MECHANICAL WORKING AND TESTING OF MATERIALS

B.TECH, 5th SEMESTER

LECTURES NOTE

COMPILED BY

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BPUT SYLLABUS

Module I (14 Hours)

Classification of forming processes. Fundamentals of metal working – Effect of temperature, strain rate, metallurgical structure, friction & lubrication, workability and residual stress.

Rolling - Classification & processes, load, torque, power, variables controlling process, forward slip. Fundamentals of roll pass design, mill type. Rolling defects and their control.

Forging - Classification & processes, load for circular & rectangular plate.

Extrusion - Classification & processes, force & variables affecting it.

Module II (12 Hours)

Drawing of Wires and Tubes- Processes, drawing stress.

Sheet Metal Forming- Forming methods, Forming limit criterion, Special Forming techniques and defects in formed products

National and International Standards for Mechanical tests

Hardness Tests- Brinell, Rockwell, Vickers, Meyer, Knoop, etc., relationship with flow curve.

Compression Test- Comparison with tension, phenomenon of buckling & barreling.

Torsion Test- Stresses for elastic & plastic strain, Torsion vs. Tension.

Bend Test- Pure bending & flexure formula.

Impact Test- Notched bar impact tests, transition temperature & metallurgical factors affecting it.

Module III (14 Hours)

Fracture- Energy based criterion, Strain energy release rate, stress intensity factor, fracture toughness estimation and design of engineering component.

Fatigue – Stress cycles & S-N curve, effect of mean stress, stress concentration, surface, size, metallurgical factors etc. on endurance limit, Cyclic stress-strain curve, Low cycle fatigue, High cycle Fatigue, Paris law.

Creep- Creep & Stress rupture tests, Mechanism of creep deformation, Deformation mechanism Maps, Development of creep resistant alloys, Prediction of long time properties, Creep-Fatigue interaction.

Non Destructive Testing: Scope and significance of non-destructive testing. Principles, equipment, specifications and limitations of liquid penetrant, Magnetic particle, Eddy current, Ultrasonic and Acoustic emissions, and Radiography (X-Ray and Gamma Ray).

Books for reference:

1. Mechanical Metallurgy by G. E. Dieter, McGraw-Hill.
2. Roll Pass Design, The United Steel Companies Ltd., U.K.
3. Testing of Metallic materials by C. Suryanarayana.
4. Principles of Industrial Metal Working Processes by C. Russak, G. W. Rowe.
5. Practical Non Destructive Testing by Baldev Raj.

CONTENTS

CHAPTER-1

HARDNESS TEST

Testing of materials are generally classified in two categories.

1. Destructive testing (tensile test, hardness test, fatigue test, creep test and impact test)
2. Non-destructive testing (dye penetrant test, magnetic test, ultrasonic test, radiography, eddy current test etc.)

In this section we will deal with destructive testing.

HARDNESS- Hardness usually implies resistance to deformation, resistance to permanent or plastic deformation or resistance to indentation.

There are three general types of hardness measurements depending upon the manner in which the test is conducted. These are

1. Scratch hardness
2. Indentation hardness
3. Rebound, or dynamic, hardness.

- Only indentation hardness is of major engineering interest for metals.

SCRATCH HARDNESS

- With this measure of hardness, various minerals and other materials are rated on their ability to scratch one another.
- Hardness is measured according to the Mohs scale.
- This consists of 10 standard minerals arranged in the order of their ability to be scratched. The softest mineral in this scale is **talc (scratch hardness 1)**, while **diamond has a hardness of 10**. A **fingernail has a value of about 2**, **annealed copper has a value of 3**, and **martensite a hardness of 7.**
- Most hard metals fall in the Mohs hardness range of 4 to 8.
- A different type of scratch-hardness test measures the depth or width of a scratch made by drawing a diamond stylus across the surface under a definite load.

DYNAMIC OR REBOUND HARDNESS

Shore sceleroscope

- In dynamic-hardness measurements the indenter is usually dropped onto the metal surface, and the hardness is expressed as the energy of impact.
- One of the instrument measuring rebound hardness is shore sceleroscope which measures the hardness in terms of the height of rebound of the indenter.

INDENTATION HARDNESS

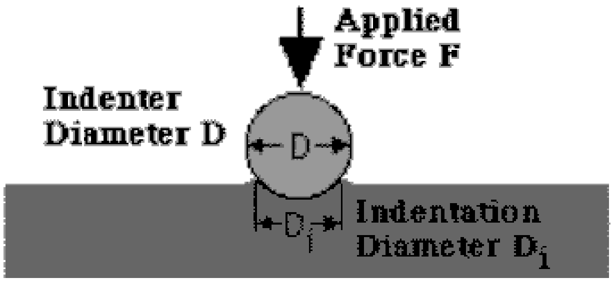
There are different hardness tests are there for measuring hardness by in this category which are discussed one by one.

BRINELL HARDNESS

- 10-mm-diameter steel ball at a load of 3,000 kg.
- For soft metals the load is reduced to 500 kg to avoid too deep an impression, and for very hard metals a tungsten carbide ball is used to minimize distortion of the indenter.
- The load is applied for a standard time, usually 30 sec.
- The diameter of the indentation is measured with a low-power microscope after removal of the load.
- The average of two readings of the diameter of the impression at right angles should be made.

Brinell hardness tester

- The surface on which the indentation is made should be relatively smooth and free from dirt or scale.
- The Brinell hardness number (BHN) is expressed as the load P divided by the surface area of the indentation.



$$BHN = \frac{F}{\frac{\pi}{2} D \cdot (D - \sqrt{D^2 - D_i^2})}$$

Where F= applied load, kg   D = diameter of ball, mm   d = diameter of indentation, mm.

- Units of BHN are kilograms per square millimeter.

Assignment 1. Put d = D sin□ *and derive the formula for BHN.*

- From the above assignment we can derive that P/D^2 ratio is constant during testing.
- Brinell hardness is less influenced by surface scratches and roughness than other hardness test.

MEYER HARDNESS

- According to this harness, the mean pressure between the surface of the indenter and the indentation is equal to the load divided by the projected area of the indentation.

$$p_m = \frac{P}{\pi r2}$$

- Meyer proposed that this mean pressure should be taken as the measure of hardness. It is referred to as the Meyer hardness.

MHN= 4P/□d^2

- Unit= kilogram per square millimeter
- The Meyer hardness is less sensitive to the applied load than the Brinell hardness. For a cold-worked material the Meyer hardness is essentially constant and independent of load, while the Brinell hardness decreases as the load increases. For an annealed metal the Meyer hardness increases continuously with the load because of strain hardening produced by the indentation. The Brinell hardness, however, first increases with load and then decreases for still higher loads. The Meyer hardness is a more fundamental measure of indentation

hardness; yet it is rarely used for practical hardness measurements. Meyer proposed an empirical relation between the load and the size of the indentation. This relationship is usually called Meyer's law.

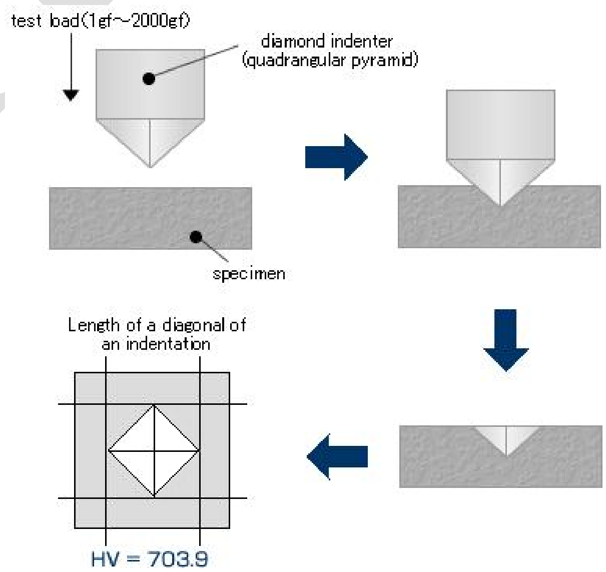
$$P = k\, d^{n'}$$

Where P = applied load, kg, d = diameter of indentation, mm, n' = a material constant related to strain hardening of metal (n'= n+2 where n is strain hardening exponent), k= a material constant expressing resistance of metal to penetration.

- Fully annealed metals have a value of n' of about 2.5, while n' is approximately 2 for fully strain-hardened metals.
- For a 10-mm-diameter ball the load should exceed 50 kg for copper with a BHN of 100, and for steel with a BHN of 400 the load should exceed 1,500 kg. For balls of different diameter the critical loads will be proportional to the square of the diameter.

VICKERS HARDNESS

- The Vickers hardness test uses a square-base diamond pyramid as the indenter. The included angle between opposite faces of the pyramid is 136°.
- This angle was chosen because it approximates the most desirable ratio of indentation diameter to ball diameter in the Brinell hardness test.
- Because of the shape of the indenter this is frequently called the diamond pyramid hardness test.
- The diamond-pyramid hardness number (DPH), or Vickers hardness number (VHN, or VPH), is defined as the load divided by the surface area of the indentation.

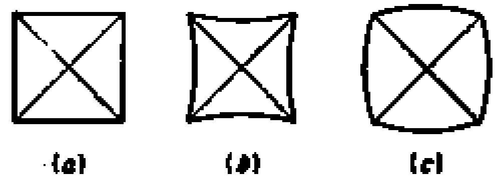


- The DPH may be determined from the following equation,

$$DPH = 2P \sin\left(\frac{\theta}{2}\right) / L^2 = 1.854P/L^2$$

Where P = applied load, kg L = average length of diagonals, mm θ = angle between opposite faces of diamond = 136º

- A perfect indentation made with a perfect diamond-pyramid indenter would be a square. (a)
- Pincushion indentation is due to sinking in of the metal around the fiat faces of the pyramid. This condition is observed with annealed metals and results in an overestimate of the diagonal length.



a. perfect indentation b. pincushion indentation due to sinking in c. barreled indentation due to ridging.

- The barrel-shaped indentation is found in cold worked metals. It results from ridging or piling up of the metal around the faces of the indenter. Underestimation diagonal length.

<u>ROCKWELL HARDNESS</u>

- Its general acceptance is due to its speed, freedom from personal error, ability to distinguish small hardness differences in hardened steel, and the small size of the indentation, so that finished heat-treated parts can be tested without damage.
- This test utilizes the depth of indentation, under constant load, as a measure of hardness.
- A minor load of 10 kg is first applied to seat the specimen. This minimizes the amount of surface preparation needed and reduces the tendency for ridging or sinking in by the indenter. The major load is then applied, and the depth of indentation is automatically recorded on a dial gage in terms of arbitrary hardness numbers. The dial contains 100 divisions, each division representing a penetration of 0.00008 in. The dial is reversed so that a high hardness, which corresponds to a small penetration, results in a high hardness number.
- Unit less.
- A 120° diamond cone with a slightly rounded point, called a Brale indenter, and 1/16" diameter steel balls are generally used as indenters. Major loads of 60, 100, and 150 kg are used.

scale	*Type of indenter*	*Major load(kgf)*
A	Brale indenter	60
B	1/16” diameter steel ball	100
C	Brale indenter	150

MICROHARDNESS TEST (*KNOOP HARDNESS TEST)*

- The Knoop indenter is a diamond ground to a pyramidal form that produces a diamond-shaped indentation with the long and short diagonals in the approximate ratio of 7: 1. The Knoop hardness number (KHN) is the applied load divided by the unrecovered projected area of the indentation.

$$KHN= P/A_P = P/L^2C$$

Where P = applied load, kg Ap = unrecovered projected area of indentation, mm^ L = length of long diagonal, mm C = a constant for each indenter supplied by manufacturer.

- The low load used with micro hardness tests requires that extreme care be taken in all stages of testing. The surface of the specimen must be carefully prepared. Metallographic polishing is usually required. Work hardening of the surface during polishing can influence the results.
- The long diagonal of the Knoop impression is essentially unaffected by elastic recovery for loads greater than about 300 g. However, for lighter loads the small amount of elastic recovery becomes appreciable. Further, with the very small indentations produced at light loads the error in locating the actual ends of the indentation become greater.
- Both these factors have the effect of giving a high hardness reading, so that it is usually observed that the Knoop hardness number increases as the load is decreased below about 300 g.
- Knoop hardness number is constant with load down to 100 g.

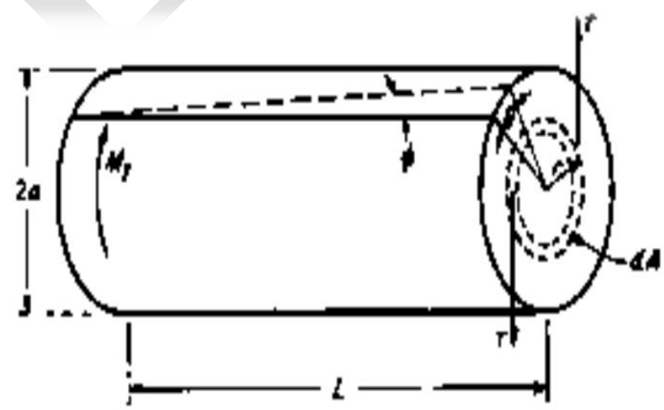
CHAPTER- 2

TORTION TEST

- Torsion tests are made on materials to determine such properties as the modulus of elasticity in shear, the torsional yield strength, and the modulus of rupture.
- Torsion-testing equipment consists of a twisting head, with a chuck for gripping the specimen and for applying the twisting moment to the specimen, and a weighing head, which grips the other end of the specimen and measures the twisting moment, or torque.
- The deformation of the specimen is measured by a twist-measuring device called a troptometer.
- Determination is made of the angular displacement of a point near one end of the test section of the specimen with respect to a point on the same longitudinal element at the opposite end.

<u>MECHANICAL PROPERTIES IN TORSION</u>

Consider a cylindrical bar which is subjected to a torsional moment at one end. The twisting moment is resisted by shear stresses set up in the cross section of the bar. The shear stress is zero at the center of the bar and increases linearly with the radius.



Equating the twisting moment to the internal resisting moment, twisting moment to the internal resisting moment,

$$M_T = \int_{r=0}^{r=a} \tau r \, dA = \frac{\tau}{r} \int_0^a r^2 \, dA \qquad (10\text{-}1)$$

But $\int r^2 \, dA$ is the polar moment of inertia of the area with respect to the axis of the shaft. Thus,

$$M_T = \frac{\tau J}{r}$$

or

$$\tau = \frac{M_T r}{J} \qquad (10\text{-}2)$$

where τ = shear stress, psi
M_T = torsional moment, lb-in.
r = radial distance measured from center of shaft, in.
J = polar moment of inertia, in.^{4}

Since the shear stress is a maximum at the surface of the bar, for a solid cylindrical specimen where $J = \pi D^4/32$, the maximum shear stress is

$$\tau_{max} = \frac{M_T D/2}{\pi D^4/32} = \frac{16 M_T}{\pi D^3} \qquad (10\text{-}3)$$

For a tubular specimen the shear stress on the outer surface is

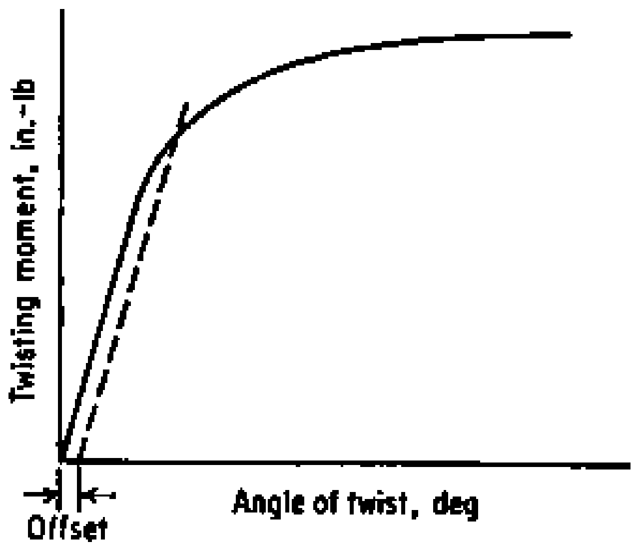
$$\tau = \frac{16 M_T D_1}{\pi (D_1^4 - D_2^4)} \qquad (10\text{-}4)$$

where D_1 = outside diameter of tube
D_2 = inside diameter of tube

The troptometer is used to determine the angle of twist, d, usually expressed in radians. If L is the test length of the specimen, it will be seen that the shear strain is given by,

$$\gamma = \tan \phi = \frac{r\theta}{L}$$

During a torsion test measurements are made of the twisting moment M_T and the angle of twist, θ. A torque-twist diagram is usually obtained,



Once the torsional yield strength has been exceeded the shear-stress distribution from the center to the surface of the specimen is no longer linear. An ultimate torsional shearing strength, or modulus of rupture, is frequently determined by substituting the maximum measured torque into these equations. The results obtained by this procedure overestimate the ultimate shear stress.

Within the elastic range the shear stress can be considered proportional to the shear strain. The constant of proportionality, G, is the modulus of elasticity in shear, or the modulus of rigidity.

$$\tau = G\,\gamma$$

So,

$$G = \frac{M_T L}{J\theta}$$

TORSIONAL STRESSES FOR LARGE PLASTIC STRAINS

To simplify the analysis, we shall consider the angle of twist per unit length, θ', where θ' = θ/L.

So, γ = rθ'

For the resisting torque in a cross section of the bar, can be expressed as follows,

$$M_T = 2\pi \int_0^a \tau r^2 \, dr$$

Now the shear stress is related to the shear strain by the stress-strain curve in shear.

$$\tau = f(\gamma)$$

Now,

$$M_T = 2\pi \int_0^{\gamma_a} f(\gamma) \, \frac{\gamma^2}{(\theta')^2} \frac{d\gamma}{\theta'}$$

$$M_T(\theta')^3 = 2\pi \int_0^{\gamma_a} f(\gamma)\gamma^2 \, d\gamma$$

where $\gamma_a = a\theta'$

On differentiating,

$$\frac{d}{d\theta'}(M_T\theta'^3) = 2\pi a f(a\theta')a^2(\theta')^2 = 2\pi a^3(\theta')^2 f(a\theta')$$

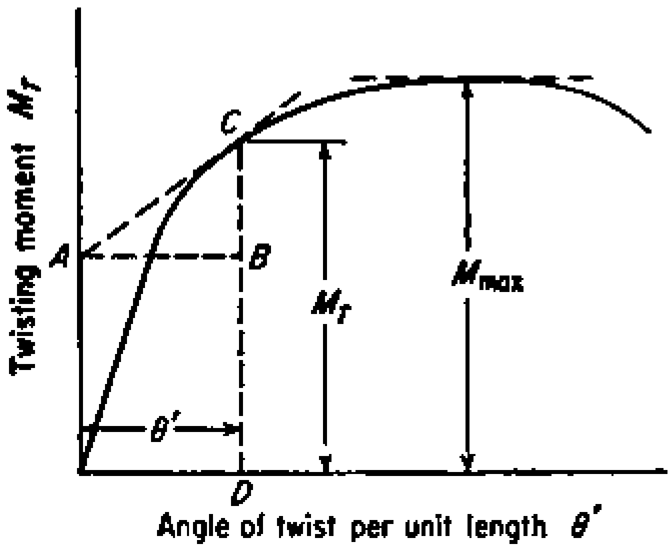
But, the maximum shear stress in the bar at the outer fiber is $\tau_a = f(a\theta')$. Therefore,

$$\frac{d(M_T\theta'^3)}{d\theta'} = 2\pi a^3(\theta')^2\tau_a$$

$$3M_T(\theta')^2 + (\theta')^3\frac{dM_T}{d\theta'} = 2\pi a^3(\theta')^2\tau_a$$

Therefore, $$\tau_a = \frac{1}{2\pi a^3}\left(\theta' \frac{dM_T}{d\theta'} + 3M_T\right)$$ ([redacted])

If a torque-twist curve is available, the shear stress can be calculated with the above equation.



It can be written in terms of the geometry of figure,

$$\tau_e = \frac{1}{2\pi a^3}(BC + 3CD)$$

At the maximum value of torque $dM_T/d\theta' = 0$. Therefore, the ultimate torsional shear strength,

$$\tau_u = \frac{3M_{max}}{2\pi a^3}$$

TORSION TEST VS. TENSION TEST

Tension test	*Torsion test*
$\sigma_1 = \sigma_{max};\ \sigma_2 = \sigma_3 = 0$	$\sigma_1 = -\sigma_3;\ \sigma_2 = 0$
$\tau_{max} = \frac{\sigma_1}{2} = \frac{\sigma_{max}}{2}$	$\tau_{max} = \frac{2\sigma_1}{2} = \sigma_1$
$\epsilon_{max} = \epsilon_1;\ \epsilon_2 = \epsilon_3 = -\frac{\epsilon_1}{2}$	$\epsilon_{max} = \epsilon_1 = -\epsilon_3;\ \epsilon_2 = 0$
$\gamma_{max} = \sinh\frac{3\epsilon_1}{2}$	$\gamma_{max} = \epsilon_1 - \epsilon_3 = 2\epsilon_1$

$$\bar{\sigma} = \frac{\sqrt{2}}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2}$$

$$\bar{\epsilon} = [2/3(\epsilon_1^2 + \epsilon_2^2 + \epsilon_3^2]^{1/2}$$

Tension test	Torsion test
$\bar{\sigma} = \sigma_1$	$\bar{\sigma} = \sqrt{3}\sigma_1$
$\bar{\epsilon} = \epsilon_1$	$\bar{\epsilon} = \frac{2}{\sqrt{3}}\epsilon_1 = \frac{\gamma}{\sqrt{3}}$

CHAPTER- 3

FRACTURE

- Fracture is the separation or fragmentation of solid body into two or more parts under the action of stress is called fracture.
- The process of fracture can be consider to be made of two component.
  - Crack propagation
  - Crack initiation
- Fracture can be classified into two categories,
  - Brittle fracture
  - Ductile fracture

BRITTLE FRACTURE:

- Brittle fracture in metals is characterized by a rapid rate of crack propagation with no gross deformation and very little micro deformation.

It occurs without warning and usually produces disastrous consequence.

DUCTILE FRACTURE:

Ductile fracture is characterized by appreciable plastic deformation prior to during the propagation of crack.

FRACTURE MECHANICS:

- Fracture mechanics shows, how these concept developed into the important tool of engineering analysis called fracture mechanics.
- Fracture mechanics makes it possible to determine whether a crack of given length in a material is known as fracture toughness is dangerous because it will propagate to fracture at a given stress level.
- It also permits the selection of material for resistance to fracture and a selection of the design which is most resistant to fracture.

Fracture mechanics is given by,

$$\sigma p = \sqrt{\frac{2E\gamma s}{\pi c}}$$ Equation (1)

$\sigma s = surface\ energy$

E - Young's modulus

C - Crack length

ORWAN'S MODIFIACTION:

- Griffith theory was modified by organ's to allow for the degree of plasticity always present in the brittle fracture of metal.

According to this approach the fracture stress is

Given by,

$$\sigma f = \varepsilon\sqrt{\frac{(\gamma s + \gamma p)}{c}} \approx \sqrt{\frac{\varepsilon\gamma p}{c}}$$ Equation (2)

E – Young's modulus, σP *- surface energy due to plastic deformation*

IRWIN'S MODIFICATION:

Equation(ii) was modified by irwin's to replace the haqrd to measure γP with a term, that was directly measurable. $\sigma f = \sqrt{\frac{EG}{\pi C}}$ Equation(3)

G – Strain energy realease rate

STRAIN ENERGY RELEASE RATE:

- In this section , we will consider the significance of the strain-energy release rate in grater.
- It is the rate of transfer of energy from elastic field of crack initiation to the plastic stress field of crack propagation.

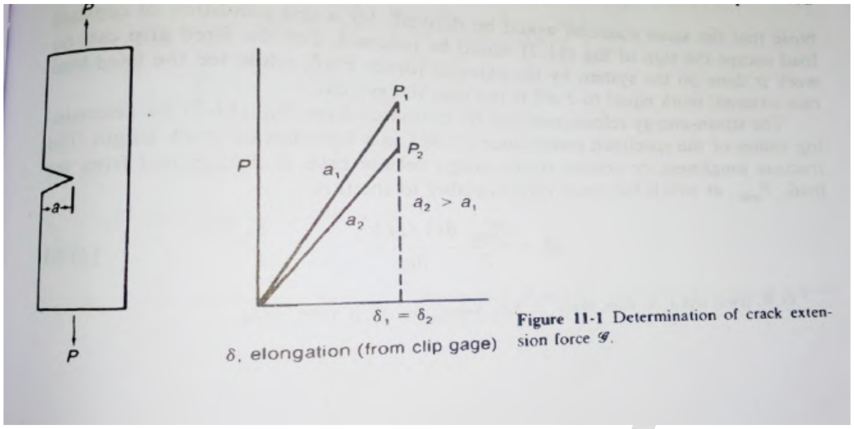


Figure 11-1 Determination of crack extension force 𝒢.

- A single edge-notch specimen is loaded axially through pins
- The sharp possible notch is produced by introducing a fatigue crack at the root of the machine notch.
- Load vs displacement curves are determine for different length notches.

$$P = M\delta$$

$$\delta = \frac{P}{M} \qquad \text{Equation (1)}$$

Where,

M = Stiffness of a specimen with a crack length “a”

Since,

$$U = \frac{1}{2}p\delta = \frac{p^2}{2m} \qquad \text{Equation (2)}$$

Consider, where the specimen is rigidly gripped, so that an increment of crack growth “da” results in a drop in load from p1 to p2.

$$\delta_1 = \delta_2 = \frac{P_1}{M_1} = \frac{P_2}{M_2} \qquad \text{Equation (3)}$$

Since,

P/M = Constant

$$\left(\frac{\partial p}{\partial a}\right)\frac{1}{M} + P\frac{r(\frac{1}{M)}}{ra} = 0$$

$$\frac{\partial p}{\partial a} = - PM\frac{\partial(\frac{1}{M})}{\partial a}$$

The crack extension force is,

G – Strain energy release rate

$$\frac{duo}{dc} = G$$

$$\frac{duo}{dc} = \frac{d}{dc}\left[\frac{1}{2} - \frac{p^2}{M}\right]$$

$$=> \frac{duo}{dc} = \frac{1}{2}\left[\frac{2p}{m}\frac{dp}{dc} + \frac{P^2 d\left(\frac{1}{M}\right)}{dc}\right]$$

$$\boxed{\delta_1 = \delta_2}$$

$$\frac{p_1}{M_1} = \frac{P_2}{M_2} = \frac{P}{M}\ (Constant)$$

$$=> \frac{d}{dc}\left(\frac{p}{M}\right) = 0$$

$$=> \frac{1}{M}\frac{dp}{dc} + \frac{p(d\left(\frac{1}{M}\right))}{dc} = 0$$

$$=> \frac{dp}{dc} = \frac{- PMd(\frac{1}{M})}{dc}$$

Putting the value of $\frac{dp}{dc}$ in equation (i)

$$½\ \left[\frac{2p}{m}\left\{\frac{- pmd(\frac{1}{m})}{dc}\right\} + \frac{P^2 d(\frac{1}{M})}{dc}\right]$$

$$□\ \frac{1}{2}\left[\frac{- 2P^2 d(\frac{1}{M})}{dc} + \frac{P^2 d(\frac{1}{M})}{dc}\right]$$

$$\frac{1}{2}\left[\frac{-p^{2}d(\frac{1}{M})}{dc}\right] = G$$

$$G = \frac{-1}{2}\,\frac{P^{2}d(\frac{1}{M})}{dc}$$ Equation (4)

This is also known as strain energy release rate.

STRESS INTENSITY FACTOR:

- The stress distribution at the crack tip in a thin plate for an elastic solid in terms of the co-ordinates.

Where, $\sigma_x = \sigma(\frac{a}{2r})^{\frac{1}{2}}\,[\cos\frac{\theta}{2}\,(1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2})]$ $\sigma_y = \sigma(\frac{a}{2r})^{\frac{1}{2}}\,[\cos\frac{\theta}{2}$ $(1 + \sin\frac{\theta}{2}\sin\frac{3\theta}{2}]$

$$\sigma_{xy} = \sigma(\frac{a}{2r})^{\frac{1}{2}}\,[\sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}]$$ Equation(1)

$$\sigma = \text{gross nominal stress} = \frac{p}{wt}$$

$$\sigma x = \sigma y = \sigma(a/2r)^{1/2}$$ And

$$\tau_{xy} = 0$$

Irwin's pointed out that, the local stress near a crack depend on the product of the nominal stress (σ) and the square root of the half-flaw length. He called this relationship the stress intensity factor "k" where for a sharp elastic crack in an infinitely wide plate, k is defined as,

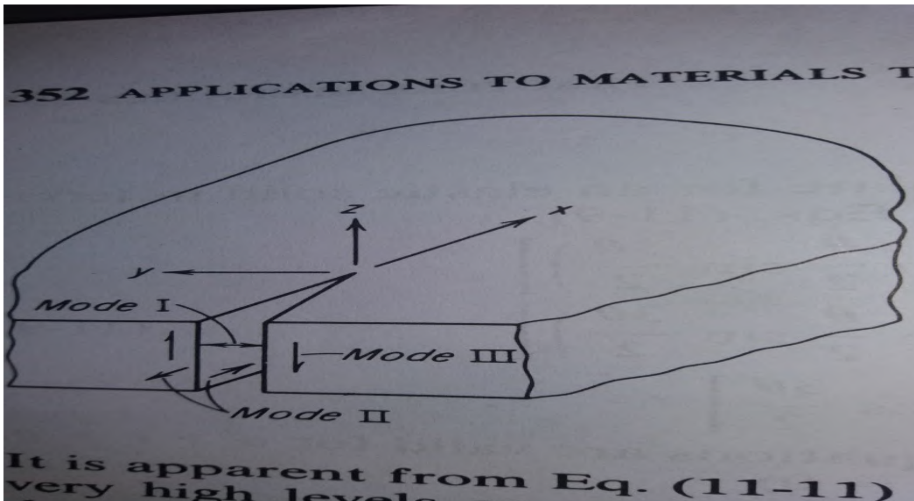
$K = \sigma\sqrt{\pi c}$ Equation (2)

The k has the unusual dimension of MN $m^{-3/2}$,using this defination for k, the equation for the stress field at the end of a crack can be written as,

$$\sigma_x = \frac{k}{\sqrt{2\pi r}}\,[\cos\frac{\theta}{2}\left(1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)]$$

$$\sigma_y = \frac{k}{\sqrt{2\pi r}}[\cos\frac{\theta}{2}\left(1 + \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)]$$

$$\sigma_{xy} = \frac{k}{\sqrt{2\pi r}}[(\sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2} \qquad \text{Equation (3)}$$



- The stress intensity factor k is a convenient way of describing the stress distribution around a flaw,for the general case the stress intensity factor is given by,

$$k=\alpha\sigma\sqrt{\pi a}$$

- Where α is a parameter that depend on the specimen and crack geometry for a plate of width w loaded in tension with a centrally located crack of length 2a.

$$K = \sigma\sqrt{\pi a}(\frac{w}{\pi a} + \tan\frac{\pi a}{w}$$

The stress intensity factor there are several modes of deformation, there are three modes,

Mode-1

- Crack opening mode
- It refers to a tensile stress applied in a y direction normal to the faces of the crack.

K_{IC} - plain strain fracture toughness

$$=> \sigma_c\sqrt{\pi a}$$

Mode-2

Forward shear mode:

It refers to a shear stress applied to the leading edge of the crack.

Mode-3

. Parallel shear mode:- Shearing stress applied parallel to the leading edge of the crack.

- The stress intensity factor "k" is preferred in working with fracture mechanics beacause it is more amenable determination.

PLAIN STRAIN FRACTURE TOUGHNESS TESTING: (K_{IC}):

- In this section , we consider the testing procedure can be used to measure meaningful material properties.
- Typical material are high-strength steel, titanium, and aluminium alloy.
- The magnitude of this stress intensity factor depends on ,
    - Geometry of the solid containing crack is present.
    - Size & Location of crack.
    - Magnitude and distribution of load across the material.
- Plain strain fracture toughness (K_{IC}) can be considered a material property which describes the inherent resistance of the material in the presence of a crack-loke defect.
- For a given type of loading and geometry the relation is given by,

$$K_{IC}=\alpha\sigma\sqrt{\pi a c}$$

α = Geometrical factor

a_c = Critical crack length

- If (KIC) is known ,then it is possible to compute the maximum allowable stress form a given flaw size.
- While KIC is a basic material property in the same sense as yield strength, it change with important variables such as temperature and strain rate.

- For material with strong temperature and strain rate dependence (KIC) usually decreases with decreased temperature and increased strain rate.
- For a given alloy, KIC is strongly dependant on such metallurgical variables as heat treatment, texture, melting practice, impurities, and inclusion.

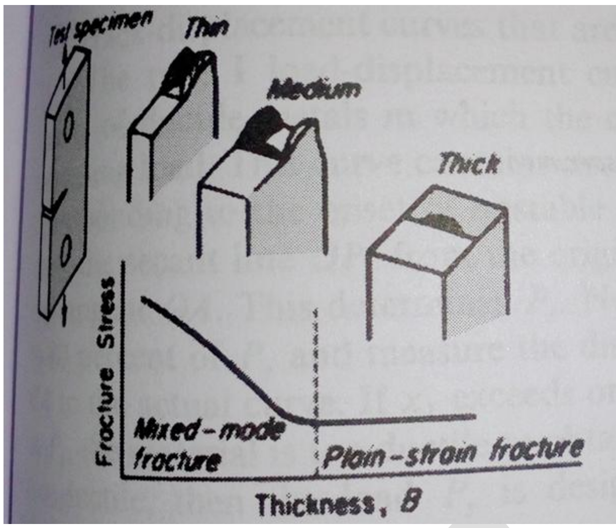


Figure 11-7 Effect of specimen thickness on stre[ss] and mode of fracture. *(From C. C. Osgood, Machi[ne] Design, August 5, 1971, p. 91.)*

- The fracture toughness measured under plain strain condition is obtained under maximum constraint or material brittleness.
- The plain-strain fracture toughness to achieve plain strain condition and valid KIC and is a true material property .
- The minimum thickness to acheive plain strain condition and valid KIC measurement is,

$$B=2.5\left(\frac{KIC}{\sigma_0}\right)^2$$

σ_0 = *OFFSET YIELD STRENGTH*

- A variety of specimen have been proposed for measuring (KIC) plain strain fracture toughness.
- The three specimen represent the most common specimen design.
- The compact tension specimen design are the single-edge-cracked plate.
- After the notch is machined in the specimen ,the sharpest possible crack is produced at the notch root by fatiguuing the specimen in a loe-cycle,high dtrain mode.

- The test must be carried out in a testing machine which provides for a contineous autographic record of load(p) anbd relative displacement across the open end of the notch(propertional to crack displacement).
- The three types of load-crack-displacement curves ,that are obtained for material.

Type-1

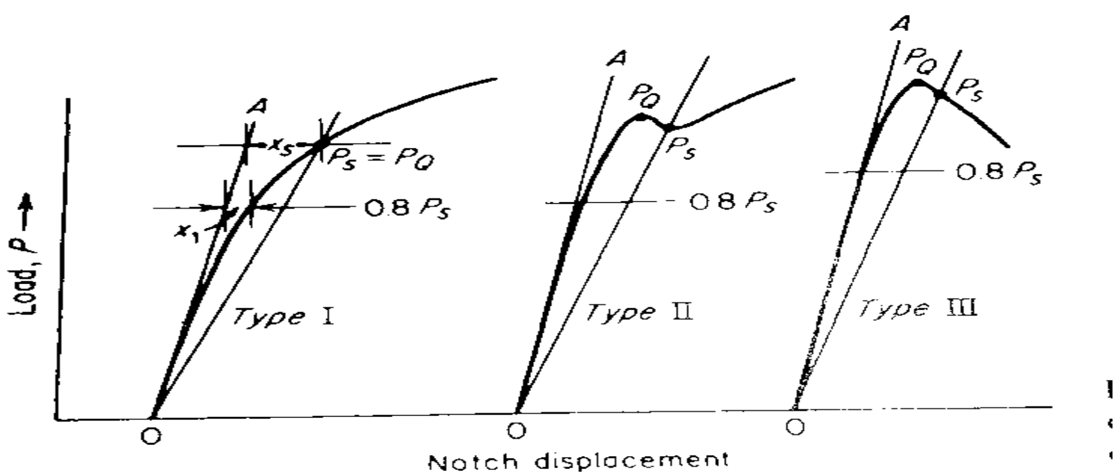
Load-displacement curve represents the behaviour for a wide variety of ductile metal in which the crack propagates by a tearing mode with increasing load.

Type-2

Load – displacement curve has a point where there is a sharp in load followed by a recovery of load.   .

Type-3

Curve shows complete “pop” in instability,where the initial crack movements propagate rapidly to complete failure.



FRACTURE TOUGHNESS & DESIGN:

A properly determined value of KIC, represents the fracture toughness of the material independent of crack length.

- It is a material property in the same sense that yield strength is a material property.

The basic equation for fracture toughness that is

inherent in fracture mechanics design.

Kic = $\sigma\sqrt{\pi a}$

- If the material is selected (kic) is fixed further , if we allow for fthe presence of a relatively large stable crack,then the design stress is fixed and must be less then (kic).

- If the system is such that high strength and light weight are required (kic) is fixed ,because of limited material with low density and high fracture toughness and stress level must be kept high because of the need to maximized payload.

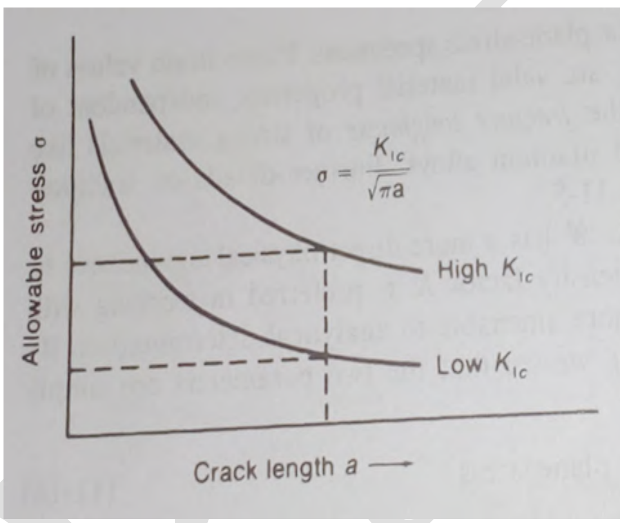


Figure 11-4 Relation between fracture toughness and allowable stress and crack size.

- These tradeoff'S between fracture toughness, allowable stress ,and crack size are illustrated.

CHAPTER- 3

FATIGUE OF METALS

FATIGUE

- The term fatigue is borrowed from human reaction of ‘tiredness’ due to repetitive work.
- When a metal is subjected to a repetitive or fluctuating stress, it will fail at stress much lower than the required to cause fracture on a single application of load i.e. nominal maximum stress is lower than UTS or yield stress limit.
- Failures occurring under the condition of dynamic loading are called fatigue failure.
- Fatigue is a progressive and localized structural damage that occurs when. Material is subjected to cyclic or dynamic loading e.g.: fatigue is generally observed in bridge, automobile, machine parts, compressor etc.
- A fatigue failure occurs without any warning and results in a brittle -appearing fracture, with no gross deformation at the fracture.
- This failure usually occurs at a point of stress concentration such as sharp corner, notch or inclusion. This is because when the applied load is above a certain value then microscopic cracks will start to form at the stress concentration and these cracks will eventually reach to a critical size, the crack will propagate suddenly and the structure crack will propagate suddenly and the structure will fracture.
- The fatigue fracture surface is usually normal to the direction of the principal tensile stress.
- The fracture surface is usually shows a smooth region because of the rubbing action (due to crack propagation) and a rough region (where it has failed in a ductile manner when the cross section was no longer able to carry the load).
- Fatigue failure progression is as series of rings / beach marks, progressing inward from the point of initiation of failure.

Three basic factor are necessary for fatigue failure are:-

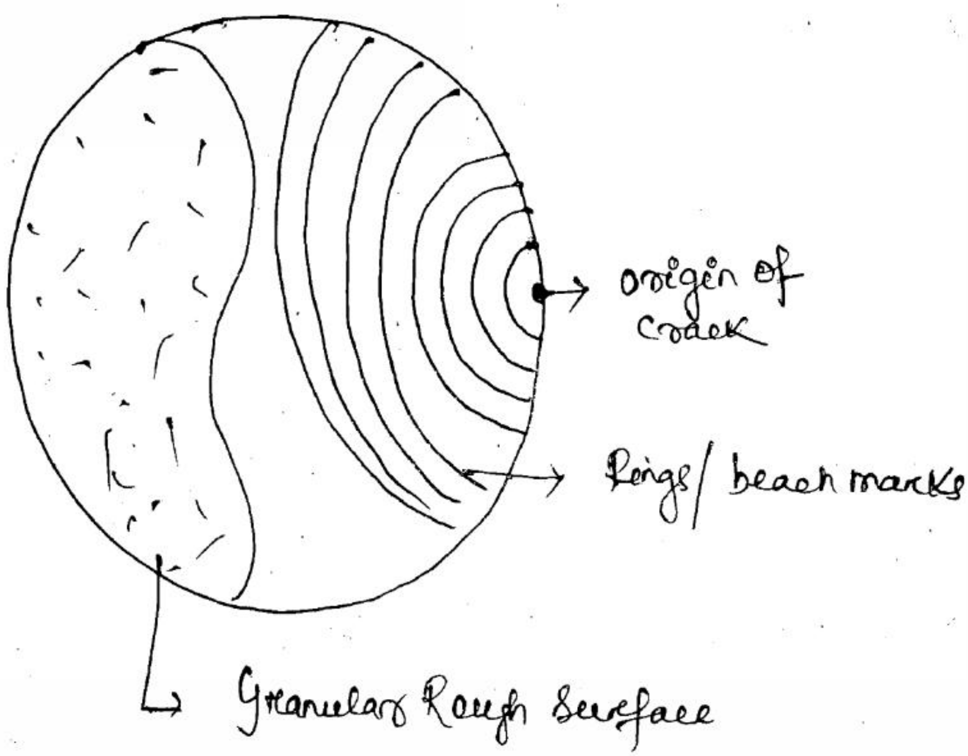


fig: fatigue fracture surface

1. A max tensile stress of high value
2. A large enough variation or fluctuation in applied stress.
3. Large no of cycles of the applied stress.

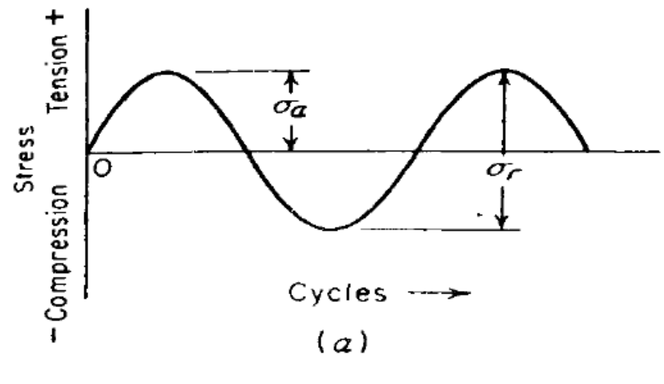
Variables affecting fatigue failure are:

1) Stress concentration
2) Corrosion
3) Temperature
4) Overload
5) Metallurgical structure
6) Residual and combined stress

Stress cycle:

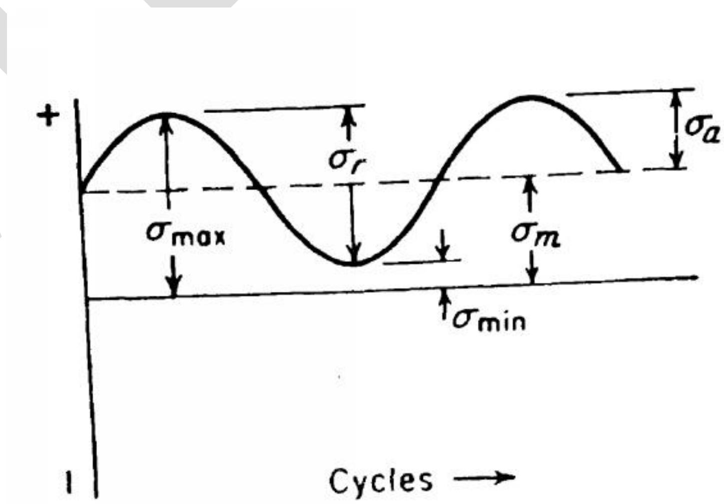
There are 3 general type of fluctuating stress which can cause fatigue

Reversed stress cycle:



- The above fig illustrates a completely reversed cycle of stress of sinusoidal form.
- This in an idealized situation, produced by R.R Moore rotating beam fatigue machine.
- In this stress cycle σ max (maximum stress) and σ min (minimum stress) are equal, where σ min is the algebraically lowest stress.
- Tensile stress is positive i.e. σ max and compressive stress is -ve i.e. σ min.

Repeated stress cycle:

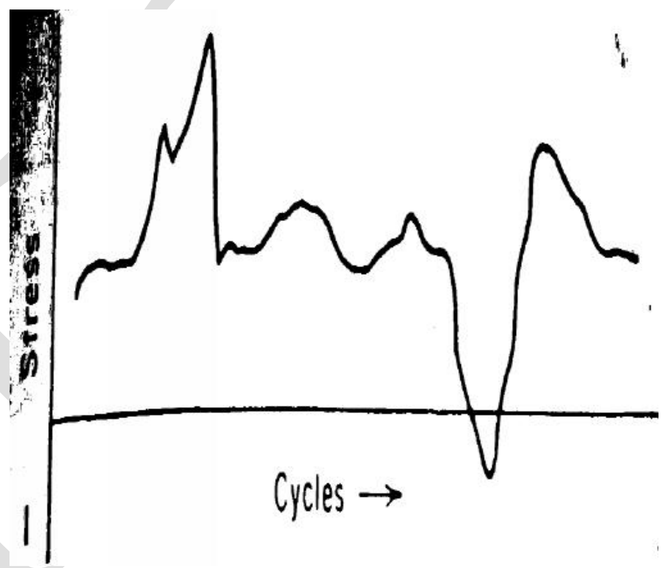


- It is the cycle of stress in which σ min and σ max are unequal i.e. they are asymmetrical relative to σ=0.
- The above diagram illustrates the σ max and σ min are both in tension, this can also be done in compression too.

Random /complicated stress cycle:

- It I generally encountered in a part of aircraft using which is subjected to periodic unpredictable overloads due to gust (sudden run rush of wind).
- it is less easy to quantify.

Components of fluctuating stress cycle:



- A fluctuating stress cycle is made up of two components

1. A mean or steady stress 'σm' and
2. an alternating or variable stress 'σa'

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:

- The basic method of presenting the engineering fatigue data is the S-N curve.
- S-N curve is a plot of stress’s’ against the no of cycles to failure 'N' in a log-log scale.
- The stress can be σ max, σ min or σ_a.
- S-N relationship is determined for a specific value of σ_a, R, A.
- S-N chiefly deals with the fatigue failure at high number of cycles i.e N> 10^5, where the stress is normally elastic but some amount of plastic deformation is also seen in highly localized way. These are called high cycle fatigue.
- At high stress fatigue life is decreased progressively.

Low cycle fatigue: (N<10^4or 10^5)

- Here low cycle fatigue tests are conducted in controlled cycles of elastic +plastic strain (called strain controlled mode, instead of stress controlled).

Types of S-N curve:

Broadly there are 2 kinds of S-N curve on the basis of their fatigue life

S-N curve having a true fatigue limit:

- Those where a stress below a threshold value gives a "very long life". This stress value is called fatigue limit or endurance limit.
- The S-N curve becomes horizontal at those stresses.
- Fatigue limit/endurance limit: defined as the maximum amplitude of stress below which the material can sustain unlimited no of cycles without fatigue failure.

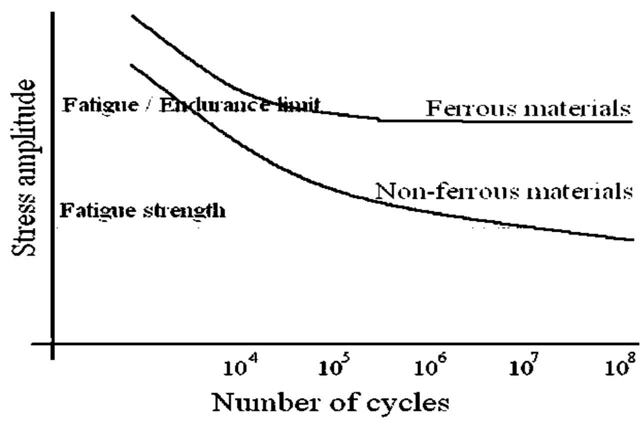


Figure-8.8: *Typical S-N curves for ferrous and non-ferrous metals.*

- Steel and titanium falls under this category at 10^6 cycles.

S-N curve without a true fatigue limit

- Nonferrous metals like AL, cu alloy falls under this category.
- In this the S-N curve has gradually downward slope with increase in the no of cycles.
- So, these materials don't have true fatigue limit because S-N curve never becomes horizontal.
- They don't have distinct fatigue life.
- Fatigue life: is defined as the no of stress cycle that the standard specimen can complete during a test before the appearance of the first fatigue crack.
- Fatigue properties are calculated by giving an arbitrary no of cycles.

The S-N curve in the high-cycle region is sometimes described by the Basquin equation:

$$N\sigma_a^p = c$$

Where σ_a is the alternating stress or stress amplitude and p and C are empirical constants.

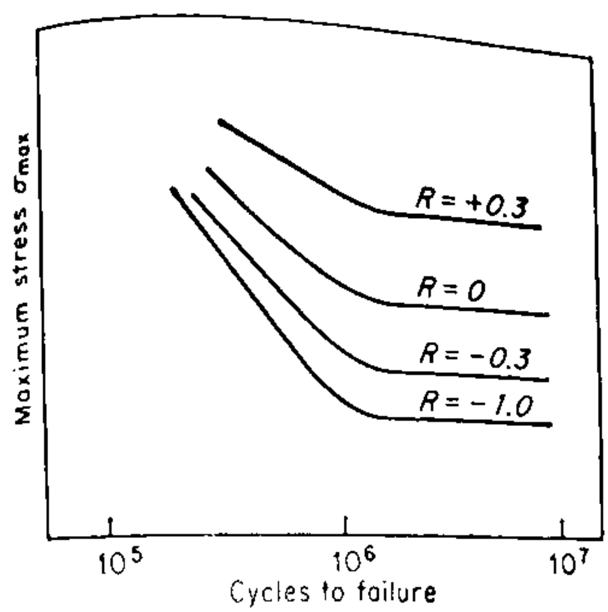
Fatigue limit: highest stress at which a runout (non-failure) is obtained is also called as fatigue limit.

Note: It will be generally found that there is a considerable amount of scatter in the results.

Thus fatigue life and fatigue strength are considered as statistical quantities. It has been observed that scatter in fatigue life decreases with increase in stress. The statistical problem of accurately determining the fatigue limit is complicated by the fact that complete S-N curve cannot obtainable using a single specimen as specimen cannot be rested during the test.

EFFECT OF MEAN STRESS:

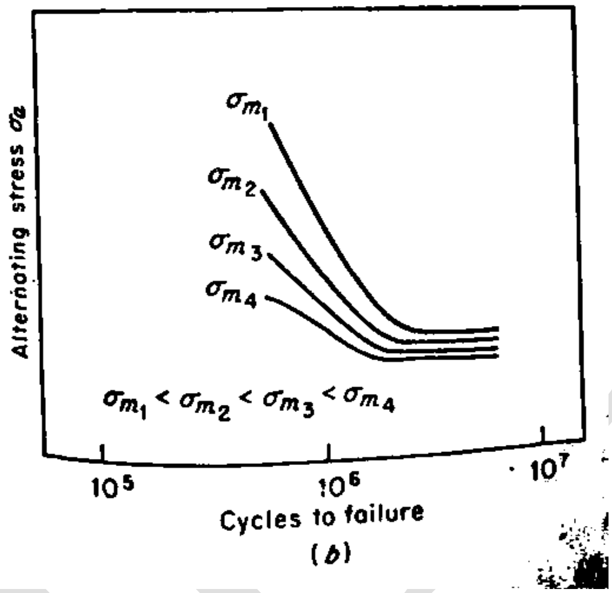
- Most of the engineering practices meet the fatigue test when σ_m= 0
- There are several methods of determining the S-N diagram for a situation where mean stress is not zero. The two most commonly practiced methods are:
  1) S-N can be obtained by plotting data against log N for constant values of stress ratio R= σ min/σ max.
  - Here R=-1.0 gives the condition of completely reversible stress (σ max = -σ min, R= σ min/σ max = -1)
  - When R increases, σ_m increases thus fatigue limit increases.



(a)

2) S-N curve is also obtained by plotting alternativestress σ_a vs N at constant values of mean stress.

 Here σm becomes positive when σa decreases.



GOODMAN'S DIAGRAM:

- For each value of σ_m there is a different value of limiting range of stress, σ max - σ min without undergoing failure.
- This problem was earlier lighted by Goodman.
- The curves which show the dependence of limiting range of stress on mean stress are frequently called Goodman diagram.
- The Goodman diagram presents the dependence of allowable stress ranges on mean stress

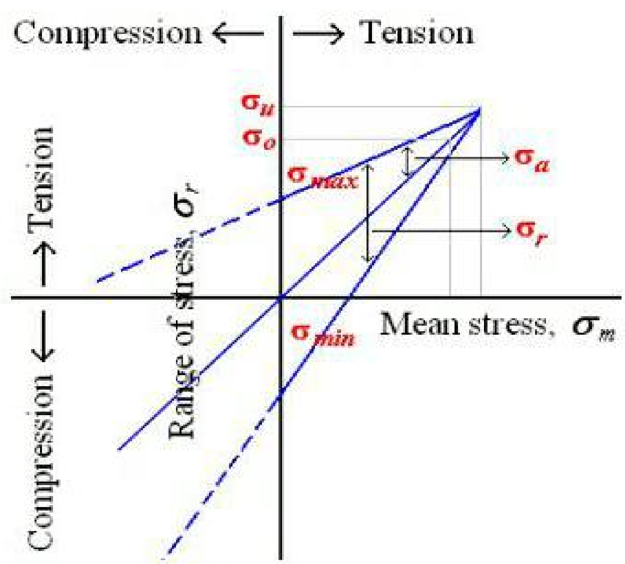
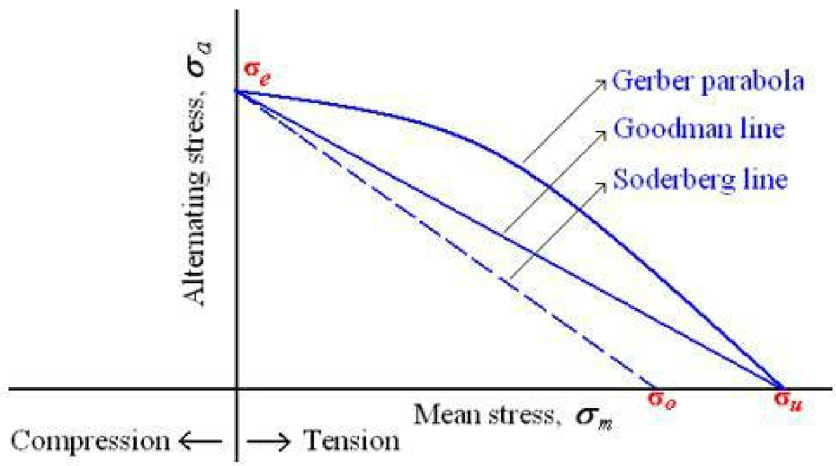


Figure-8.11: *Goodman diagram.*

- Allowable stress range increases with increasing compressive mean stress i.e. compressive stress increases the fatigue limt.

HEIG-SODERBERG DIAGRAM:



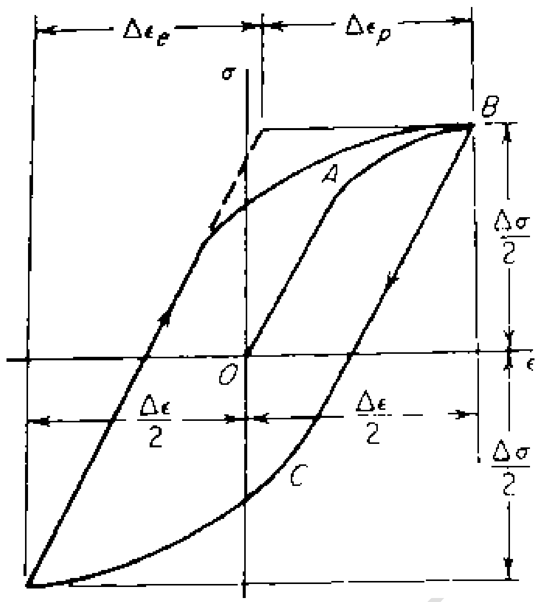
- An alternative method of presenting mean stress data is by using Heig-Soderberg diagram in which alternating stress is plotted against the mean stress.
- Goodman's criterion appears as a straight line. Test data for ductile metals, however, follows parabolic curve proposed by Gerber. Both these criteria can be expressed as:

$$\sigma_a = \sigma_e[1-(\sigma_m/\sigma_u)^x]$$

Where x=1 for Goodman line, x=2 for the Gerber parabola, and σe is the fatigue limit for completely reversed loading. Soderberg line presents the data when the design is based on yield strength (σ_0).

Cyclic stress vs cyclic strain:

- Cyclic strain control complements cyclic stress characterization: applicable to thermal fatigue, or fixed displacement conditions.
- Cyclic stress-strain testing defined by a controlled strain range, Δep
- Soft, annealed metals tend to harden; strengthened metals tend to soften.
- Thus, many materials tend towards a fixed cycle, i.e. constant stress, strain amplitudes.



$\Delta \varepsilon_e$ = strain in elastic region $= \Delta\sigma / E$

$\Delta \varepsilon_p$ = strain in plastic region

Cyclic stress-strain curve:

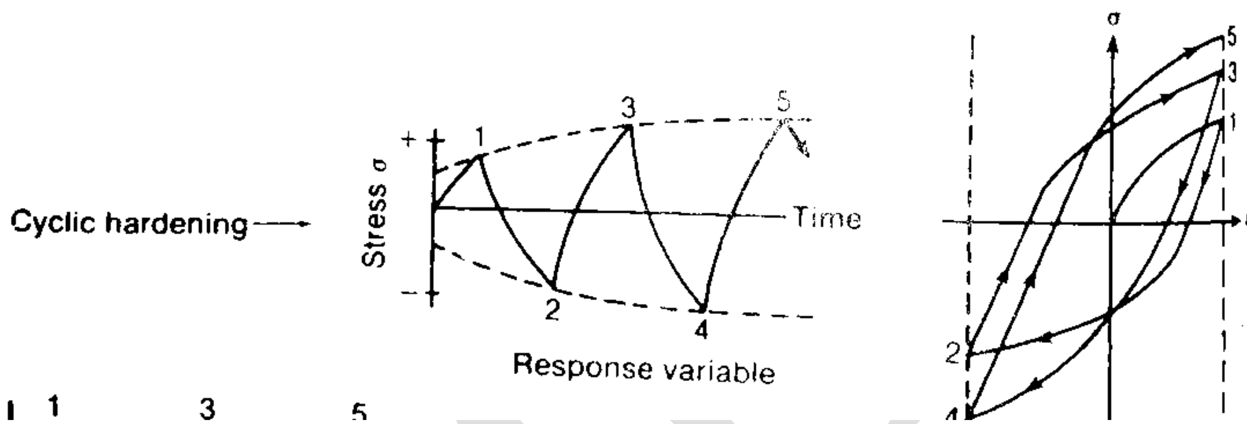
- The above diagram illustrates a stress strain loop under controlled constant strain cycling.
- During initial loading the stress strain curve is O-A-B.
- On unloading yielding begins in compression at lower stress c due to bauschinger effect.
- In reloading in tension a hysteresis loop develops.
- Width of the hysteresis loop is given by Δe (total strain range) and Δ σ(stress range).
- The width of the hysteresis loop depends on the level of cyclic strain.

$$\Delta \varepsilon_e = \frac{\Delta \sigma}{E}$$

$$\Delta \varepsilon = \Delta \varepsilon_e + \Delta \varepsilon_p$$

Depending on the initial state a material may undergo:

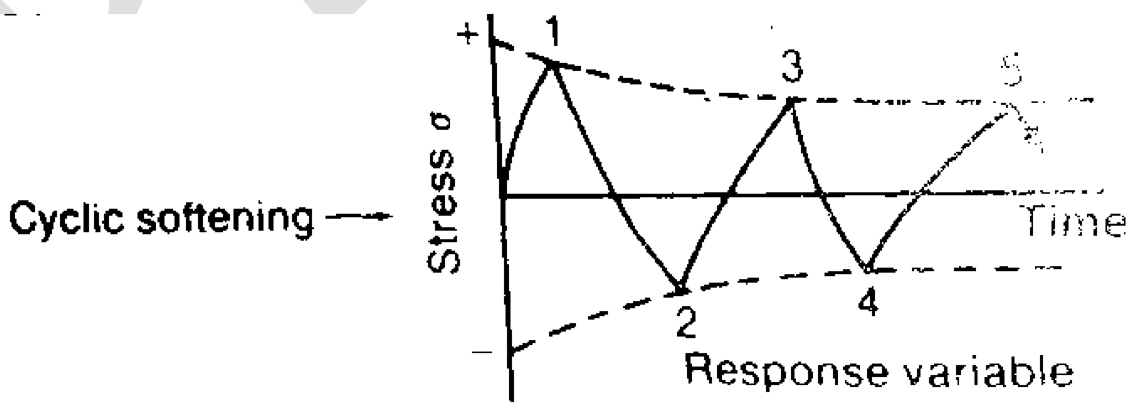
1) cyclic hardening
2) cyclic softening

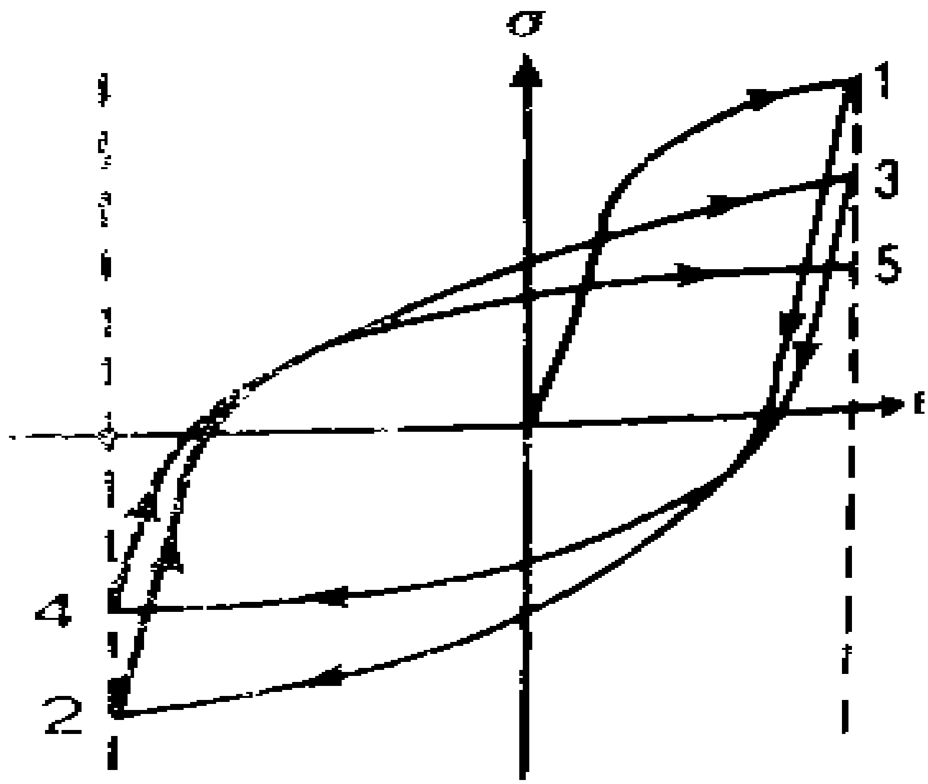


Cyclic hardening:

- cyclic hardening would lead to a continually decreasing peak strain strange with increasing no of cycles
- strain decreases ,so the metal becomes harder

Cyclic softening:





- Here the strain increases even after unloading
- So the metal becomes more softer
- Cyclic hardening or cyclic softening depends on the initial state of the material.
- If the metal is initially harder it will undergo cyclic hardening and vice-versa.

for normal stress- strain curve $\sigma = K\varepsilon^{n}$

for cyclic stress- strain curve $\Delta\sigma = K'(\Delta\varepsilon_p)^{n}$

$$\therefore \Delta\sigma = K'(\Delta\varepsilon_p)^{n'}$$

$$\frac{\Delta\sigma}{\Delta\varepsilon_e} = E$$

$$\Delta\varepsilon_p = \left(\frac{\Delta\sigma}{K}\right)^{1/n'}$$ → (which is not valid)

So,

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2}$$

$$\frac{\Delta\varepsilon}{2} = \frac{1}{2}\left(\frac{\Delta\sigma}{E}\right) + \frac{1}{2}\left(\frac{\Delta\sigma}{K}\right)^{\frac{1}{n'}}$$

↳ valid for curve equation

So:

For metal n' varies from 0.10 to 0.20

Monotonic and cyclic stress strain curve:

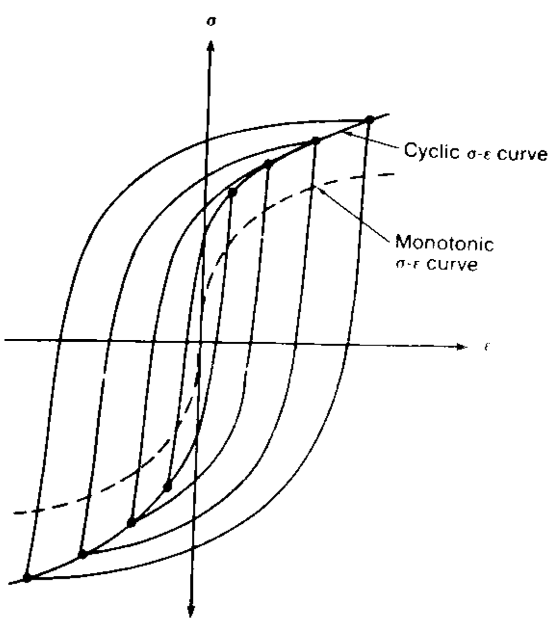


Figure 12-12 Comparison of monotonic and cyclic stress-strain curves for a material that cyclic hardens. Points on cyclic stress-strain curve represent tips of stable hysteresis loops.

- Wavy-slip materials generally reach asymptote in cyclic stress-strain: planar slip materials (e.g. brass) exhibit history dependence.
- Cyclic stress-strain curve defined by the extrema, i.e. the “tips” of the hysteresis loops.
- Cyclic stress-strain curves tend to lie below those for monotonic tensile tests.
- Polymers tend to soften in cyclic straining.

Low cycle fatigue:

- Occurs when $N<10^4$ no of cycles i.e. at high stress
- This type of failure is considered in the design of nuclear pressure vessels, steam turbine and power machinery.
- In this case fatigue results from cyclic strain rather than cyclic stress due to thermal expansion.
- Low cycle fatigue data are a plot of plastic strain range and N.
- And the resultant is a straight line when plotted in log -log scale.

$$\frac{\Delta \epsilon_p}{2} = \epsilon'_f (2N)^c$$

$\frac{\Delta \epsilon_p}{2}$ = plastic strain amplitude

ϵ'_f = fatigue ductility coefficient

$2N$ = No of strain reversal to failure

N = No of cycles to failure

c = fatigue ductility exponent

→ Stress is high in low cycle because

$$N \sigma_p^{a} = C$$

$$N \propto \frac{1}{\sigma}$$

→ eqn of low stress :-

$$\frac{\Delta \epsilon}{2} = \frac{1}{2}\left(\frac{\Delta \sigma}{E}\right) + \frac{1}{2}\left(\frac{\Delta \sigma}{K'}\right)^{1/n'}$$

→ Here the straining takes place by thermal effect → ie thermal expansion → so straining

- This is well explained by coffin -Manson relations

STRAIN-- LIFE EQUATION:

- It is the modified version of Basquins equation

- For high cycle (low strain) regime, where the nominal strains are elastic, Basquins equation

Modification of Basquin Equation

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f'}{E}(2N)^b + \varepsilon_f'(2N)^c$$

In order to calculate the critical value of the no of cycles to failure, both of the elastic strain amplitude and plastic strain amplitude must be equal.

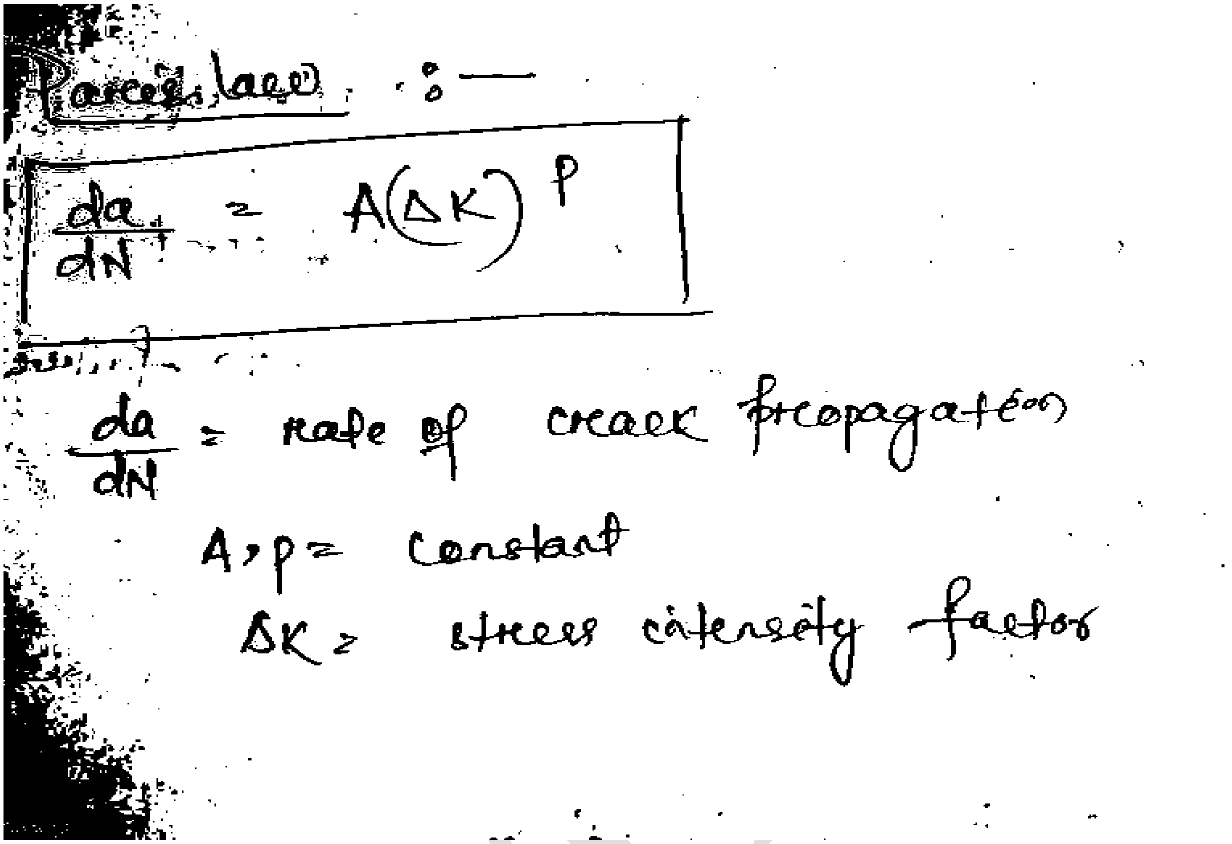
i.e $$\frac{\sigma_f'}{E}(2N)^b = \varepsilon_f'(2N)^c$$

$$\Rightarrow (2N)^{b-c} = \frac{\varepsilon_f' \cdot E}{\sigma_f'}$$

$$\Rightarrow 2N = \left(\frac{\varepsilon_f' \cdot E}{\sigma_f'}\right)^{1/b-c}$$

$$\Rightarrow N = \frac{1}{2}\left(\frac{\varepsilon_f' \cdot E}{\sigma_f'}\right)^{1/b-c}$$

is reformulated.



PARIS LAW:

Factors that affect fatigue life:

1) Mean stress and cyclic stress: Depending on the complexity of the geometry and the loading, one or more properties of the stress need to be considered, such as stress amplitude, mean stress, biaxiality, in phase or out of phase shear stress and load sequence. Increasing the mean stress levels leads to a decrease in fatigue life.
2) Surface effects: surface roughness can cause microscopic stress concentration that lower the fatigue strength.
3) Design factors: notches and variations in cross section throughout a part lead to stress concentration .the probability of fatigue failure can be reduced by avoiding these structural irregularities or by making suitable design modification.
4) Surface treatment: improving the surface finish by polishing, enhances the fatigue life is significantly increased.

CHAPTER- 4

CREEP

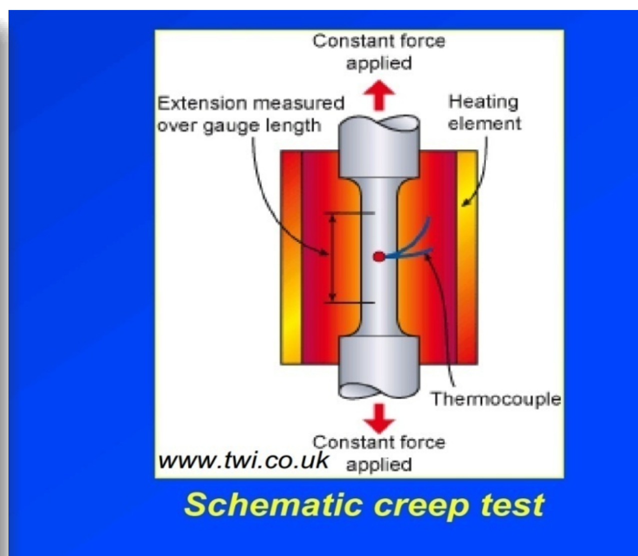
CREEP- when a metal is subjected to a constant tensile load at an elevated temperature will undergo a time dependent increases in length.

- The continuous change in the deformation of material at elevated temperature when stress is applied below yield point.
- Creep is a time-dependent deformation of a material while under an applied load that is below its yield strength.
- Material have its own melting point so temperature is not constant for all since each will creep when homologous temperature > 0.5 (homologous temperature= testing temperature/ melting temperature)

STRESS- RUPTURE- is a sudden and complete failure of a material held under a definite constant load for a given period of time of a specific temperature.

CREEP TEST- measure the dimensional change of a metal which occur when subjected to high temperature (according to ASTM E139-70)

Creep test setting



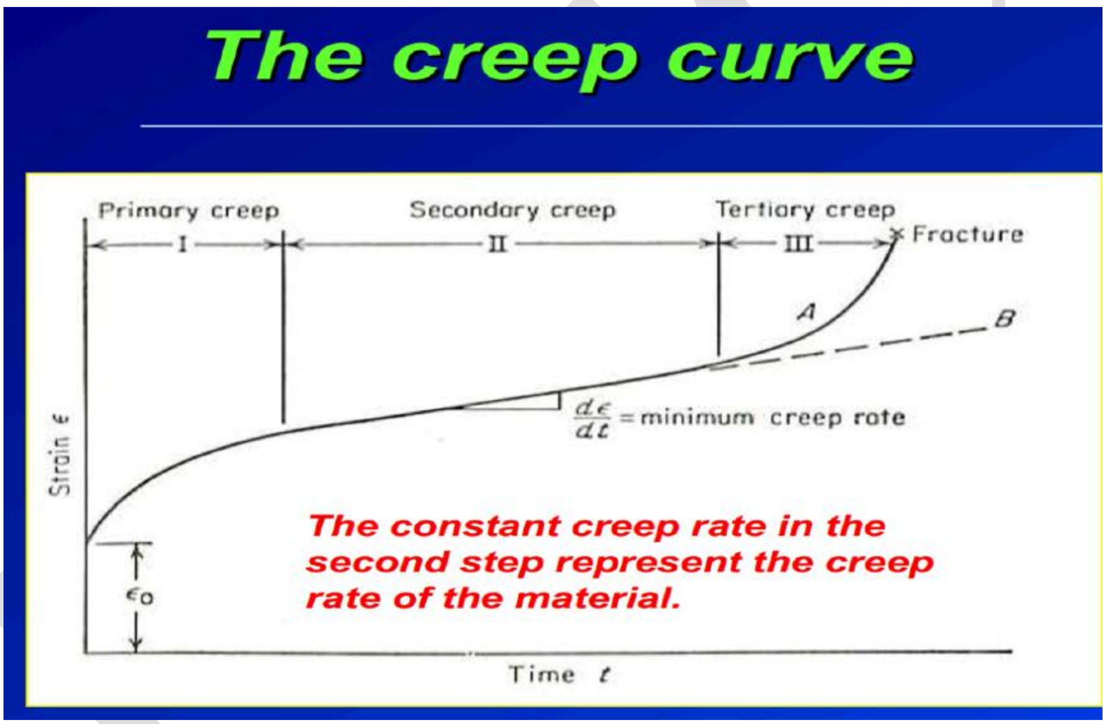
Schematic creep test

STRESS-RUPTURE TEST- measures the effect of temperature on the long time load bearing characteristics.

HIGH TEMPERATURE MATERIALS PROBLEM

- Atom move faster →diffusion-controlled process. This affects mechanical properties of materials.
- Greater mobility of dislocation (CLIMB)
- Increased amount of vacancies.
- Deformation at grain boundaries.
- Metallurgical changes, i.e., phase transformation, precipitation, oxidation and recrystallization.

CREEP CURVE



Note: B curve is obtained when the stress rather than the load is maintained

- A typical creep curve shows three distinct stages with different creep rates. After an initial rapid elongation ẹ, the creep rate decreases with time until reaching the steady state
- THREE STAGES- .
  1) Primary creep (Decreasing creep rate)
  2) Secondary creep (constant creep rate)

3) Tertiary creep (rapid creep rate)

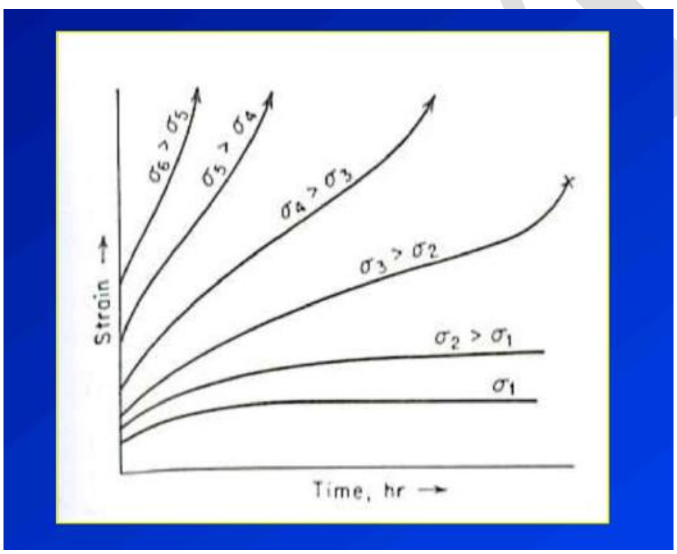
PRIMARY CREEP- primary creep is a period of transient creep. The creep resistance of the material increases due to material deformation. Predominate at low temperature test such as in the creep of lead RT. It has decreasing strain rate.

SECONDARY CREEP- provides a nearly constant creep rate. The average value of the creep rate during this period is called the minimum creep rate/ steady creep. There is a balance occur between strain hardening and recovery.

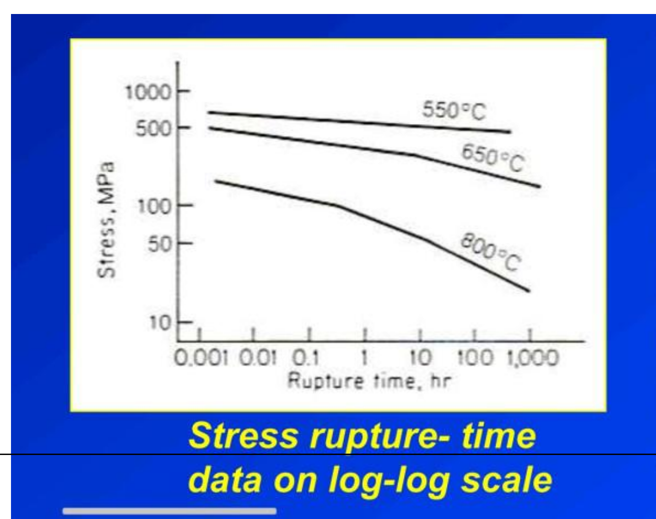
TERTIARY CREEP- shows a rapid increase in the creep rate due to effectively reduced cross sectional area of the specimen. Strain rate increases continuously up to the fracture; stress is high with increasing temperature.

This is also associated with the metallurgical change such as coarsening of precipitate particle, recrystallization, or diffusional change in the phases that are present.

EFFECT OF STRESS ON CREEP CURVES AT CONSTANT TEMPERATURE



The shape of creep curve will change according to the applied stress at constant temperature.

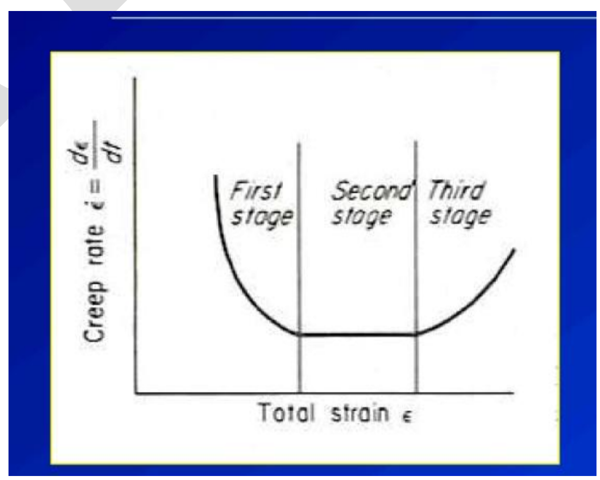


STRESS-RUPTURE TEST-The rupture test in carried out in a similar manner to the creep test but at a higher stress level until the specimen fails and the time at failure is measured.

- Rupture strength and failure are plotted, normally showing a straight line.
- Changing of the slope indicate structural change in the material, i.e., transgranual → intergranular fracture , oxidation, recrystallization, grain growth, spheroidization, precipitation
- Direct application in design.

Creep test	Stress rupture test
Minimum creep rate	high creep rate
2000h-10000h	1000h
0.5%strain	50%strain
Low load	high load

STRUCTURAL CHANGE DURING CREEP



Different creep rates result from changes in internal structure of the materials with creep rate and time.

There are three principal deformation processes at elevated temperature

1) **Deformation by slip**
   - more slip systems operate at high temperature
   - slip bands are coarser and widely spaced
2) **Sub grain formation**
   - Creep deformation produces inhomogeneity especially around grain boundaries, to arrange themselves into a low-angle grain boundary folding or grain boundary migration.

3) **Grain boundary sliding**

- Temperature or decreasing strain rate.
- Results in grain boundary folding or grain boundary migration.

MECHANISMS OF CREEP DEFORMATION

The chief creep deformation mechanisms can be grouped into;

1) DISLOCATION GLIDE

It is a dislocation motion along a crystallographic direction is called glide or slip. As a result such dislocation motion through a crystal, one part of the dislocation moves one lattice point along a plane known as the slip plane, relatively to the rest of the crystal.

Dislocation glide allows plastic deformation to occur at a much lower stress than would be required to move a while plane of atoms past another. Creep resulting from a dislocation glide mechanism occurs at stress level which is high relative to those normally considered in creep deformation.

2) DISLOCATION CREEP

It is a deformation mechanism in crystalline materials. Dislocation creep involves the movement of dislocations through the crystal lattice of the material. It causes plastic deformation of the individual crystals and in the end the materials itself''. Dislocation creep occurs by dislocation glide aided by vacancy diffusion.

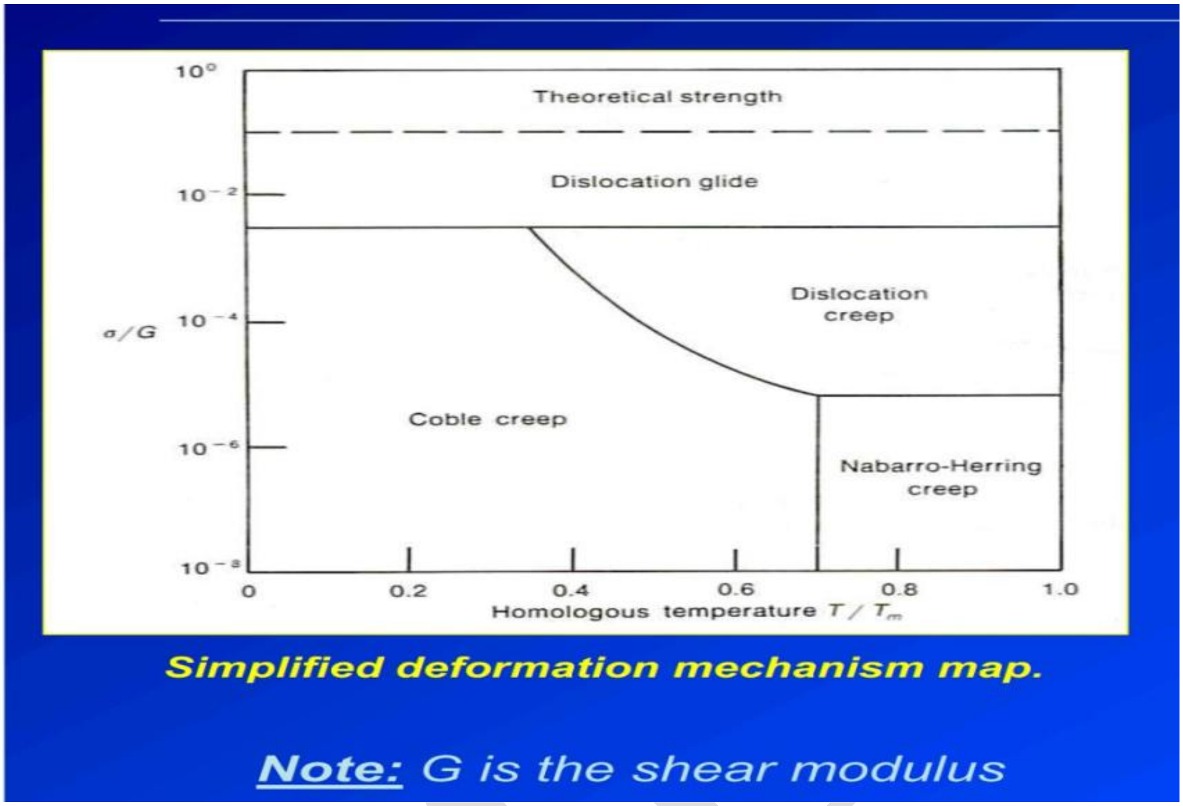
3) DIFFUSIONAL CREEP

It refers to the deformation of crystalline solids by the diffusion of vacancies through their crystal lattice. Diffusion creep results in plastic deformation rather than brittle failure of the material. Diffusion creep is more sensitive to temperature than deformation mechanisms.

4) GRAIN BOUNDARY SLIDING

It is a deformation mechanism of materials which includes displacement of grains against each other at high homologous temperature and low strain rate. This mechanism is the main reason of ceramics failure at high temperatures due to deformation of glassy phase in their grain boundary.

DEFORMATION MECHANISM MAPS

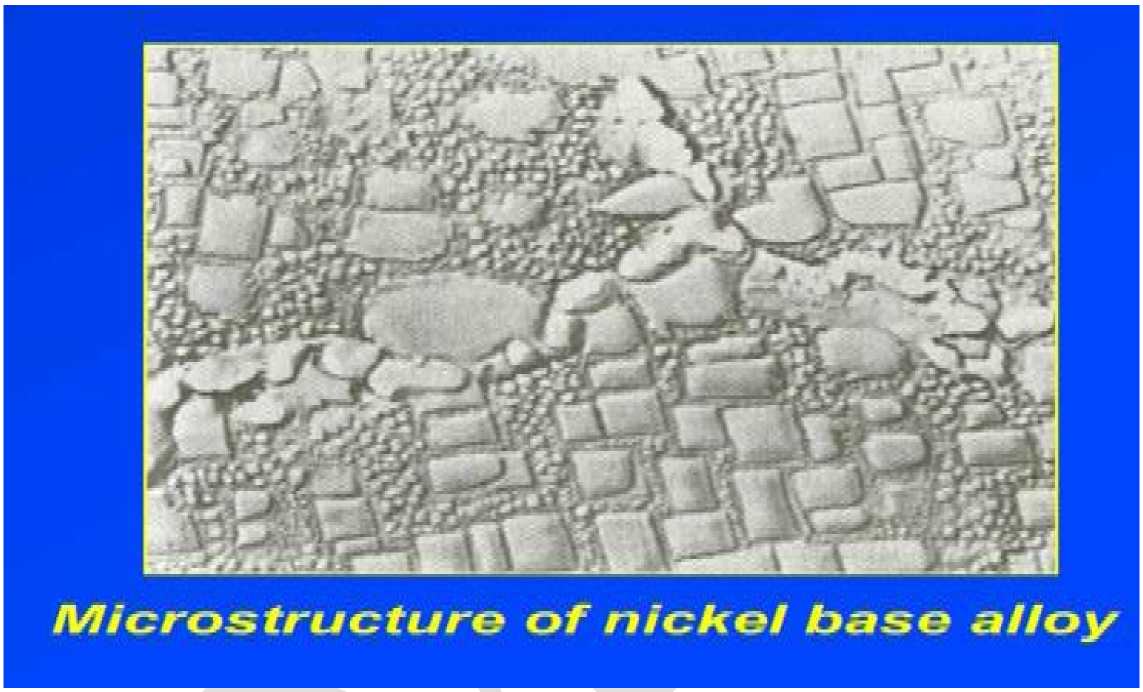


- The various regions of the map indicate the dominant deformation mechanism for the combination of stress and temperature.
- The boundaries represent combination of stress and temperature where the respective strain rates for the two deformation mechanism are equal.
- At a homologous temperature of 0.8 and a low stress the deformation occurs by diffusion flow (Nabarro- herring creep).keeping the temperature constant and increasing the stress we enter a region of power- law creep(dislocation creep) and at still higher stress the metal deform by thermally activated dislocation glide. The upper bound on the diagram is the stress to produce slip in a perfect (dislocation free). A deformation mechanism map involves in pedagogical tool and in alloy design and selection.

HIGH TEMPERATURE ALLOYS

- High temperature alloys are complex in their microstructure to obtain the properties at service temperature.
- High melting point alloys normally has high creep resistance.

- Metals with high stacking fault energy→ easy for cross slip resistance.
- Fine precipitates having high thermal stability are necessary for high creep resistance (prevent grain growth)
- EX-



The development of high-temperature alloys has, in the main. Been the result of painstaking empirical investigation, and it is really only in retrospect that principle underlying these developments have become evident.

- The nominal composition of a number of high temperature alloys is given in table.

COMPOSITION OF SOME HIGH TEMPREATURE ALLOYS

Table 13-2 Compositions of some high-temperature alloys

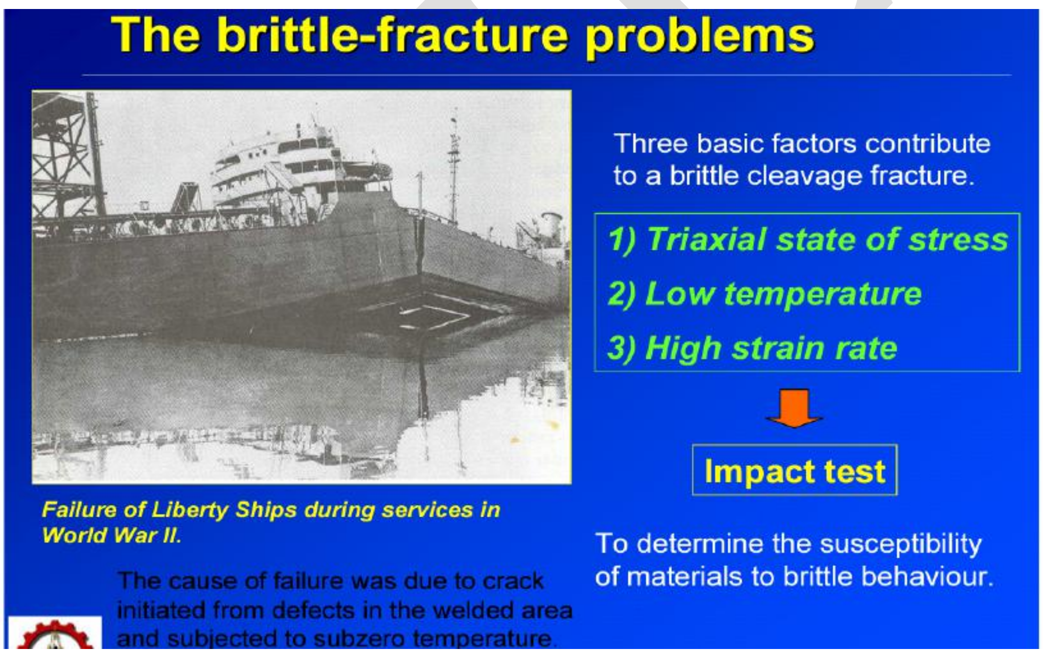
Alloy	C	Cr	Ni	Mo	Co	W	Cb	Ti	Al	Fe	Other
Ferritic steels											
1.25 Cr-Mo	0.10	1.25	—	0.50						Bal.	
5 Cr-Mo	0.20	5.00	—	0.50						Bal.	
Greek Ascoloy	0.12	13.0	2.0			3.0				Bal.	
Austenitic steels											
316	0.08	17.0	12.0	2.50						Bal.	
16-25-6	0.10	16.0	25.0	6.00						Bal.	
A-286	0.05	15.0	26.0	1.25				1.95	0.2	Bal.	
Nickel-based alloys											
Astroloy	0.06	15.0	56.5	5.25	15.0			3.5	4.4		
Inconel	0.04	15.5	76.0							7.0	
Inconel 718	0.04	19.0	Bal.	3.0			5.0	0.80	0.60	18.0	
René 41	0.10	19.0	Bal.	10.0	11.0			3.2	1.6	2.0	
Mar-M-200	0.15	9.0	Bal.	—	10.0	12.5	1.0	2.0	5.0		
TRW 1900	0.11	10.3	Bal.	—	10.0	9.0	1.5	1.0	6.3		
Udimet 700	0.15	15.0	Bal.	5.2	18.5			3.5	4.25	1.0	
In-100	0.15	10.0	Bal.	3.0	15.0			4.7	5.5		1.0 V
TD Nickel	—	—	Bal.								2.0 ThO_2
Cobalt-based alloys											
Vitallium (HS-21)	0.25	27.0	3.0	5.0	Bal.					1.0	
S-816	0.40	20.0	20.0	4.0	Bal.	4.0		4.0		3.0	

CHAPTER-5

BRITTLE FRACTURE AND IMPACT TESTING

The other common mode of fracture is known as brittle fracture that takes place with little *or* no preceding plastic deformation. It occurs, often at unpredictable levels of stress, by rapid crack propagation. The direction of crack propagation is very nearly perpendicular to the direction of applied tensile stress. This crack propagation corresponds to successive and repeated breaking to atomic bonds along specific crystallographic planes, and hence called cleavage fracture. This fracture is also said to be transgranular because crack propagates through grains. Thus it has a grainy or faceted texture. Most brittle fractures occur in a transgranular manner.

Most of the failure occurred during the winter months. Failures occurred both when the ships were in heavy seas and when they were anchored at dock. These calamities focused attention on the fact that normally ductile mild steel can become brittle under certain conditions.

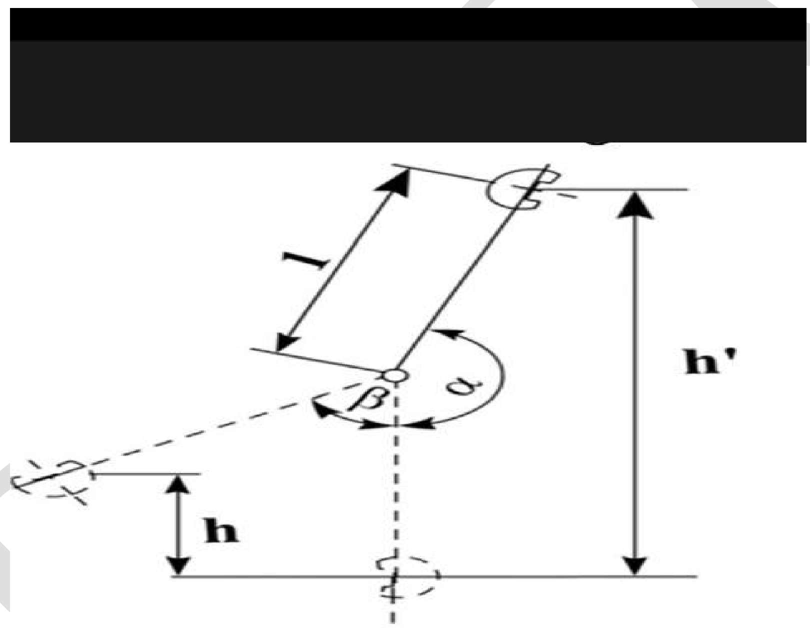


All three of these factors do not have to be present at the same time to produce brittle fracture. A triaxial state of stress, such as exists at a notch, and low temperature are responsible for most service failures of the brittle type.

Steels which have identical properties when tested in tension or torsion at slow strain rates can show pronounced differences in their tendency for brittle fracture when tested in a notched-impact test.

NOTCHED-BAR IMPACT TESTS

In impact loading notches are made intentionally in its specimens to increase the stress concentration so as to increase tendency to fracture as most of the mechanical components have stress raisers. To with stand impact force, a notched material must be toughed.



[redacted] DIAGRAM OF IMPACT TEST

This type of test will detect differences between materials which arc not observable in a tension test. A large number of notched-bar test specimens of different design have been used by investigators of the brittle fracture of metals.

Two classes of specimens have been standardized for notched-impact testing. i.e

1. Charpy
2. Izod

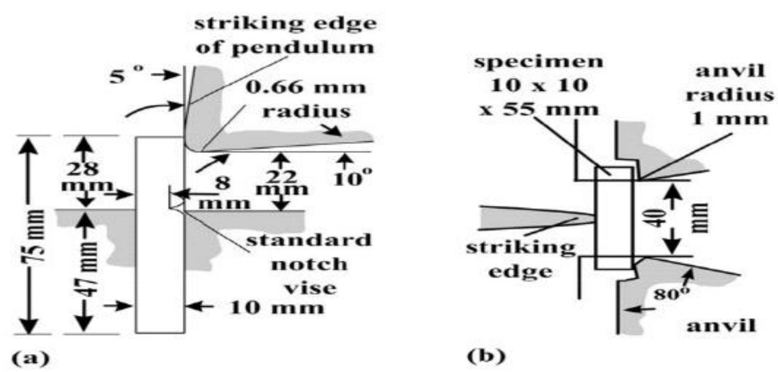
Charpy bar specimens:-

The Charpy specimen has a square cross-section (10x10mm)

And contains a 45° V notch, 2 mm deep with a 0.25 mm root radius. The specimen is supported as a beaming a horizontal position and loaded behind the notch by the impact of a heavy swinging pendulum. The specimen is forced to bend and fracture at a high strain ratio the order of 103/s.

Izod specimen:-

Which is used rarely today, has either a circular or square cross section and contains a V notch near the clamped end.



(a)Izod and (b) charpy impact test

Parameters/Measurements in impact testing:-

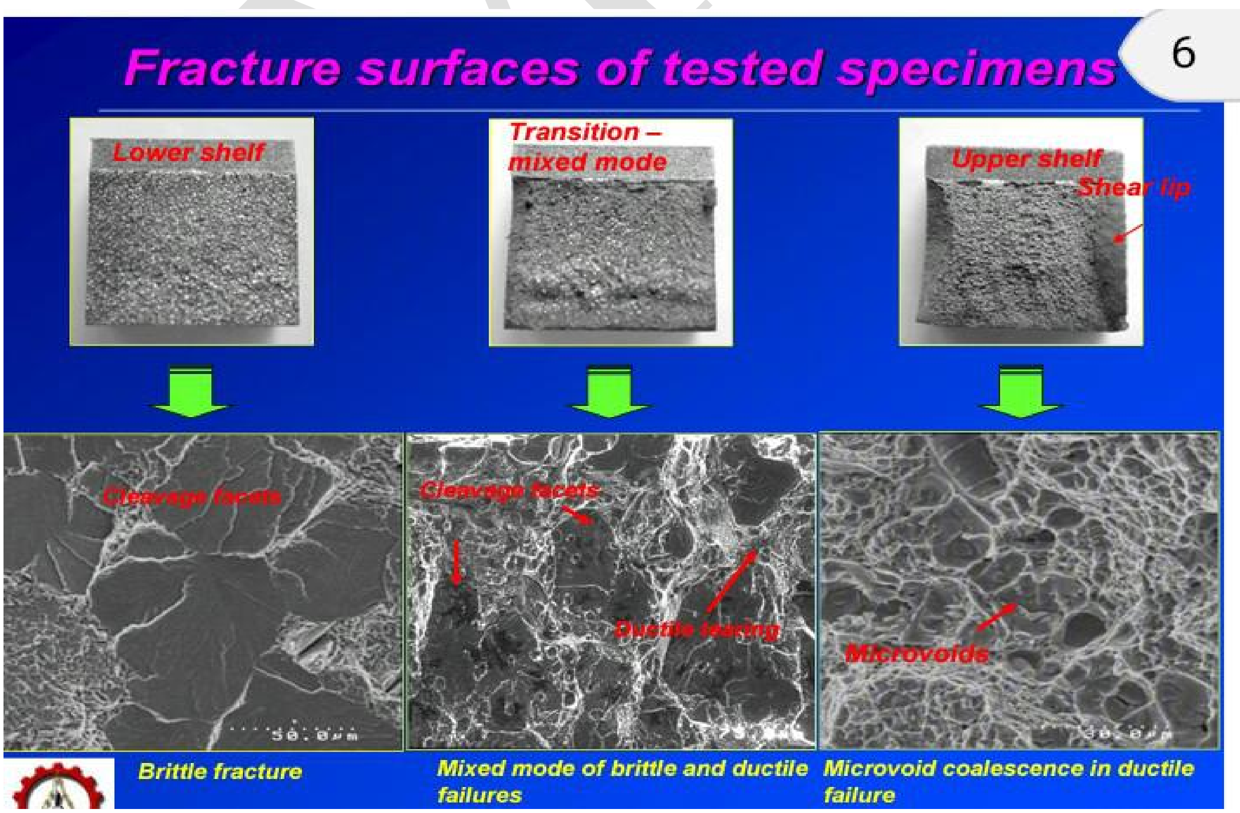
- The principal measurement from the impact test is the energy absorbed in fracturing the specimen. After breaking the test bar, the pendulum rebounds to a height which decreases as the energy absorbed in fracture increases. The energy absorbed in fracture, usually expressed in joules, is rending directly from a calibrated dial on the impact tester.

The energy required for fracture of a charpy specimen is demoted by “Cv”.

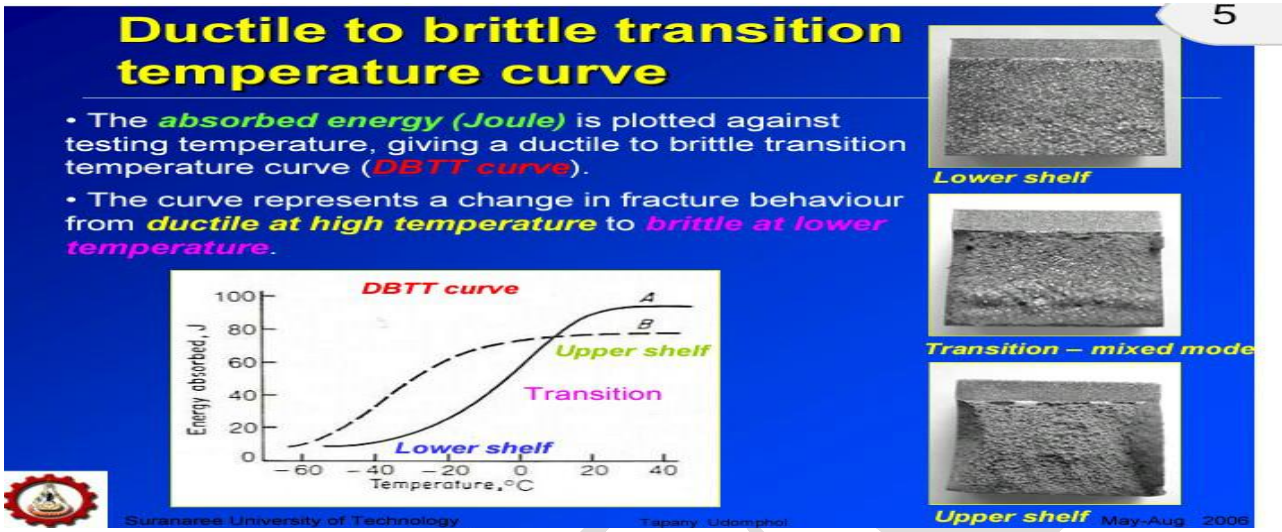
- It is important to realize that fracture energy measured by the charpy test is only a relative Energy and cannot be used directly in design equations.

- Common measurement obtained from the charpy test results from the examination of the fracture surface to determine whether the fracture is fibrous (shear fracture), granular (cleavage fracture),or a mixture of both.

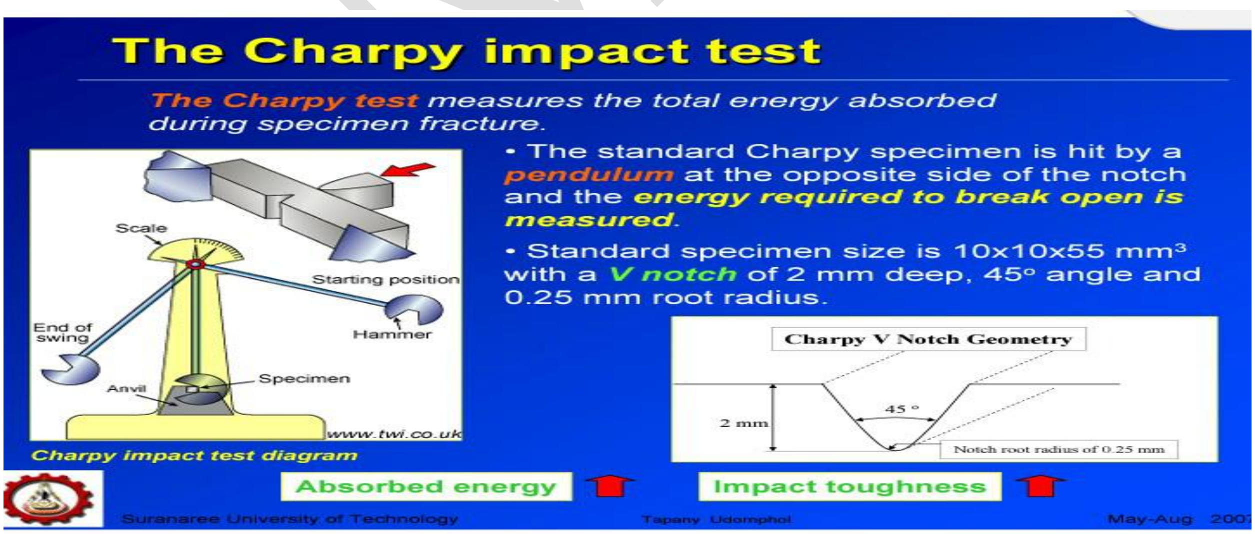
  - Provides a light-absorptive surface and dull appearance Cleavage fracture provide a high reflectivity and bright appearance, while the dimpled surface of a ductile fibrous fracture.
  - A third measurement that is sometimes made in the charpy test is the ductility, as indicated by the percent contraction of the specimen at the notch.



The notched-bar impact test is most meaningful when conducted over a range of temperatures so that the temperature at which the ductile-to-brittle transition takes place can be determined.



Instrumented Charpy Test: - The ordinary Charpy test measures the total energy absorbed in fracturing the specimen. Additional information can be obtained if the impact tester is instrumented to provide a load-line history of the specimen during each test. With this kind of record it is possible to determine the energy required for initialing fracture and the energy required for propagating fracture. It also yields information on the load for general yielding, the maximum load, and the fracture, load.



Significance of Transition-Temperature Curve

- The transition-temperature behavior of a wide spectrum of materials falls into the three categories.

- Medium- and low-strength FCC metals and most hcp metals have such high notch toughness that brittle fracture is not a problem unless there is some special reactive chemical environment.

- High-strength materials ($\sigma 0 > E/150$) have such low notch toughness that brittle fracture can occur at nominal stresses in the elastic range at all temperatures and strain rates when flaws are present. High-strength steel, aluminum and titanium alloys fall into this category.

- At lowtemperature fracture occurs by brittle cleavage, while at higher temperatures fracture occurs by low-energy rupture.

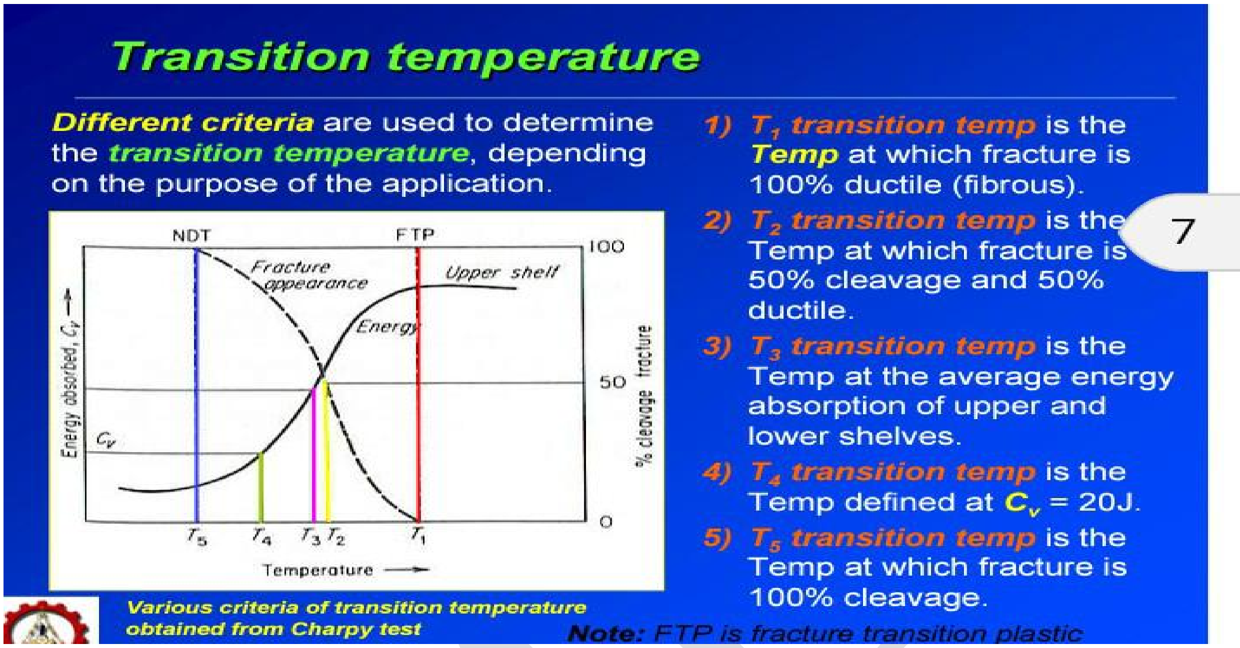
- It is under these conditions that fracture
  mechanics analysis is useful and appropriate.
  The notch toughness of low- and medium-strength bcc metals, as well as **Be**, **Zn**, and ceramic materials is strongly dependent on temperature.

- At low temperature the fracture occurs by cleavage while at high temperature the fracture occurs by ductile rupture.

- In metals this transition occurs at 0.1 to 0.2 of the absolute melting temperature Tm, while in ceramics the transition occurs at about 0.5 to 0.7 Tm.

- Transition-temperature curves centers about the determination of a temperature above which brittle fracture will not occur at elastic stress levels.

- The lower this transition temperature, the greater the fracture toughness of the material, there is no single criterion that defines the transition temperature.



- The most conservative criterion for transition temperature to select T1, corresponding to the upper shelf on fracture and temperature above is the fracture is 100% (i.e. 0% cleavage). This transition temperature criterion is called the **fracture transition plastic** (FTP).The FTP is the temperature at which the fracture changes from totally ductile to substantially brittle.

- An arbitrary but less conservative criterion is to base the transition temperature on 50% cleavage-50% shear, T2.This is called **FRACTURE-APPEARANCE TRANSITION TEMPERATURE** (FATT).

- Failure will not occur at or above the temperature if the stress does not exceed about one-half of the yield stress. Roughly similar result are often obtain by defining the transition temperature as the average of the upper and lower shelf values, T3.

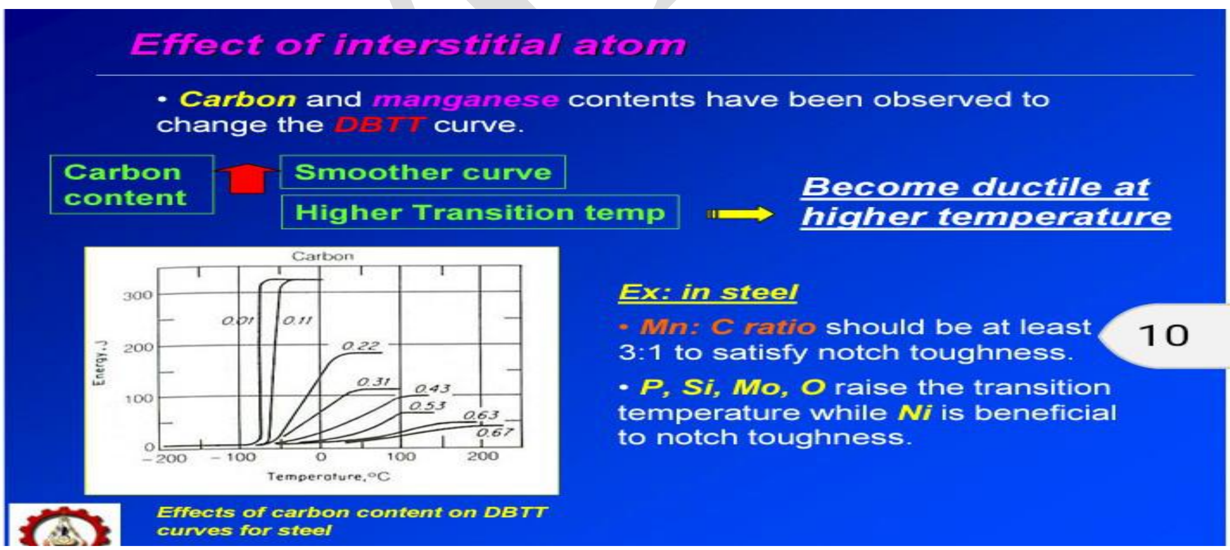
- A common criterion define the transition temperature T4 on the basis of an arbitrary low value of energy absorb Cv.This is often called the ductility transition temperature.

- A well-defined criterion is to base the transition temperature on the temperature at which the fracture becomes 100 percent cleavage,T5. This point is known as nil ductility temperature (NDT). The NDT is the temperature at which fracture initiates with essentially no prior plastic deformation. Below the NDT the probability of ductile fracture is negligible.

Metallurgical Factors Affecting Transition Temperature:-

- Changes in transition temperature of over 55°C (100°F) can be produced by changes in the chemical composition or microstructure of mild steel. The largest changes in transition temperature result from changes in the amount of carbon and manganese.

- The 15 ft-lb transition temperature is raised about 25°F for each increase of 0.1% carbon. This transition temperature is lowered about 5.5°C (10°F) for each increase of 0.1% manganese.



- Phosphorus also has a strong effect in raising the transition temperature. The transition temperature is raised about 13°F for each 0.01% phosphorus.

- Nickel is generally accepted to be beneficial to notch toughness in amounts up to 2 percent and seems to be particularly effective in lowering the ductility transition temperature.

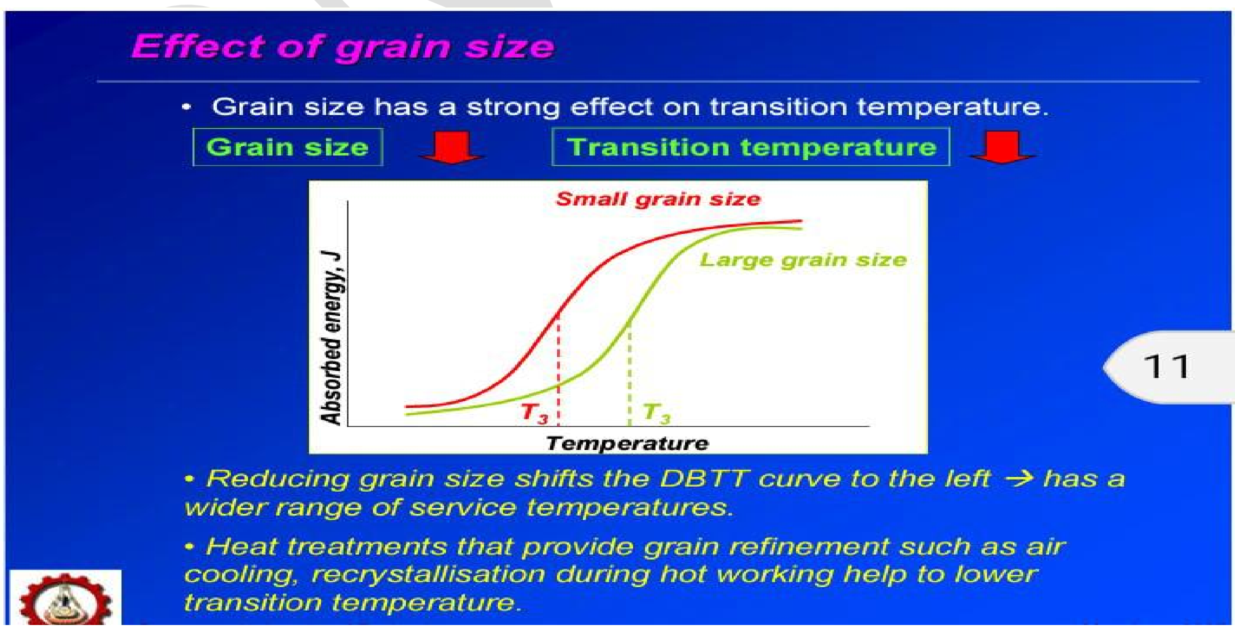
- Silicon, in amounts over 0.25 percent, appears to raise the transition temperature.

- Molybdenum raises the transition almost as rapidly as carbon, while chromium has little effect.

- Notch toughness is particularly influenced by oxygen. For high-purity iron it was found that oxygen contents above 0.003 percent produced intergranular fracture and corresponding low energy absorption.

When the oxygen content was raised from 0.001% to the high value of 0.057%, the transition temperature was raised from 5 to 650°F.

- Deoxidation practice has an important effect on the transition temperature. semi killed steels, which are deoxidized with silicon, have a lower transition temperature, while for steels which are fully killed with silicon+aluminium the transition temperature will be



around -75°F.

- Grain size has a strong effect on transition temperature. An increase of one ASTM number in the ferrite grain size (actually a decrease in grain diameter), results in a decrease in transition temperature of 16°C (30°F) for mild steel.

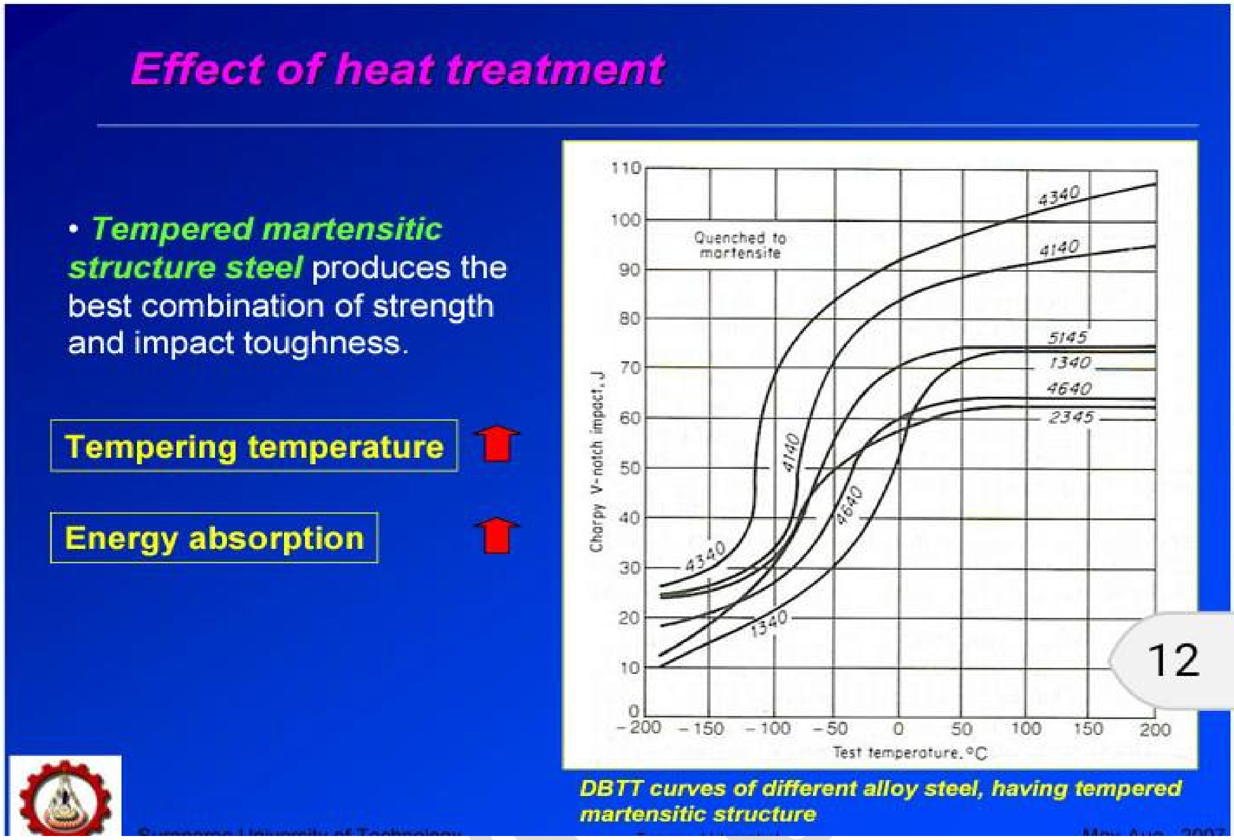
- Decreasing the grain diameter from ASTM grain size 5 to ASTM grain size 10 can change the 10 ft/lb Charpy V-notch transition temperature from about 39°C to -33°C (70°F to -60°F).

- Since normalizing after hot rolling results in a grain refinement, if not carried out at too high a temperature, this treatment results in reduced transition temperature.

- Air cooling and aluminum deoxidation results in a lower transition temperature.

- Aging phenomena which produce an increase in transition temperature.

- Strain aging occurs in low-carbon steel which has been cold-worked. Cold-working by itself will increase the transition temperature.



- The energy absorbed in the impact test of an alloy steel at a given test temperature generally increases with increasing tempering temperature. However, there is a minimum in the curve in the general region of 200 to 320°C (400 to 600°F). This has been called 260°C (500°F) embritilement, but because the temperature at which it occurs depends on both the composition of the steel and the tempering time, a more appropriate name is tempered-martensitic embrittlement.

CLASSIFICATION OF FORMING PROCESSES

It is the ease with which large part can be formed into useful shapes.

Objectives

Plastic forming operations are performed for at least two reasons: (i) to produce a desired shape, (ii) to improve the properties of the material through the alteration of the distribution of micro constituents, the refinement of grain size, and the introduction of strain hardening.

Plastic working processes which are designed to reduce an ingot or billet to a standard mill product of simple shape, such as sheet, plate, and bar, are called primary mechanical working processes. Forming methods which produce a part to a final finished shape are called secondary mechanical working processes. Most sheet-metal forming operations, wire drawing, and tube drawing are secondary processes. The terminology in this area is not very precise. Frequently the first category is referred to as processing operations, and the second is called fabrication. An important purpose of plastic working operations is to break down and refine the columnar or dendritic structure present in cast metals and alloys. Frequently the low strength and ductility of castings are due to the presence of a brittle constituent at the grain boundaries and dendritic boundaries. By compressive deformation it is often possible to fragment a brittle micro constituent in such a way that the ductile matrix flows into the spaces between fragments and welds together to leave a perfectly sound structure.

Once the brittle constituent is broken up, its effect on the mechanical properties is minor and ductility and strength are increased. Forging and rolling are the processes ordinarily used for breaking down a cast structure. However, extrusion is the best method because the billet is subjected to compressive forces only.

Hundreds of processes have been developed for specific metalworking applications. However, these processes may be classified into only a few categories on the basis of the type of forces applied to the work piece as it is formed into shape. These categories are:

1. Direct-compression-type processes

2. Indirect-compression processes

3. Tension-type processes

4. Bending processes

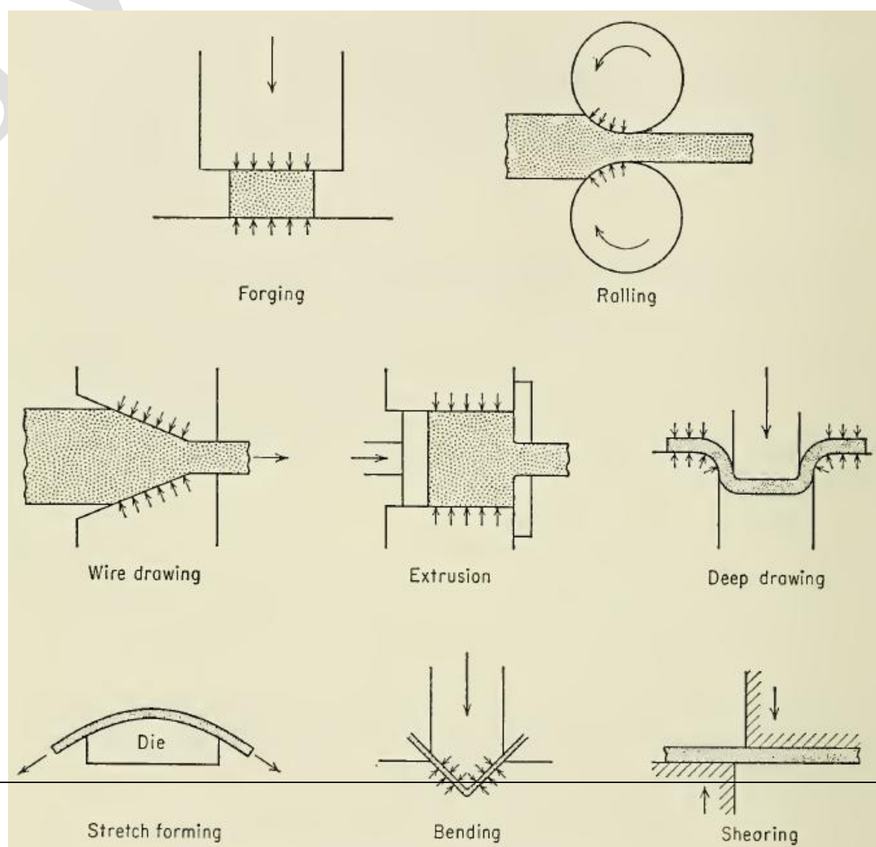
5. Shearing processes

In direct-compression processes the force is applied to the surface of the workpiece, and the metal flows at right angles to the direction of the compression. The chief examples of this type of process are forging and rolling.

Indirect-compression processes include wire and tube drawing, extrusion, and the deep drawing of a cup. The primary applied forces are frequently tensile, but the indirect compressive forces developed by the reaction of the workpiece with the die reach high values. Therefore, the metal flows under the action of a combined stress state which includes high compressive forces in at least one of the principal directions.

The best example of a tension-type forming process is stretch forming, where a metal sheet is wrapped to the contour of a die under the application of tensile forces.

Bending involves the application of bending moments to the sheet, while shearing involves the application of shearing forces of sufficient magnitude to rupture the metal.



Effect of Temperature on Forming Processes

Forming processes are commonly classified into hot-working and cold working operations.

- Hot working is defined as deformation under conditions of temperature and strain rate such that recovery processes take place simultaneously with the deformation.
- Cold working is deformation carried out under conditions where recovery processes are not effective.
- In hot working the strain hardening and distorted grain structure produced by deformation are very rapidly eliminated by the formation of new strain-free grains as the result of recrystallization.
- Very large deformations are possible in hot working because the recovery processes keep pace with the deformation. Hot working occurs at an essentially constant flow stress, and because the flow stress decreases with increasing temperature, the energy required for deformation is generally much less for hot working than for cold working. Since strain hardening is not relieved in cold working, the flow stress increases with deformation.
- Therefore, the total deformation that is possible without causing fracture is less for cold working than for hot working, unless the effects of cold work are relieved by annealing.

Hot Working

- Hot working is the initial step in the mechanical working of most metals and alloys. Not only does hot working result in a decrease in the energy required to deform the metal and an increased ability to flow without cracking, but the rapid diffusion at hot-working temperatures aids in decreasing the chemical inhomogeneities of the cast-ingot structure.

- Blowholes and porosity are eliminated by the welding together of these cavities, and the coarse columnar grains of the casting are broken down and refined into smaller equated recrystallized grains. These changes in structure from hot working result in an increase in ductility and toughness over the cast state.

However, there are certain **disadvantages** to hot working.

- Because high temperatures are usually involved, surface reactions between the metal and the furnace atmosphere become a problem.
- Ordinarily hot working is done in air, oxidation results, and a considerable amount of metal may thus be lost. Reactive metals like molybdenum are severely embrittled by oxygen, and therefore they must be hot-worked in an inert atmosphere or protected from the air by a suitable container.
- Surface decarburization of hot-worked steel can be a serious problem, and frequently extensive surface finishing is required to remove the decarburized layer.

Cold Working

- Cold working of a metal results in an increase in strength or hardness and a decrease in ductility.
- When cold working is excessive, the metal will fracture before reaching the desired size and shape. Therefore, in order to avoid such difficulties, cold-working operations are usually carried out in several steps, with intermediate annealing operations introduced to soften the cold-worked metal and restore the ductility. This sequence of repeated cold working and annealing is frequently called the cold-work-anneal cycle.
- Although the need for annealing operations increases the cost of forming by cold working, particularly for reactive metals which must be annealed in vacuum or inert atmospheres, it provides a degree of versatility which is not possible in hot-working operations.
- If the finished product must be stronger than the fully annealed material, then the final operation must be a cold-working step with the proper degree of deformation to produce the desired strength. This would probably be followed by a stress relief to remove residual stresses.
- Such a procedure to develop a certain combination of strength and ductility in the final product is more successful than trying to achieve the same combinations of properties by partially softening a fully cold-worked material, because the recrystallization process proceeds relatively rapidly and is quite sensitive to small temperature fluctuations in the furnace. If it is desired to have the final part in the fully softened condition, then an anneal follows the last cold working step.

Effect of Speed of Deformation on Forming Processes

- The response of a metal to forming operations can be influenced by the speed with which it is deformed.
- This transition-temperature phenomenon is more pronounced for rapid rates of deformation. Thus, for certain metals there may be a temperature region below which the metal will shatter when subjected to a high speed or impact load. For example, iron and steel will crack if hammered at temperatures well below room temperature, whereas a limited amount of slow-speed deformation can be accomplished in the same temperature range.
- For cold working a change in the forming speed of several orders of magnitude results in only about a 20 per cent increase in the flow curve, so that for practical purposes the speed of deformation can be considered to have little effect.
- High-speed deformation may produce regions of non-uniform deformation (stretcher strains) in a steel sheet which shows no stretcher strains on slow-speed deformation.
- The flow stress for hot working is quite markedly affected by the speed of deformation.
- There are no routine methods for measuring the flow stress during hot working. However, a high-speed compression testing machine, called the cam plastometer, is one device which has given good results.
- Because the time at temperature is shorter for high forming speeds, the minimum recrystallization temperature is raised and the minimum hot-working temperature will be higher.
- On the other hand, because the metal retains the heat developed by deformation to a greater extent at high forming speeds, there is a greater danger of hot shortness.
- For metals which have a rather narrow hot-working range these opposing effects serve to close the gap still further and make it impractical to carry out hot working at very high forming speeds.

Effect of Metallurgical Structure on Forming Processes

The forces required to carry out a forming operation are directly related to the flow stress of the metal being worked. This, in turn, depends on the metallurgical structure and composition of the alloy. For pure metals the ease of mechanical working will, in general, decrease with increasing melting point of the metal. Since the minimum recrystallization temperature is approximately proportional to the melting point, the lower temperature limit for hot work will also increase with melting point. (As a rough approximation, this temperature is about one-half the melting point.)

The addition of alloying elements to form a solid-solution alloy generally raises the flow curve, and the forming loads increase proportionately. Since the melting point is often decreased by solid-solution alloying additions, the upper hot-working temperature must usually be reduced in order to prevent hot shortness. The plastic working characteristics of two-phase (heterogeneous) alloys depend on the microscopic distribution of the second-phase particles. The presence of a large volume fraction of hard uniformly dispersed particles, such as are found in the SAP class of high-temperature alloys, greatly increases the flow stress and makes working quite difficult. If the second-phase particles are soft, they have only a small effect on the working characteristics. If these particles have a lower melting point than the matrix, then difficulties with hot shortness will be encountered. The presence of a massive, uniformly distributed micro constituent, such as pearlite in mild steel, results in less increase in flow stress than for very finely divided second-phase particles. The shape of the carbide particles can be important in cold-working processes.

For annealed steel, a spheroidization heat treatment, which converts the cementite platelets to spheroidal cementite particles, is often used to increase the formability at room temperature.

An important exception to the general rule that the presence of a hard second phase increases the difficulty of forming is brass alloys containing 35 to 45 per cent zinc (Muntz metal). These alloys, which consist of a relatively hard beta phase in an alpha-brass matrix, actually have lower flow stresses in the hot-working region than the single-phase alpha-brass alloys. In the cold-working region the flow stress of alpha-beta brass is appreciably higher than that of alpha brass.

The forming characteristics of an alloy can be affected if it undergoes a strain-induced precipitation or strain-induced phase transformation. If a precipitation reaction occurs in a metal while it is being formed, it will produce an increase in the flow stress but, more important, there will be an appreciable decrease in ductility, which can result in cracking. When brittleness is caused by precipitation, it usually results when the working is carried out at a temperature just below the solvus line or from cold working after the alloy had been heated to the same temperature region. Since precipitation is a diffusion-controlled process, difficulty from this factor is more likely when forming is carried out at a slow speed at an elevated temperature. To facilitate the forming of age hardenable aluminum alloys, they are frequently refrigerated just before forming in order to suppress the precipitation reaction.

Work of Plastic Deformation

- The total work required to produce a shape by plastic deformation can be broken down into a number of components. The work of deformation W_d is the work required for homogeneous reduction of the volume from the initial to final cross section by uniform deformation. Often part of the total work is expended in redundant work W_r. The redundant, or internal-deformation, work is the energy expended in deforming the body which is not involved in a pure change in shape. Finally, part of the total work must be used to overcome the frictional resistances at the interface between the deforming metal and the tools. Therefore, the total work can be written as the summation of three components.
-

$$Wt = Wd + Wr + W,$$

- From the above definitions, it can be seen that the work of deformation represents the minimum energy which must be expended to carry out a particular forming process. This is equal to the area under the effective stress-strain curve multiplied by the total volume.
- The efficiency of a forming process is the work of deformation divided by the total work of deformation. The standard measures of ductility which are obtained from the tension test, elongation and reduction of area, give only a very crude indication of the ease with which the metal may be formed without cracking. However, at least a qualitative indication of the forming limits for sheet-metal forming can be obtained from a more detailed analysis of the tensile stress-strain curve. In forming operations where the sheet is restricted from deforming in one area while it is stretched into shape in another region the metal must be able to deform to a large extent without localized deformation.

Friction in Forming Operations and lubrication

- An important consideration in the forming of metals is the friction forces developed between the workpiece and the forming tools. Friction forces can materially increase the deformation resistance. They are difficult to measure/ and therefore they represent one of the major uncertainties in the analysis of forming operations. Various methods of lubrication are used to minimize friction forces. In fact, the ability to find a suitable lubricant often determines whether or not a forming operation will be successful.

- The friction between the work and the tools gives rise to shearing stresses along the contact surfaces. The relationship between the shearing stress r, the normal stress on the interface between the work and the tools, 0-, and the coefficient of friction is generally expressed by Coulomb's law of sliding friction. Friction increases with an increase in the relative motion between the work and the tools, but at high speeds it decreases appreciably. The lowest coefficients of friction are of the order of 0.01 to 0.05.
- The coefficients of friction are usually higher for hot working because oxidation roughens the work and the tools. A sensitive measurement of friction can be made with a pressure-sensitive pin
- inserted at an angle to the interface, friction drops to 0.2 because of a change in the frictional characteristics of the oxide film.

FORGING

Classification of Forging Processes

Forging is the working of metal into a useful shape by hammering or pressing. It is the oldest of the metalworking arts, having its origin with the primitive blacksmith of Biblical times. The development of machinery to replace the arm of the smith occurred early during the Industrial Revolution. Today there is a wide variety of forging machinery which is capable of making parts ranging in size from a bolt to a turbine rotor or an entire airplane wing. Two major classes of equipment are used for forging operations.

The forging hammer, or drop hammer, delivers rapid impact blows to the surface of the metal, while the forging press subjects the metal to a slow-speed compressive force. With impact forging the pressure is at maximum intensity when the hammer touches the metal, and it decreases rapidly in intensity as the energy of the blow is absorbed in deforming the metal. Therefore, impact forging produces deformation primarily in the surface layers.In press forging the pressure increases as the metal is being deformed, and its maximum value is obtained just before the pressure is released. Therefore, press forging results in deeper penetration of the deformed zone.

The simplest forging operation is the upsetting of a cylinder between two flat dies.The compressive forces cause the metal to flow out equally in all directions, so that ideally the final shape would be a cylinder of increased diameter and decreased height

However, because there is always friction between the dies and the metal, the cylinder flows to a lesser extent at these interfaces than it does at the center. The resulting shape is therefore a cylinder which is barreled at the center. If the workpiece has a non-cylindrical shape, the greatest flow will occur along the narrowest sides. Edging dies are used to shape the ends of bars and to gather metal.

Forging operations.

- Edging
- Fullering
- Drawing
- Swaging
- Piercing
- Punching.

Forging Equipment

In forging hammers the force is supplied by a falling weight, or ram. The two basic types of forging hammers are the hoard hammer and the steam hammer. In the board hammer the upper die and ram are raised by rolls gripping the board. When the ram is released, it falls owing to gravity. The energy supplied to the blow is equal to the potential energy due to the weight of the ram and the height of the fall. Board hammers are rated by the weight of the falling part of the equipment. They range from 400-lb hammers with a 35-in. fall to 7,500-lb hammers with a 75-in. fall. This type of equipment is capable of producing forgings weighing up to about 100 lb. Greater forging capacity, in the range from 1,000 to 50,000 lb, is available with the steam hammer. Steam is admitted to the bottom of a cylinder to raise the ram, and it enters the top to drive the ram down. Since the falling ram is accelerated by steam pressure, the energy supplied to the blow is related to the kinetic energy of the falling mass Forging presses are of either mechanical or hydraulic design.

Vertical hydraulic presses usually have the pressure chamber located on top of the press .High pressures are built up in the intensifier cylinders by using oil or water as the hydraulic medium. Hydraulic presses are generally built to ratings of 500 to 18,000 tons, although several presses with ratings of 50,000 tons have been built. Large hydraulic presses are particularly adaptable to the open-die forging of steel ingots and the closed-die forging of aluminum and magnesium. Forging machines, also known as upsetters, or headers, are horizontal presses which are very useful for the high-production forging of symmetrical shapes from bar stock. The machine is basically a double-acting press with dies which firmly grip the work around the circumference and forming tools which upset the metal. Bolts, rivets, and gears are typical parts made with forging machines. Forging machines are rated in terms of the maximum-diameter bar which can be gripped by the machine.

Forging Defects

- Cracking at the flash
- Cold shut or fold
- Internal cracking due to secondary tensile stresses

ROLLING

Classification of Rolling Processes

The process of plastically deforming metal by passing it between rolls is known as rolling. This is the most widely used metalworking process because it lends itself to high production and close control of the final product. In deforming metal between rolls, the work is subjected to high compressive stresses from the squeezing action of the rolls and to surface shear stresses as a result of the friction between the rolls and the metal. The frictional forces are also responsible for drawing the metal into the rolls. The initial breakdown of ingots into blooms and billets is generally done by hot rolling. This is followed by further hot rolling into plate, sheet, rod, bar, pipe, rails, or structural shapes. The cold rolling of metals has reached a position of major importance in industry. Cold rolling produces sheet, strip, and foil with good surface finish and increased mechanical strength, at the same time maintaining close control over the dimensions of the product. A bloom is the product of the first breakdown of the ingot. Generally the width of a bloom equals its thickness, and the cross-sectional area is greater than 36 in. A further reduction by hot rolling results in a billet. A slab refers to a hot-rolled ingot with a cross-sectional area greater than 16 in.^ and with a width that is at least twice the thickness. Blooms, billets, and slabs are known as semifinished products because they are subsequently formed into other mill products. The differentiation between plate and sheet is determined by the thickness of the product. Generally rolling starts with a cast ingot, but this is not a necessary requirement. A recent development is powder rolling. Metal powder is introduced between the rolls and compacted into a "green strip," which is subsequently sintered to high density.

Rollins Equipment

A rolling mill consists basically of rolls, bearings, a housing for containing these parts, and a drive for applying power to the rolls and controlling their speed. The forces involved in rolling can easily reach many millions of pounds. Therefore, very rigid construction is needed, and very large motors are required to provide the necessary power. When these requirements are multiplied several times for the successive stands of a large continuous mill, it is easy to see why a modern rolling-mill installation demands many millions of dollars of capital investment and many man-hours of skilled engineering design and construction.

Rolling mills can be conveniently classified with respect to the number and arrangement of the rolls. The simplest and most common type of rolling mill is the two-high mill. Rolls of equal size are rotated only in one direction. The stock is returned to the entrance, or rear, of the rolls for further reduction by hand carrying or by means of a platform which can be raised to pass the work above the rolls. An obvious improvement in speed results from the use of a two-high reversing mill, in which the work can be passed back and forth through the rolls by reversing their direction of rotation. Another solution is the three-high mill consisting of an upper and lower driven roll and a middle roll which rotates by friction. A large decrease in the power required for rolling can be achieved by the use of small-diameter rolls. However, because small-diameter rolls have less strength and rigidity than large rolls, they must be supported by larger-diameter backup rolls.The Sendzimir mill is a modification of the cluster mill which is very well adapted to rolling thin sheet or foil from high-strength alloys.

For high production it is common to install a series of rolling millsone after another in tandem. Each set of rolls is called a stand.

Hot Rolling

The first hot -working operation for most steel products is done in the blooming mill (also called cogging mill). Blooming mills are usually two-high reversing mills with 24- to 54-in. -diameter rolls. Because blooming represents the initial breakdown of the ingot structure, it is done in small, careful steps with repeated reheating. It is not unusual to require 25 passes for the blooming of a large alloy-steel ingot. To produce the size of billet required by smaller finishing mills, it is often necessary to reroll the blooms on a three-high, or continuous, billet mill The billets may then be rolled into round bars, hexagons, special shapes, or flats on various types of finishing mills. Sheared plate is produced by cross-rolling billets on two-high, three- high, and four-high mills and then shearing all edges to size. The other common method of rolling plate is on a universal mill.

Forces and Geometrical Relationships in Rolling

$h_{max} = \mu^2 R$

Main Variables in Rollins

The main variables which control the rolling process are

- the roll diameter
- the deformation resistance of the metal
- the friction between the rolls and the metal
- the presence of front tension and back tension.

Defects in Rolled Products

- Centre split
- Alligatoring
- Zipper crack
- Edge crack
- Wavy edge

EXTRUSION

Classification of Extrusion Processes

Extrusion is the process by which a block of metal is reduced in cross section by forcing it to flow through a die orifice under high pressure. In general, extrusion is used to produce cylindrical bars or hollow tubes, but shapes of irregular cross section may be produced from the more readily extrudable metals, like aluminum. Because of the large forces required in extrusion, most metals are extruded hot under conditions where the deformation resistance of the metal is low.

However, cold extrusion is possible for many metals and is rapidly achieving an important commercial position. The reaction of the extrusion billet with the container and die results in high compressive stresses which are effective in reducing the cracking of materials during primary breakdown from the ingot. This is an important reason for the increased utilization of extrusion in the working of metals difficult to form, like stainless steels, nickel-base alloys, and molybdenum. The two basic types of extrusion are direct extrusion and indirect extrusion (also called inverted, or back, extrusion).The metal billet is placed in a container and driven through the die by the ram.

A dummy block, or pressure plate, is placed at the end of the ram in contact with the billet. A hollow ram carries the die, while the other end of the container is closed with a plate. Frequently, for indirect extrusion, the ram containing the die is kept stationary, and the container with the billet is caused to move.

Extrusion Equipment

Most extrusions are made with hydraulic presses. Hydraulic extrusion presses are classified into horizontal and vertical presses, depending upon the direction of travel of the ram. Vertical extrusion presses are generally built with capacities of 300 to 1,000 tons. They have the advantages of easier alignment between the press ram and the tools,higher rate of production, and the need for less floor space than hori-zontal presses. However, they need considerable headroom, and to make extrusions of appreciable length, a floor pit is frequently necessary.Vertical presses will produce uniform cooling of the billet in the container, and thus symmetrically uniform deformation will result. In a horizontal extrusion press the bottom of the billet which lies in contact with the container will cool more rapidly than the top surface, unless the extrusion container is internally heated, and therefore the deformation will be nonuniform. Warping of bars will result, and nonuniform wall thickness will occur in tubes. In commercial operations the chief use for vertical presses is in the production of thin-wall tubing, where uniform wall thickness and concentricity are required.

Extrusion Defects

- Cheveron crack/ centre brust
- Surface crack

ROD, WIRE, AND TUBE DRAWING

Introduction

Drawing operations involve the forcing of metal through a die by means of a tensile force applied to the exit side of the die. Most of the plastic flow is caused by compression force which arises from the reaction of the metal with the die. Usually the metal has a circular symmetry, but this is not an absolute requirement. The reduction in diameter of a solid bar or rod by successive drawing is known as har, rod, or wire drawing, depending on the diameter of the final product. When a hollow tube is drawn through a die without any mandrel to support the inside of the tube, this is known as tube sinking. When a mandrel or plug is used to support the inside diameter of the tube as it is drawn through a die, the process is called tube drawing. Bar, wire, and tube drawing are usually carried out at room temperature. However, because large deformations are usually involved, there is considerable temperature rise during the drawing operation.

Rod and Wire Drawing

The principles involved in the drawing of bars, rod, and wire are basically the same, although the equipment that is used is different for the different-sized products. Rods and tubes, which cannot be coiled, are produced on draw benches. The rod is pointed with a swager, inserted through the die, and clamped to the jaws of the draw head. The drawhead is moved either by a chain drive or by a hydraulic mechanism. Draw benches with 300,000 lb pull and 100 ft of runout are available. Draw speeds vary from about 30 to 300 ft/min. The cross section through a typical conical drawing die .The entrance angle of the die is made large enough to allow room for the lubricant that adheres to the die. An important characteristic of a drawing die is the half-die angle, denotedby a. At the present time most drawing dies are made from tungsten carbide because it provides long die life. Wire drawing starts with hot-rolled wire rod. The rod is first cleaned by pickling to remove any scale which would lead to surface defects and excessive die wear. For the production of steel wire the next step consists in coating the wire rod with lime or plating it with a thin layer of copper or tin. The lime serves as an absorber and carrier of the lubricant during dry drawing, and it also serves to neutralize any acid remaining from pickling. In dry drawing the lubricant is grease or soap powder, while in wet drawing the entire die is immersed in a lubricating fluid of fermented rye-meal liquor or alkaline soap solution. The electroplated coating of copper or tin is used in the wet drawing of steel wire. No coating is generally used for drawing copper wire.

After surface preparation of the wire rod, it is pointed, passed through the die, and fastened to the draw block For coarse wire, with a final diameter greater than i in., a single draw block, called a hull hock, is used.

Tube-drawing Processes

Hollow cylinders, or tubes, which are made by hot-forming processes such as extrusion or piercing and rolling are often cold finished by drawing. Cold drawing is used to obtain closer dimensional tolerances, to produce better surface finishes, to increase the mechanical properties of the tube material by strain hardening, to produce tubes with thinner walls or smaller diameters than can be obtained with hot- forming methods, and to produce tubes of irregular shapes. Tube drawing is essentially the same as wire drawing. Tubes are produced on a drawbench and with dies similar to those employed in wiredrawing. However, in order to reduce the wall thickness and accurately to control the inside diameter, the inside surface of the tube must be supported while it passes through the die. This is usually accomplished by inserting a mandrel, or plug, inside the tube.The mandrel is often fastened to the end of a stationary rod attached to one end of the draw bench and is positioned so that the mandrel is located in the throat of the die. The mandrel may have either a cylindrical or a tapered cross-section. Tube drawing may be accomplished also with a moving mandrel, either by pulling a long rod through the die with the tube or by pushing a deep-drawn shell through the die with a punch. Because of difficulties in using long rods for mandrels, tube drawing with a rod usually is limited to the production of small-sized tubing, where the rod supporting the stationary mandrel would be too thin to have adequate strength. Another tube-producing method is tube sinking, in which no mandrel is used to support the inside surface of the tube as it is drawn through the die. Since the inside of the tube is not supported in tube sinking, the wall thickness will either increase or decrease, depending on the conditions imposed in the process. On a commercial basis tube sinking is used only for the production of small tubes. However, it represents an important problem in plastic-forming theory because it occurs as the first step in tube drawing with a mandrel.

DEFECTS

- Centre brust

SHEET-METAL FORMING

Introduction

The ability to produce a variety of shapes from flat sheets of metal at high rates of production has been one of the real technological advances of the twentieth century. This transition from hand-forming operations to mass-production methods has been an important factor in the great improvement in the standard of living which occurred during the period. In essence, a shape is produced from a flat blank by stretching and shrinking the dimensions of all its volume elements in the three mutually perpendicular principal directions. The resulting shape is then the result of the integration of all the local stretching and shrinking of the volume elements. Attempts have been made to classify the almost limitless number of shapes which are possible in metal forming into definite categories depending upon the contour of the finished part.

sheet-metal parts have five categories.

- Singly curved parts
- Contoured flanged parts—including parts with stretch flanges and shrink flanges
- Curved sections
- Deep-recessed parts—including cups and boxes with either vertical or sloping walls
- Shallow-recessed parts—including dish-shaped, beaded, embossed,and corrugated parts

Forming Methods

The old method of hand forming of sheet metal is today used primarily as a finishing operation to remove wrinkles left by forming machines. In the metalworking industries hand forming is primarily limited to experimental work where only a few identical pieces are required. Most high-production-volume sheet-metal forming is done on a press, driven either by mechanical or by hydraulic action. In mechanical presses energy is generally stored in a flywheel and is transferred to the movable slide on the down stroke of the press. Mechanical presses are usually quick-acting and have a short stroke, while hydraulic presses are slower-acting but can apply a longer stroke. Presses are usually classified according to the number of slides which can be operated independently of each other. In the single-action press there is only one slide, generally operating in the vertical direction. In the double-action press there are two slides. The second action is ordinarily used to operate the hold down, which prevents wrinkling in deep drawing. A triple-action press is equipped with two actions above the die and one action below the die. The basic tools used with a metalworking press are the punch and the die. The punch is the convex male tool which mates with the concave female die. Generally the punch is the moving element. Because accurate alignment between the punch and die is usually required, it is common practice to mount them permanently in a suppress, or die set, which can be quickly inserted in the press. An important consideration in tooling for sheet-metal forming is the frequent requirement for a clamping pressure, or hold-down, to prevent wrinkling of the sheet as it is being formed. Hold-down can be best provided by a hold-down ring, which is actuated by the second action of a double-action press.

Frequently punches and dies are designed so that successive stages in the forming of the part are carried out in the same die on each stroke of the press. This is known as progressive forming. A simple example is a progressive blanking and piercing die to make a plain, flat washer. As the strip is fed from left to right, the hole for the washer is first punched and then the washer is blanked from the strip. At the same time as the washer is being blanked from the strip, the punch A is piercing the hole for the next washer. The stripper plate is used to prevent the metal from separating from the die on the up stroke of the punch. The die materials depend on the severity of the operation and the required production run. In aircraft work, where production runs are often small, tooling is frequently made from a zinc-base alloy called Kirksite or from wood or epoxy resins. For long die life, however, tool steel is required.

Rubber hydroforming

It is a modification of the conventional punch and die in which a pad of rubber serves as the female die. Rubber forming, or the Guerin process. A form block (punch) is fastened to the bed of a single-action hydraulic press, and a thick blanket of rubber is placed in a retainer box on the upper platen of the press. When a blank is placed over the form block and the rubber forced down on the sheet, the rubber transmits a nearly uniform hydrostatic pressure against the sheet. A unit pressure of around 1,500 psi is sufficient for most parts, and higher local pressures can be provided by auxiliary tooling. Rubber forming is used extensively in the aircraft industry. Shallow flangedparts with stretch flanges are readily produced by this method, but shrink flanges are limited because the rubber provides little resistance to wrinkling. Another limitation is that the blank tends to move on the form block unless holes for the part. A modification to this process, known as Mar forming, provides a controlled hold-down pressure that results in deeper, wrinkle-free draws. The hydraulic analog of rubber forming is the hydroforming process. In this process the rubber pad is replaced by a flexible diaphragm backed up by hydraulic fluid with pressures as high as 15,000 psi.

Shearing and Blanking

Shearing is the separation of metal by two blades moving. In shearing, a narrow strip of metal is severely plastically deformed to the point where it fractures at the surfaces in contact with the blades. The fracture then propagates inward to provide complete separation. The depth to which the punch must penetrate to produce complete shearing is directly related to the ductility of the metal.

The penetration is only a small fraction of the sheet thickness for brittle materials, while for very ductile materials it may be slightly greater than the thickness.

Bending

Bending is the process by which a straight length of metal is transformed into a curved length. The definitions of the terms used in bending. The bend radius R is defined as the radius of curvature on the concave, or inside, surface of the bend. The neutral axis is the circumferential fiber across the thickness at which the strain passes through zero. In plastic bending the neutral axis does not remain at the half thickness, as is the case for elastic bending. For a sharp bend the neutral axis is closer to the inside than the outside of the bend. To estimate the change in length produced by bending, the neutral axis is usually taken at a distance of 0.45 times the sheet thickness from the inside surface of the bend.

When metal is bent, its final length is increased over its original length in the blank because the metal thickness is decreased. As the bend radius becomes smaller, the decrease in thickness increases. The initial or developed length of the center line of the bent section is called the hand allowance B. The bend allowance is useful for determining the length of the blank required for making a bend.

Stretch Forming

Stretch forming is the process of foraging by the application of primarily tensile forces in such a way as to stretch the material over a tool or form block. The process is an outgrowth of the stretcher leveling of rolled sheet. Stretch forming is used most extensively in the aircraft industry to produce parts of large radius of curvature, frequently with double curvature. An important consideration is that spring back is largely eliminated in stretch forming because the stress gradient is relatively uniform. On the other hand, because tensile stresses predominate, large deformations can be obtained by this process only in materials with appreciable ductility.

Stretch-forming equipment consists basically of a hydraulically driven ram (usually vertical) which carries the punch or form block and two jaws for gripping the ends of the sheet No female die is used in stretch forming. The grips may be pivoted, so that the tension force is always in line with the edge of the unsupported sheet, or they can be fixed, in which case a large radius is needed to prevent tearing the sheet at the jaws. In using a stretch-forming machine the sheet metal blank is first bent or draped around the form block with relatively light tensile pull, the grips are applied, and the stretching load is increased until the blank is strained plastically to final shape. This differs from wrap forming. In that in the latter process the blank is first gripped and then while still straight is loaded to the elastic limit before wrapping around the form block.

Defects in Formed Parts

- Orange peeling
- Stretcher strains, or "worms."
- Yield-point elongation
- Earing

Registration no: | 1 | 3 | 0 | 1 | 1 | 0 | 5 | 3 | 7 | 7 |

Total Number of Pages: 02

B.Tech
PCMT4304

6^{th} Semester Regular / Back Examination 2015-16
MECHANICAL WORKING AND TESTING OF MATERIALS

BRANCH: METTA,MME
Time: 3 Hours
Max Marks: 70
Q.CODE:W203

Answer Question No.1 which is compulsory and any five from the rest.
The figures in the right hand margin indicate marks.

Q1 **Answer the following questions:** (2 x 10)

a) How does fracture stress and mode of fracture vary with specimen thickness?
b) Explain why minor load is applied prior to the application of major load in Rockwell hardness testing method.
c) What are the different types of indentations frequently observed with a pyramid indenter?
d) What is limiting drawing ratio (LDR)?
e) Define Meyer's law.
f) What is zipper crack?
g) Explain angle of bite.
h) What is rubber hydro-forming?
i) Explain the terms ingot, slab, bloom and billet.
j) What is nil ductility temperature?

Q2 a) What is the significance of recrystallisation temperature? Mention what are the specific advantages of cold working over hot working process? (5)

b) Determine the engineering strain, true strain, and reduction for (a) a bar which is doubled in length; (b) a bar which is halved in length. (5)

Q3 a) Using simplified theory of rolling, express the geometrical relationships of roll diameter, coefficient of friction and sheet thickness for solid and cylindrical bars. (5)

b) Calculate the rolling load if steel sheet is hot rolled 30% from 40 mm-thick slab using a 900 mm-diameter roll. The slab is 760 mm wide. Assume μ = 0.30. The plain strain flow stress is 140 MPa at entrance and 200 MPa at the exit from the roll gap due to the increasing velocity. (5)

Q4 Explain the testing procedure and method to determine K_{Ic} the plain-strain fracture toughness. (10)

Q5	a)	Discuss the different types of forming processes.	(5)
	b)	What is S-N curve? What are the factors which affect fatigue life of a material?	(5)
Q6	a)	How the forming limit diagram is helpful for controlling the failure in sheet-metal forming?	(5)
	b)	Differentiate between direct and indirect extrusion process.	(5)
Q7	a)	Express and explain the mathematical equations of Brinell Hardness testing with preferable sketches.	(5)
	b)	Differentiate the Charpy impact test and Izod impact test.	(5)
Q8		Write short notes on any two:	(5 x 2)
	a)	Coffin-Manson relation.	
	b)	Scope and significance of non-destructive testing	
	c)	Transition temperature	
	d)	Production of seamless pipes and tubes.	

Total number of printed pages – 2

B. Tech
PCMT 4304

Sixth Semester Regular Examination – 2015

MECHANICAL WORKING AND TESTING MATERIALS

BRANCH (S) : MM, MME

QUESTION CODE : J 214

Full Marks – 70

Time : 3 Hours

*Answer Question No. **1** which is compulsory and any **five** from the rest.*
The figures in the right-hand margin indicate marks.

1 Write short notes on : 2×10

(a) Explain why minor load is applied prior to the application of major load in Rockwell hardness testing method.

(b) What is springback and its effect in bending ?

(c) What is the difference between diffuse necking and localized necking ?

(d) Define Pari's law.

(e) What is the function of flash in close-die forging ?

(f) Explain why Ugine-Sejournet process is used in hot extrusion.

(g) State the difference between open and cold die forging.

(h) How does strain hardening affect creep strength of a material ?

(i) Explain why fatigue life of a material is highly sensitive to the surface smoothness.

(j) What is the difference between bulk forming and sheet forming ?

2. State the forces which are acting during rolling and their geometrical relationships. Mention the variables which affect the rolling load. 10

P.T.O.

Calculate the rolling load if steel is hot rolled 40% from a 30mm thick slab using a 900mm diameter roll. The slab is 750mm wide. Assume $\mu=0.30$. The plane strain flow stress is 130 MPa at entrance and 200MPa at the exit from the roll gap due to the increasing velocity.

3. Explain the Griffith theory of Brittle Fracture and give the stress required to propagate a crack in a brittle material as a function of the size of the micro-crack in plane stress and plane strain conditions. 10

4. (a) Explain briefly what is the effect of mean stress on fatigue. 5

   (b) Differentiate between low cycle fatigue and high cycle fatigue. 5

5. (a) Compare the advantages and disadvantages of the tension test, compression test and torsion test for determining the flow stress for the metal working processes. 5

   (b) Describe the relationship between hardness and flow curve. 5

6. (a) Why is it necessary to provide proper clearance between the punch and die in a shearing operation ? Give reasons. 5

   (b) Classify the metal extrusion process with respect to the direction, operating temperature and equipment. 5

7. (a) What is rubber hydroforming and how it is different from Verson-Wheelon process ? 5

   (b) Derive the expression for forging load in a plain strain condition. 5

8. Write short notes any two of the following : 5×2

   (a) Hydrostatic extrusion

   (b) Rockwell hardness

   (c) Liquid penetrant test

   (d) Stretch forming.

Total number of printed pages – 2

B. Te

PCMT 43

Sixth Semester Regular Examination – 2014

MECHANICAL WORKING AND TESTING OF MATERIALS

BRANCH(S) : MM, MME

QUESTION CODE : F 244

Full Marks – 70

Time : 3 Hours

*Answer Question No. **1** which is compulsory and any **five** from the rest.*

The figures in the right-hand margin indicate marks.

1. Answer the following questions : 2 × 10

   (a) Define the term "troptometer".

   (b) Explain angle of bite.

   (c) What are the different types of indentations frequently observed with a pyramid indenter ?

   (d) Define Meyer's law.

   (e) State the advantages of indirect extrusion over direct extrusion.

   (f) State the relationship between hardness and flow curve.

   (g) What is patenting ?

   (h) How does an increasing mean stress influence the allowable alternating stress and fatigue limit ?

   (i) How does fracture stress and mode of fracture vary with specimen thickness ?

   (j) Based on the basic structural changes that occur when a metal is subjected to cyclic stress what are the different stages of the fatigue process ?

(a) Discuss briefly about the types of rolling mills with sketches.

(b) Describe the different types of rolling defects and explain their causes. 5

(a) Discuss the basic factors that can contribute to brittle-cleavage fracture. 5

(b) Differentiate the Charpy impact test and Izod impact test. 5

Describe the torsion test and express the following properties:

(a) Twisting moment of solid bar.

(b) Shear stress of solid bar.

(c) Maximum shear stress for cylindrical specimen. 10

(a) Discuss the scope and significance of non-destructive testing. 5

(b) Write the principle, specifications and limitations of liquid penetrant test. 5

(a) Explain low cycle fatigue and the Coffin-Manson relation. 5

(b) Explain cyclic strain control fatigue and the response of metals to cyclic strain cycle. Explain the cyclic stress-strain curve. 5

(a) Distinguish between stress intensity factor and fracture toughness. Explain fracture toughness and the design tradeoff that is inherent in fracture mechanics design through suitable sketches. 5

(b) Draw a typical creep curve and explain the various stages. 5

(a) Derive the expression for the maximum draft (Δh_{max}) that can be taken in rolling. 5

(b) Differentiate between hot rolling and cold rolling. 5

B. Tech
PCMT 4304

Sixth Semester Examination – 2013

MECHANICAL WORKING AND TESTING OF MATERIALS

BRANCH : MME / MM

QUESTION CODE : A 182

Full Marks – 70

Time : 3 Hours

Answer Question No. **1** *which is compulsory and any* **five** *from the rest.*

The figures in the right-hand margin indicate marks.

1. Answer the following questions : 2×10

(a) Define and explain the role of flash gutter.

(b) What is stress-corrosion cracking ?

(c) Explain the reason for designing the complex clusters of rolls.

(d) Draw and explain the distribution of roll pressure along the arc of contact.

(e) In Rockwell hardness test, hardened steel is tested on ________ scale with the ________ indenter and a ________ kg major load.

(f) State the equation of polar moment of inertia in terms of torsion moment and write its dimensions.

(g) Explain the eddy current method of detecting defects.

(h) Briefly explain the crack deformation modes.

(i) Why is a notch in a thick plate far more damaging than in a thin plate ?

(j) What are the three basic factors necessary to cause fatigue failure ?

P.T.O.

2. (a) Discuss the different types of forming processes. 5

(b) Describe the effect of temperature, strain rate, metallurgical structure, frict and lubrication on metal working processes. 5

3. (a) Discuss the significance of ductile to brittle transition temperature curve. 5

(b) Explain the metallurgical factors affecting the ductile to brittle transition temperature. 5

4. Explain the testing procedure and method to determine K_{IC}, the plain-strain fracture toughness. 10

5. (a) Explain with suitable diagrams the open die and closed die forging processes. 5

(b) Derive the expression for mean forging pressure of plate forged in plain strain with suitable diagram. 5

6. (a) Describe the usual procedure for determining an S-N curve and obtaining the fatigue limit of a material. 5

(b) Show and explain the dependence of limiting range of stress and alternating stress in fatigue on mean stress through Goodman diagrams. 5

7. (a) Using simplified theory of rolling express the geometrical relationships of roll diameter, coefficient of friction and sheet thickness for solid and cylindrical bars. 5

(b) Determine the maximum possible reduction for cold rolling a 300 mm-thick slab when $\mu=0.08$ and the roll diameter is 600 mm. What is the maximum reduction on the same mill for hot rolling when $\mu=0.5$? 5

8. Write short notes on any *two* of the following : 5×2

(a) Ultrasonic testing for flaw detection

(b) Comparison between torsion test and tension test in terms of state of stress and strain

(c) Comparison between compression test and tension test.