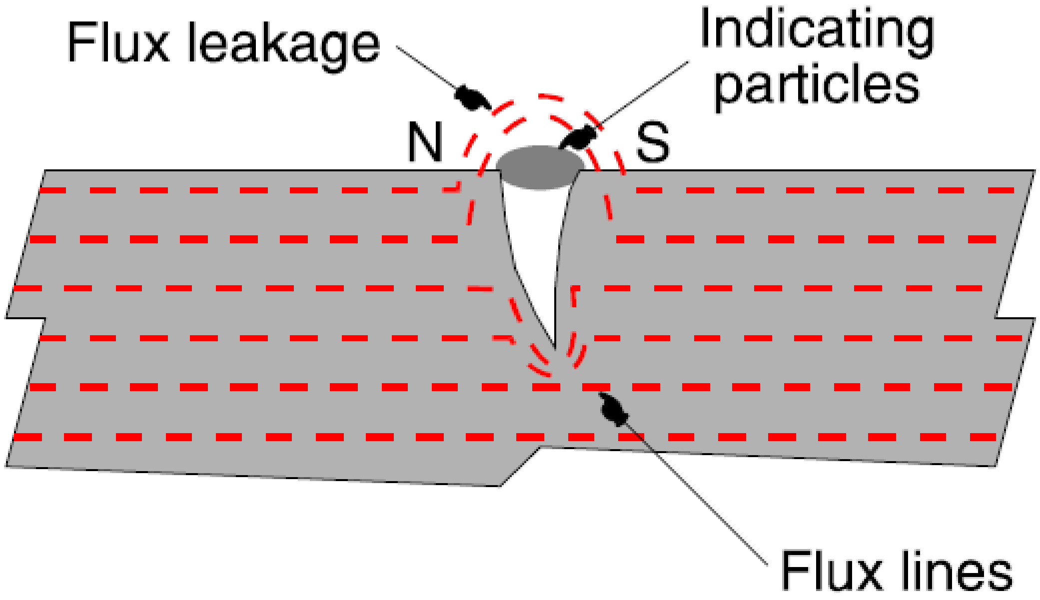
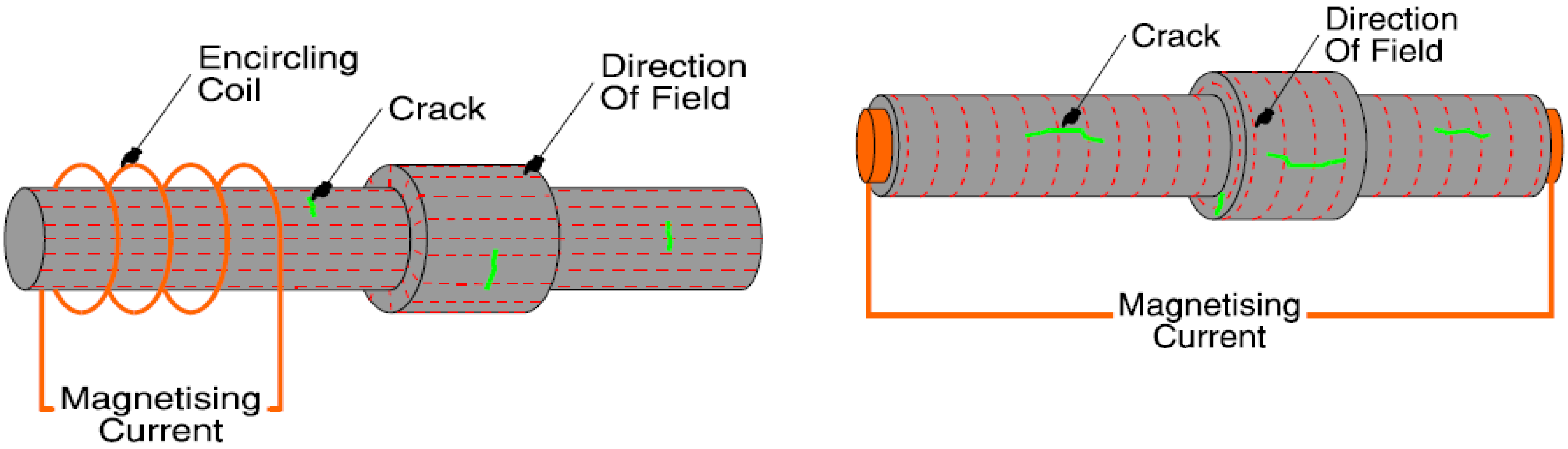


Diagram showing the Working principle of Magnetic particle crack Detection.

Procedure

- ❑ The principle is to generate magnetic flux in the article to be examined, with the flux lines running along the surface at right angles to the suspected defect. Where the flux lines approach a discontinuity they will stray out in to the air at the mouth of the crack.
- ❑ The crack edge becomes magnetic attractive poles North and South. These have the power to attract finely divided particles of magnetic material such as iron fillings.
- ❑ Usually these particles are of an oxide of iron in the size range 20 to 30 microns, and are suspended in a liquid which provides mobility for the particles on the surface of the test piece, assisting their migration to the crack edges. However, in some instances they can be applied in a dry powder form.



Figures showing the direction of Magnetic flux perpendicular to the orientation of Crack

Advantages

- Simplicity of operation and application.
- Can be automated, apart from viewing. (Though modern developments in automatic defect recognition can be used in parts of simple geometry e.g. billets and bars. In this case a special camera captures the defect indication image and processes it for further display and action)

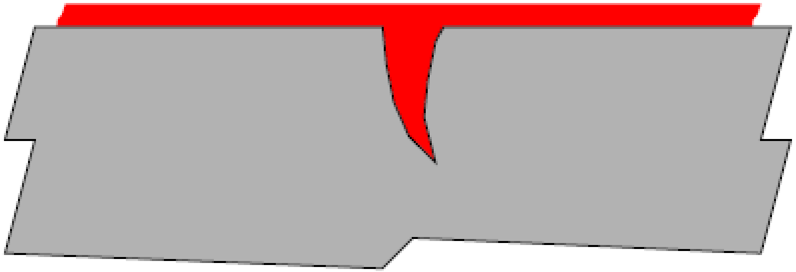
Disadvantages

- Restricted to ferromagnetic materials.
- Restricted to surface or near surface flaws.

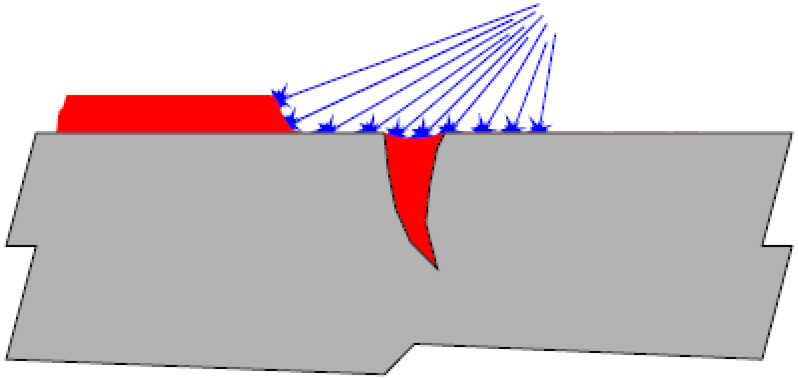
Dye Penetrant Testing

- This method is frequently used for the detection of surface breaking flaws in non-ferromagnetic materials.
- The subject to be examined is first of all chemically cleaned, usually by vapour phase, to remove all traces of foreign material, grease, dirt, etc. from the surface generally, and also from within the cracks.

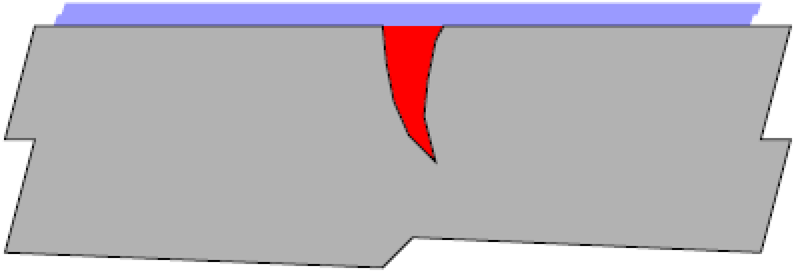
Process



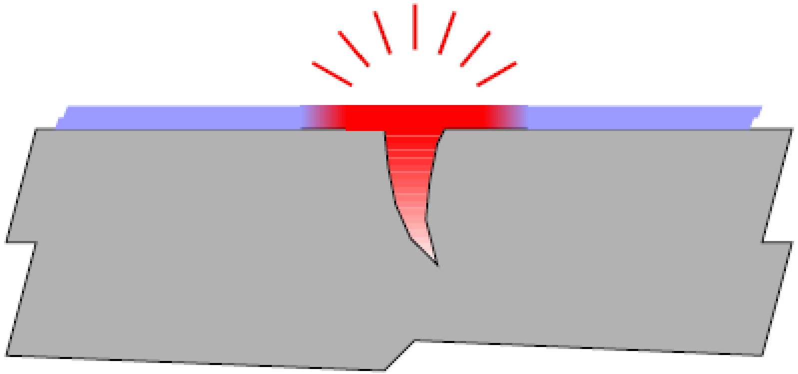
A. Penetrant applied to the surface and enters defect



B. Excess penetrant removed from surface



C. Developer powder applied to draw penetrant out of crack.



D. Accentuated indication of crack as penetrant spreads around the opening.

Advantages

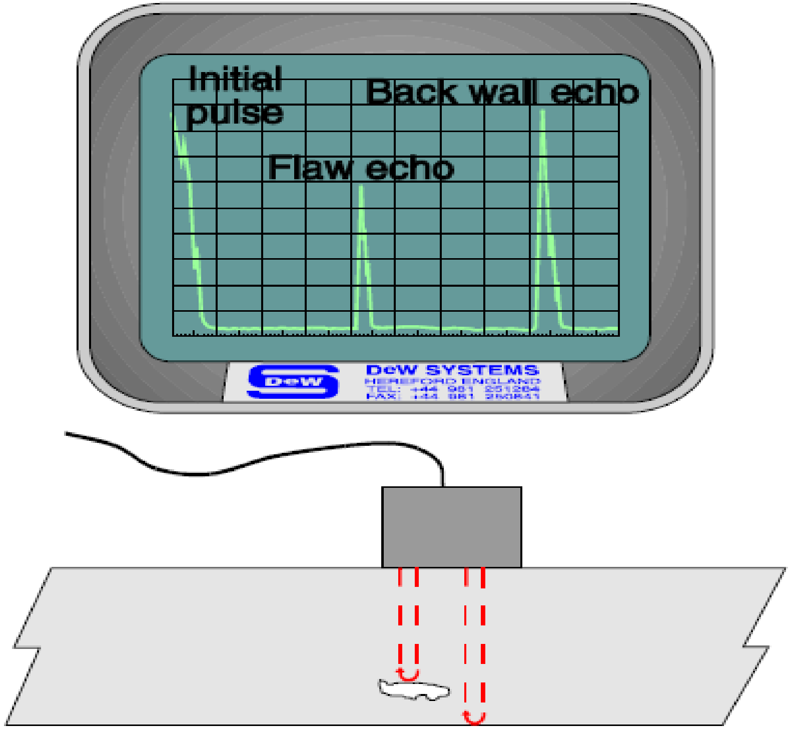
- Simplicity of operation.
- Best method for surface breaking cracks in non-ferrous metals.
- Suitable for automatic testing, with reservation concerning viewing. (See automatic defect recognition in Magnetic Particle Inspection)
- Quantative.

Disadvantages

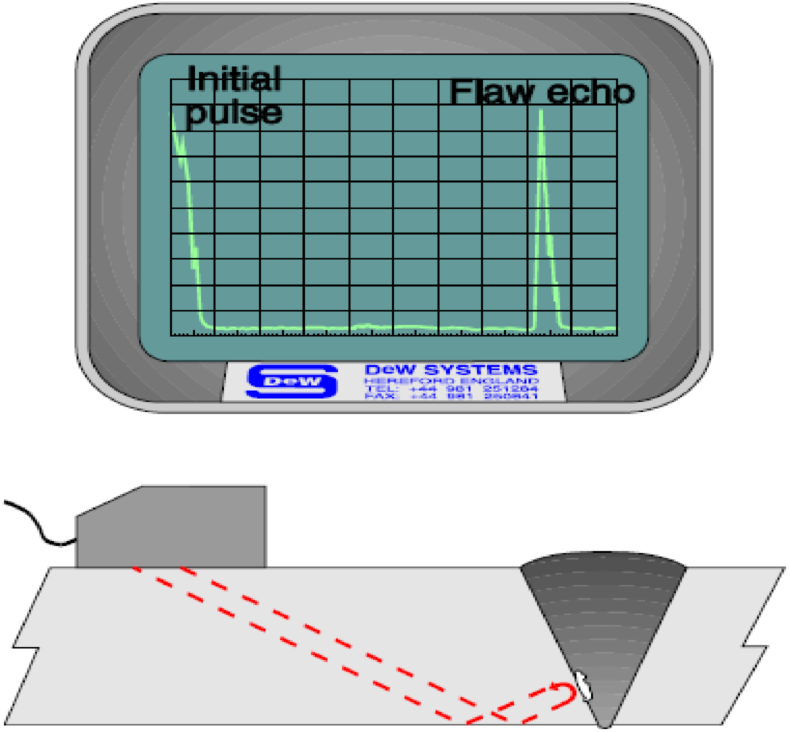
- Restricted to surface breaking defects only.
- Decreased sensitivity.
- Uses a considerable amount of consumables.

Ultrasonic Flaw Detection

This technique is used for the detection of internal and surface (particularly distant surface) defects in sound conducting materials.



Schematic diagram of ultrasonic detection of slag in steel section using a normal probe.



Schematic diagram of the use of an angle probe to detect defects not directly under the probe. Such as in weld inspection.

ULTRASONIC TEST

1. Measure of time required by ultrasonic vibrations to penetrate material of interest , reflect from opposite side or from internal discontinuity and return to point from where first introduced.
2. Behaviour of waves through cycle with regard to time is recorded on CRO screen.
3. By observing this presence of defect and their location can be detected.

☐ Two types of Ultrasonic testing method- i)Pulse –echo method

ii) Transmission Method

Advantages of Ultrasonic Test

- ❑Better detection of flaws situated deep in metal due to superior penetrating power of ultrasonic waves.
- ❑High sensitivity, better accuracy and reliability
- ❑The equipment is portable and easy to handle
- ❑Output of test can be processed by computer which lead to improved result reliability
- ❑Capable of being fully automated.
- ❑Access to only one side necessary.
- ❑No consumables.

Disadvantages of Ultrasonic Test

- Due to manual operation, careful attention and highly skilled operators are required .
- Irregular shaped and rough parts are very difficult to examine .
- Subsurface discontinuities are more difficult to detect.
- No permanent record available unless one of the more sophisticated test results and data collection systems is used.
- Very thin sections can prove difficult.

EDDY CURRENT TEST

Basic Principle:- When coil carrying alternating current is brought near metallic specimen, eddy currents are developed in specimen due to electromagnetic induction.

Magnitude of induced EMI depend on –

i)Magnitude and frequency of alternating current flowing in coil.

ii) Electrical conductivity of specimen.

iii) Magnetic permeability of specimen

iv)Shape of specimen.

v)Relative positions of coil and specimen.

vi)Microstructure and hardness of Specimen.

vii)Amount and type of defects in the specimen

Advantages ECT

- Test is quick and less time consuming
- Test can be automated easily
- Permanent record of test results can be easily available
- Test is versatile and can be used for various applications

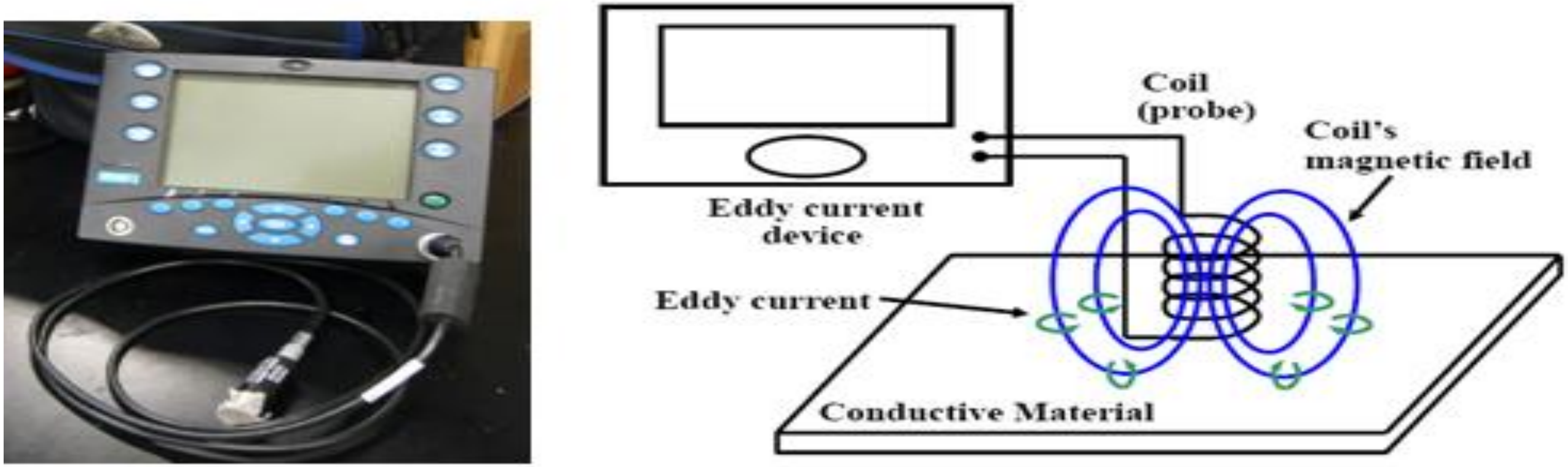


Figure.

Disadvantages of ECT

- The instrument standardization and calibration is necessary from time to time
- Instruments and display units are costly
- Test can be applied to components of limited size and shape

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MATERIAL SCIENCE AND ENGINEERING

UNIT 2

COROSSION

Dr. SWATI GANGWAR

Mr. KAPIL KUMAR

Department Of Mechanical Engineering, MMMUT Gorakhpur

CORROSION

- ☐ Corrosion is defined as the destructive and unintentional attack of a metal; it is electrochemical and ordinarily begins at the surface.
- ☐ The problem of metallic corrosion is one of significant proportions; in economic terms, it has been estimated that approximately *5% of an industrialized nation's income* is spent on corrosion prevention and the maintenance or replacement of products lost or contaminated as a result of corrosion reactions.

Continue…..

- The consequences of corrosion are all too common. Familiar examples include the rusting of automotive body panels and radiator and exhaust components.
- Corrosion processes are occasionally used to advantage. For example, etching procedures, make use of the selective chemical reactivity of grain boundaries or various microstructural constituents.

Corrosion rate

- The corrosion rate, or the rate of material removal as a consequence of the chemical action, is an important corrosion parameter. This may be expressed as the **corrosion penetration rate (CPR), or the thickness loss of material per unit of time.**

$$\mathbf{CPR = KW/pAt}$$

- where *W is the weight loss after exposure time t; p and A represent the density and* exposed specimen area, respectively, and *K is a constant, its magnitude depending on* the system of units used.

Forms of Corrosion in Metals

- ❑ Metallic corrosion is sometimes classified into eight different forms:

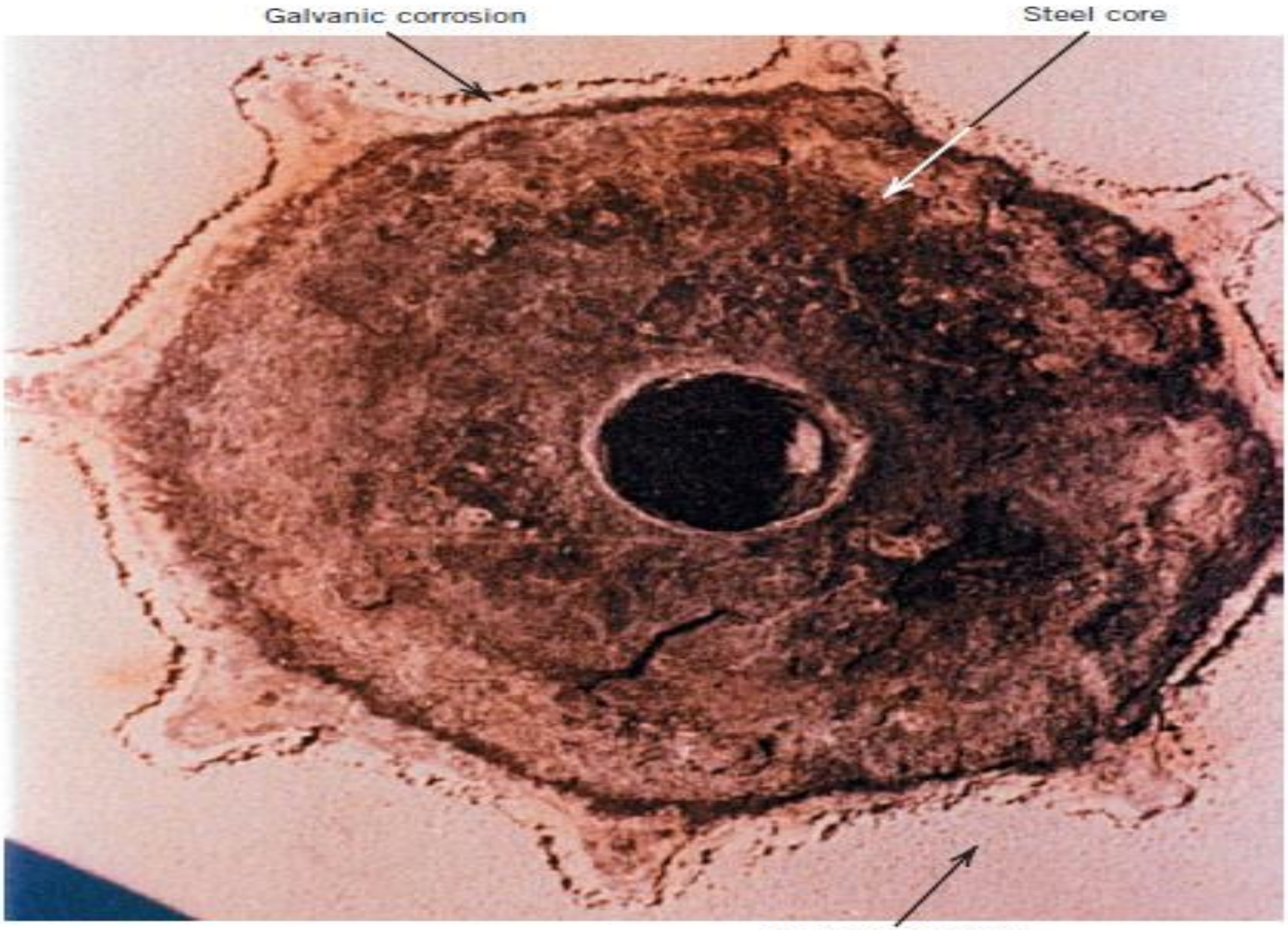
Uniform Attack

- ❑ Uniform attack is a form of electrochemical corrosion that occurs with equivalent intensity over the entire exposed surface and often leaves behind a scale or deposit. In a microscopic sense, the oxidation and reduction reactions occur randomly over the surface. Some familiar examples include general rusting of steel and iron and the tarnishing of silverware. This is probably the most common form of corrosion

Galvanic Corrosion

- **Galvanic corrosion occurs when two metals or alloys having different compositions** are electrically coupled while exposed to an electrolyte.
- This is the type of corrosion or dissolution. The less noble or more reactive metal in the particular environment will experience corrosion; the more inert metal, the cathode, will be protected from corrosion.
- For example, steel screws corrode when in contact with brass in a marine environment; or if copper and steel tubing are joined in a domestic water heater, the steel will corrode in the vicinity of the junction.

Galvanic Corrosion Figure.

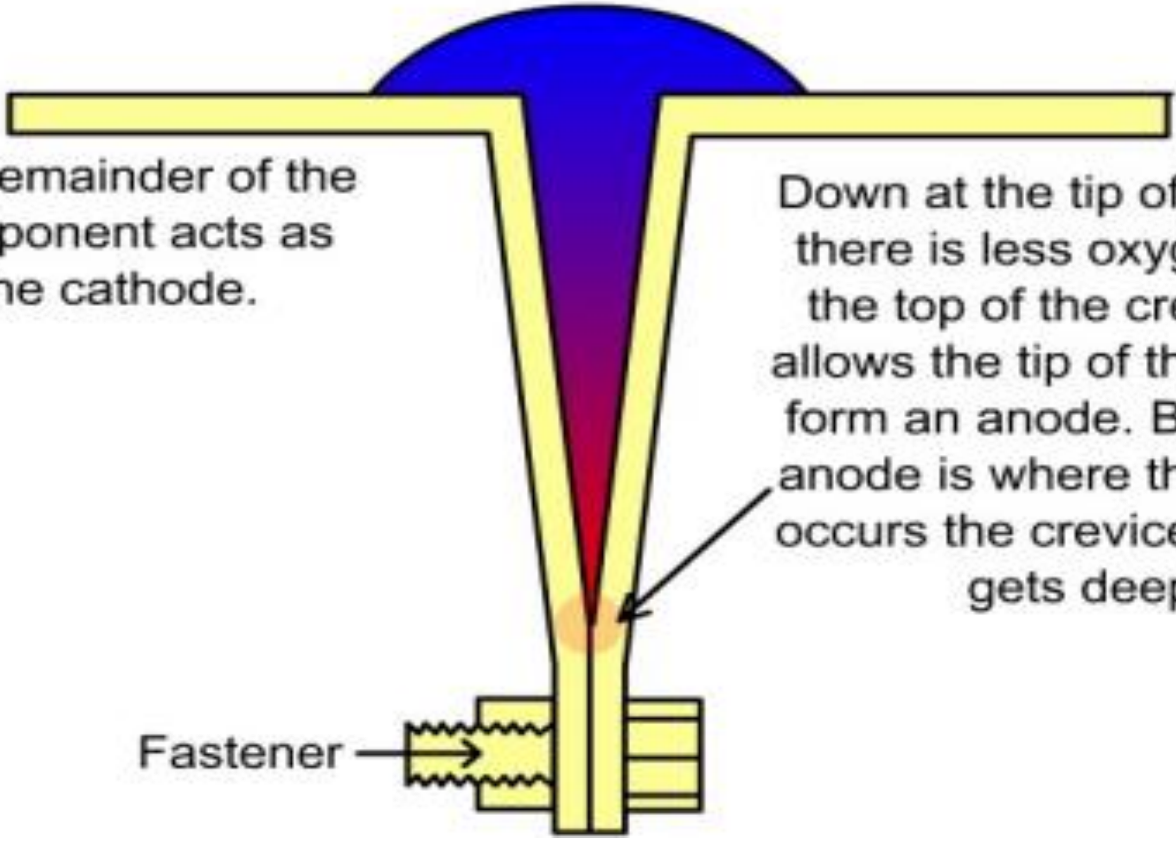


Crevice Corrosion

- Electrochemical corrosion may also occur as a consequence of concentration differences of ions or dissolved gases in the electrolyte solution, and between two regions of the same metal piece.
- For such a *concentration cell, corrosion occurs in the* locale that has the lower concentration.
- A good example of this type of corrosion occurs in crevices and recesses or under deposits of dirt or corrosion products where the solution becomes stagnant and there is localized depletion of dissolved oxygen. Corrosion preferentially occurring at these positions is called **crevice corrosion**

Figure. On this plate, which was immersed in seawater, crevice corrosion has occurred at the region that were covered by washers.

Example:-



The water in the crevice has more oxygen at the top surface because oxygen from the air can enter the water.

The remainder of the component acts as the cathode.

Down at the tip of the crevice there is less oxygen than at the top of the crevice. This allows the tip of the crevice to form an anode. Because the anode is where the corrosion occurs the crevice grows and gets deeper.

Pitting

- ❑ **Pitting is another form of very localized corrosion attack in which small pits or holes form**.
- ❑ They ordinarily penetrate from the top of a horizontal surface downward in a nearly vertical direction.
- ❑ It is an extremely insidious type of corrosion, often going undetected and with very little material loss until failure occurs.
- ❑ Found in passive metals and alloys such as aluminium alloys, stainless steels, and stainless alloys when the ultra-thin passive film (oxide film) is chemically or mechanically damaged and does not immediately re-passivate.

- Stainless steels are somewhat susceptible to this form of corrosion; however, alloying with about 2% molybdenum enhances their resistance significantly.

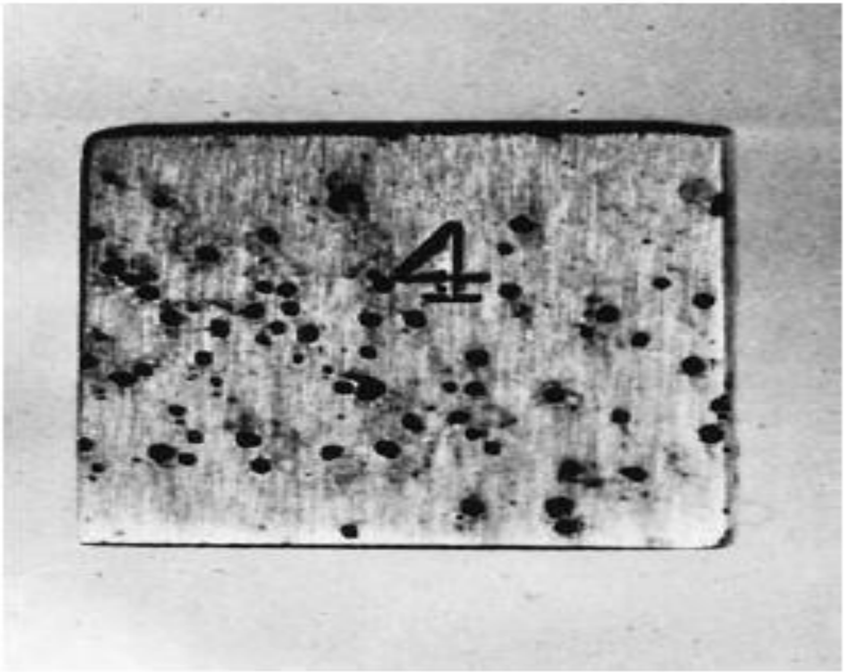
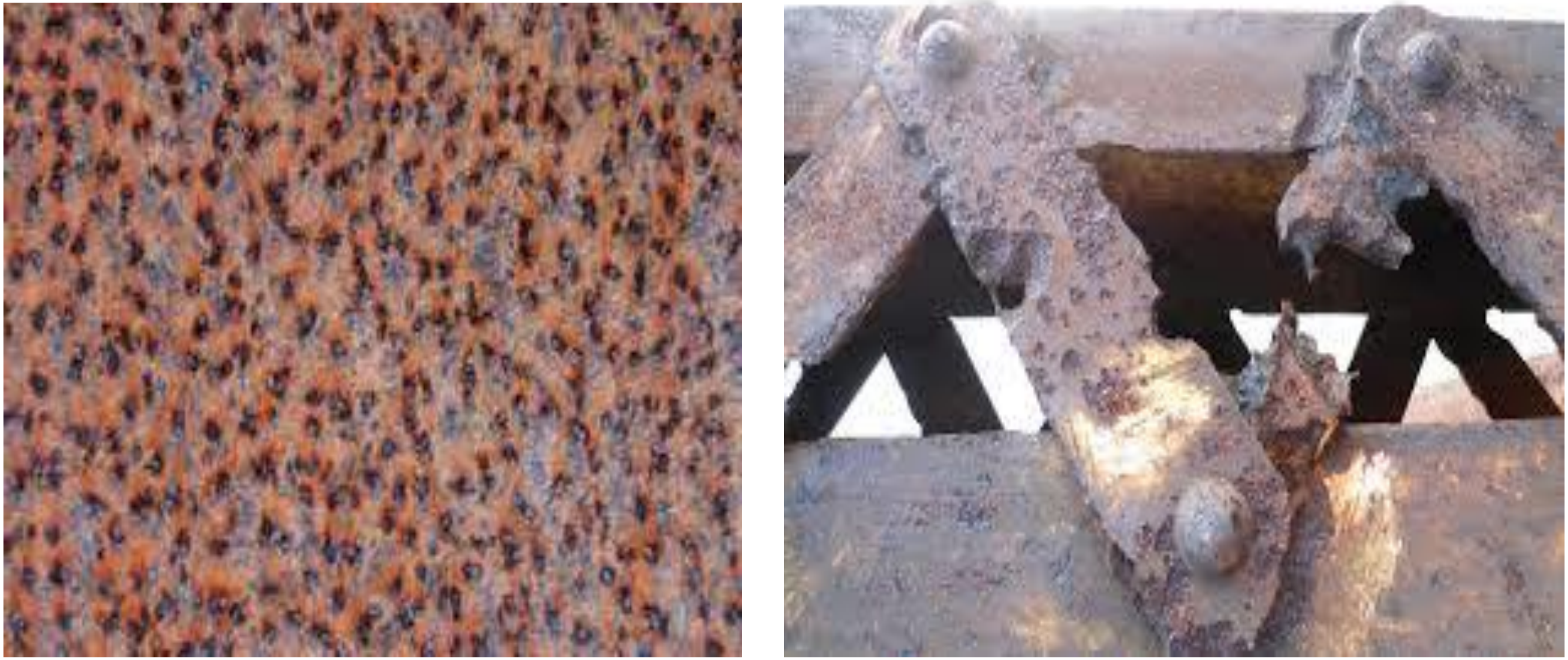


Figure. The pitting of a 304 stainless steel plate by an acid-chloride solution.

Figures showing Consequences of Pitting



Stress Corrosion

- ❑**Stress corrosion, sometimes termed stress corrosion cracking, results from the** combined action of an applied tensile stress and a corrosive environment; both influences are necessary.
- ❑ In fact, some materials that are virtually inert in a particular corrosive medium become susceptible to this form of corrosion when a stress is applied.
- ❑Small cracks form and then propagate in a direction perpendicular to the stress, with the result that failure may eventually occur

Stress Corrosion Cracking in an Aircraft panel

Continue…..

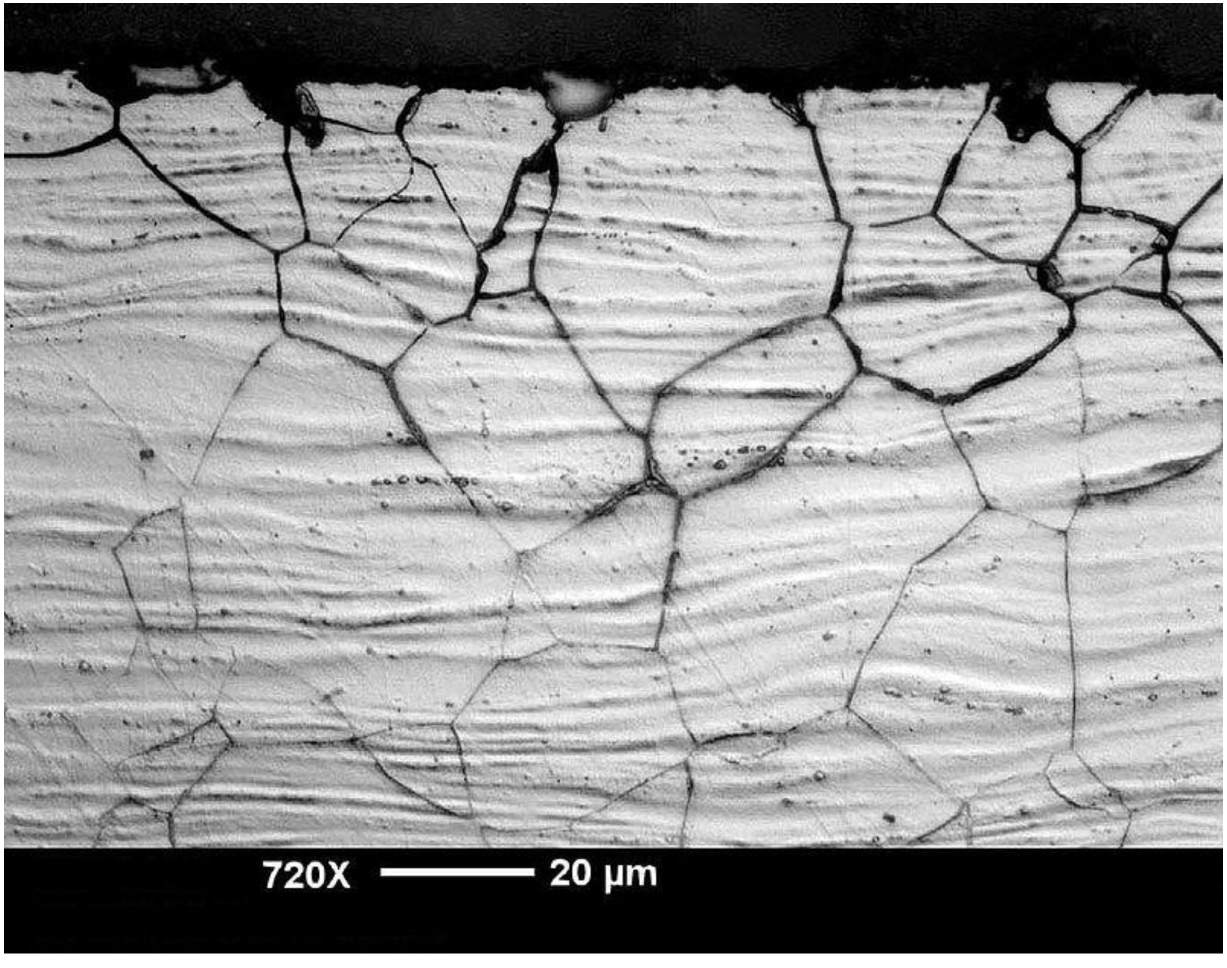
- ☐ **Intergranular corrosion**—occurs preferentially along grain boundaries for specific metals/alloys (e.g., some stainless steels). Intergranular corrosion is an especially severe problem in the welding of stainless steels, when it is often termed **weld decay.**

- ☐ **Selective leaching**—the case wherein one element/constituent of an alloy is removed selectively by corrosive action.

- ☐ **Erosion–corrosion**—the combined action of chemical attack and mechanical wear as a consequence of fluid motion.

- ☐ **Hydrogen embrittlement**—a significant reduction in ductility that accompanies the penetration of atomic hydrogen into a metal/alloy.

Intergranular Corrosion



Selective Leaching in Cast Iron

Corrosion of Ceramic Materials

- Ceramic materials, being inherently corrosion resistant, are frequently used at elevated temperatures and/or in extremely corrosive environments.

Degradation of Polymers

- Polymeric materials deteriorate by noncorrosive processes. Upon exposure to liquids, they may experience degradation by swelling or dissolution. With swelling, solute molecules actually fit into the molecular structure.
- Dissolution may occur when the polymer is completely soluble in the liquid. Scission, or the severance of molecular chain bonds, may be induced by radiation, chemical reactions, or heat. This results in a reduction of molecular weight and a deterioration of the physical and chemical properties of the polymer.

Corrosion Prevention

- ❑Several measures may be taken to prevent, or at least reduce, corrosion.
- ❑These include material selection, environmental alteration, the use of inhibitors, design changes, application of coatings, and cathodic protection.
- ❑With cathodic protection, the metal to be protected is made a cathode by supplying electrons from an external source.