3.8 . HARDNESS TESTS

Hardness Test

Hardness is a surface property and is defined as the resistance of a material against permanent deformation of scratch, cutting, indentation or mechanical wear.

In various hardness tests, the indenters are used to introduce indentation on the surface. The shape of indenters may be a spherical ball, a cone, or a pyramid. Various hardness test methods are given as below:

1. Brinell's hardness test
2. Rockwell's hardness test.
3. Vicker's hardness test
4. Knoop's hardness test .

3.8.1. Brinell Hardness Test

This test employs a diamond or hardened steel ball as indenter. The ball is placed suitably in the upper housing of Brinell Hardness testing machine shown in the figure below. This machine is called a push-pull button type machine because the indenting load is applied by pushing a button. There are several push buttons, each of them specifies a known load. Before conducting the test, the surface of the specimen is made free from oil, grease, dust and dirt. The indenting load P is applied on the specimen gradually for a minimum of 30 seconds.

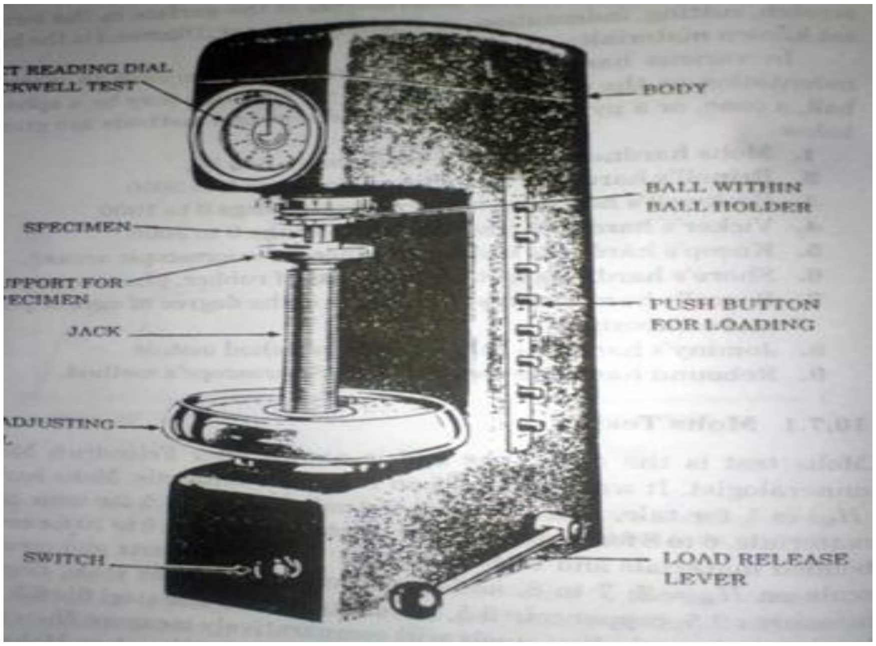


Fig.3.8.1(a). Brinell hardness test machine

The effect of this load is to make an indentation of depth t and diameter d as shown in the figure below:

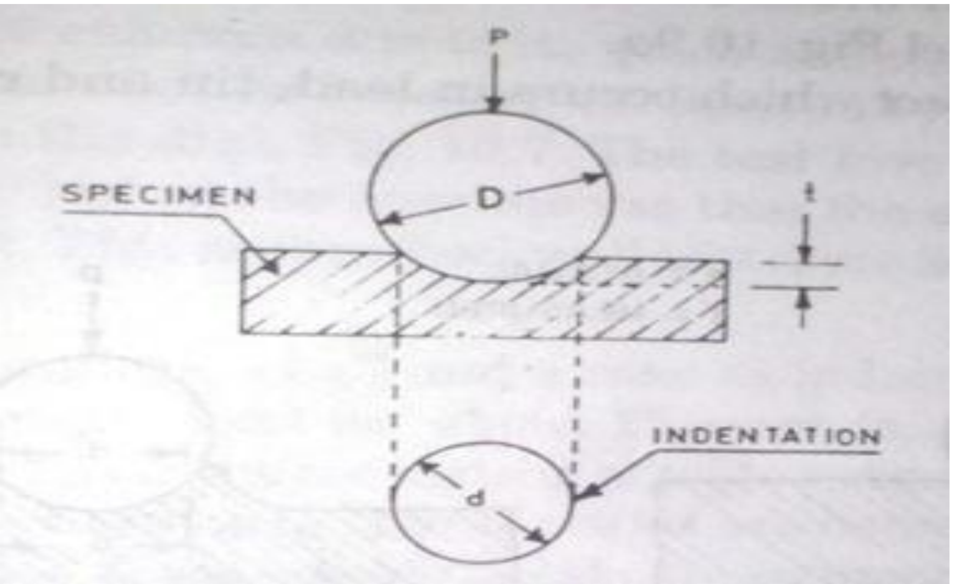


Fig.3.8.1. (b) Indentation due to load

Brinell hardness test showing load, ball diameter, indented diameter and its thickness.

The Brinell Hardness Number (BHN) is then calculated as below after measuringd by an optical microscope.

$$\text{BHN} = \frac{\text{Applied load}}{\text{Area of impression of steel}}$$

$$= \frac{P}{\frac{\pi D}{2}[D - \sqrt{D^2 - d^2}]}$$

Where P-load applied

D- Diameter of steel ball (mm)

d- Diameter of indentation

Scale Information: Test requirements, observations, and limitations of Brinell hardness test can be enumerated as below:

1. The steel ball indenter may be used to test the specimen of cast iron, unhardened steel and light alloys.
2. Standard diameters of the ball are 2.5 mm, 5 mm and 10 mm.
3. Deformation of the ball during application of indenting load is neglected in calculating Brinell hardness number.

4. Usually, the diameter of indentation d = 0.2D to 0.7D.

5. Thickness of the specimen should not be less than 10 times of the impression.

6. If the impression of indentation is non-circular, the mean value should be taken from two diameters that are normal to each other.

7. Value of BHN is expressed in kg/mm2 or N/mm2.

8. For most of the metals, BHN is proportional to their tensile strengths.

9. For steel, the tensile strength = 35 BHN

Drawbacks of Brinell Hardness test:

i).Sinking effect which occurs in manganese steel and austenite stainless steel.

ii)Piling-up effect which occurs in lead, tin and magnesium.

iii)Brinell hardness test is not accurate for BHN > 500, as the ball itself deforms.

3.4 CREEP TEST

CREEP RESISTANCE:

It is the resistance offered by the material for its continuous deformation under steady load.

Creep **(sometimes called** cold flow**) is the tendency of a solid material to move slowly or deform permanently under the influence of persistent mechanical stresses. It can occur as a result of long-term exposure to high levels of stress that are still below the yield strength of the material. Creep is more severe in materials that are subjected to heatfor long periods and generally increases as they near their melting point.**

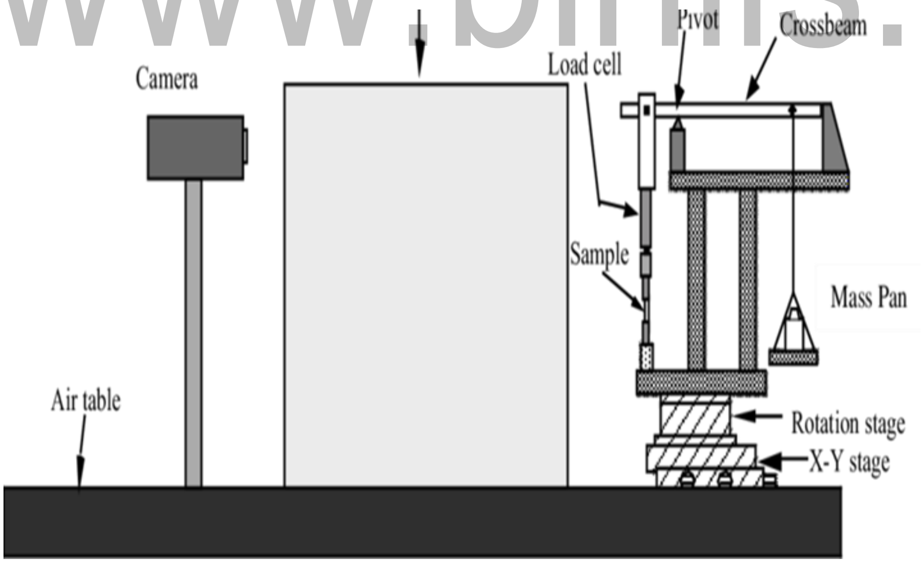


Fig 3.4.1 Creep test machine

Method for determining creep or stress relaxation behaviour. To determine creep properties, material is subjected to prolonged constant tension or compression loading at constant temperature. Deformation is recorded at specified time intervals and a creep vs time diagram is plotted. Slope of curve at any point is creep rate. If failure occurs, it terminates test and time for rupture is recorded. If specimen does not fracture within test period, creep recovery may be measured. To determine stress relaxation of material, specimen is deformed a given amount and decrease in stress over prolonged period of exposure at constant temperature is recorded Viscoplasticity is a theory in continuum mechanics that describes the rate-dependent inelastic behaviour of solids. Rate-dependence in this context means that the deformation of the material depends on the rate at which loads are applied. The inelastic behaviour that is the subject of viscoplasticity is plastic deformation which means that the material undergoes unrecoverable deformations when a load level is reached. Rate-dependent plasticity is important for transient plasticity calculations. The main difference between rate- independent plastic and viscoplastic material models is that the later exhibit not only permanent deformations after the application of loads but continue to undergo a creep flow as a function of time under the influence of the applied load.

The yield surface is usually assumed not to be rate-dependent in such models. An alternative approach is to add a strain rate dependence to the yield stress and use the techniques of rate independent plasticity to calculate the response of a material. For metals and alloys, viscoplasticity is the macroscopic behaviour caused by a mechanism linked to the movement of dislocations in grains, with superposed effects of inter-crystalline gliding. The mechanism usually becomes dominant at temperatures greater than approximately one third of the absolute melting temperature. However, certain alloys exhibit viscoplasticity at room temperature (300K). For polymers, wood, and bitumen, the theory of viscoplasticity is required to describe behaviour beyond the limit of elasticity or viscoelasticity.

In general, viscoplasticity theories are useful in areas such as the calculation of permanent deformations, the prediction of the plastic collapse of structures, the investigation of stability, crash simulations, systems exposed to high temperatures such as turbines in engines, e.g. a power plant, dynamic problem s and systems exposed to high strain rates, deals of rate-independent plasticity that have a rate-dependent yield stress.

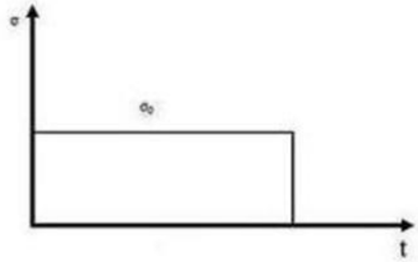


Figure 3a. Creep test

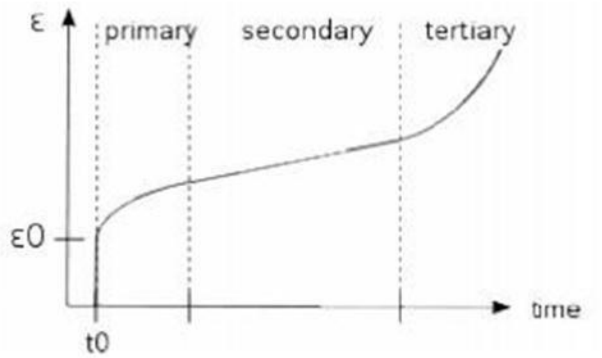


Figure 3b. Strain as a function of time in a creep test.

Creep is the tendency of a solid material to move slowly or deform permanently under constant stresses. Creep tests measure the strain response due to a constant stress as shown in Figure 3a. The classical creep curve represents the evolution of strain as a function of time in a material subjected to uniaxial stress at a constant temperature. The creep test, for instance, is performed by applying a constant force/stress and analyzing the strain response of the system. In general as shown in figure 3b, this curve usually shows three phases or periods of behaviour. A primary creep stage, also known as transient creep, is the starting stage during which hardening of the material leads to a decrease in the rate of flow which is initially very high.

3.7 FATIGUE TEST

Fatigue

Fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading.

Fatigue occurs when a material is subjected to repeated loading and unloading. If the loads are above a certain threshold, microscopic cracks will begin to form at the surface. Eventually a crack will reach a critical size, and the structure will suddenly fracture. The shape of the structure will significantly affect the fatigue life; square holes or sharp corners will lead to elevated local stresses where fatigue cracks can initiate. Round holes and smooth transitions or fillets are therefore important to increase the fatigue strength of the structure.

Fatigue testing apparatus:

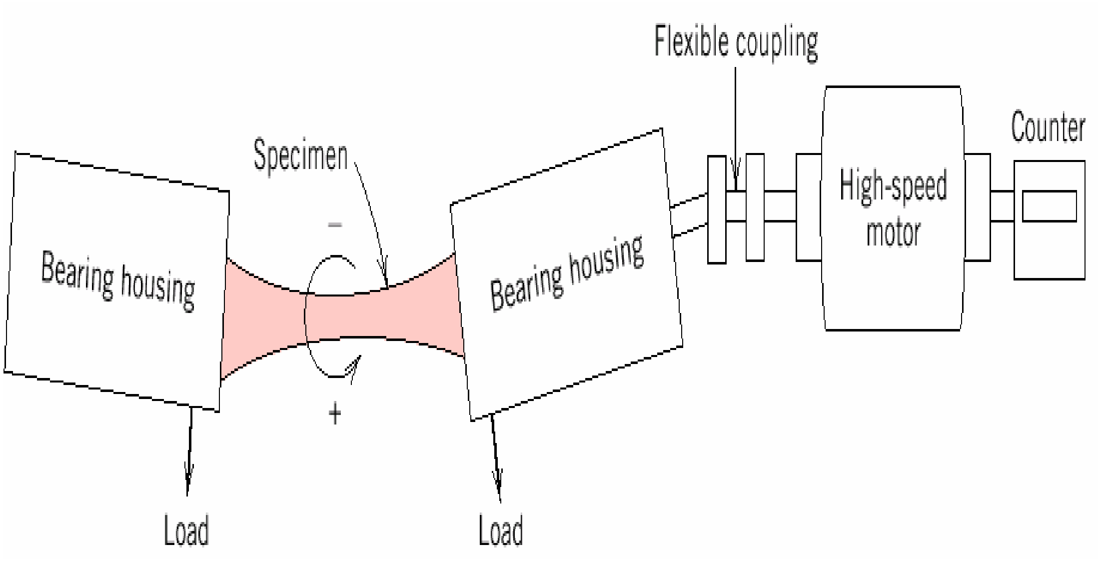


Fig 3.7.1 Fatigue test apparatus

Fatigue: S-N Curves

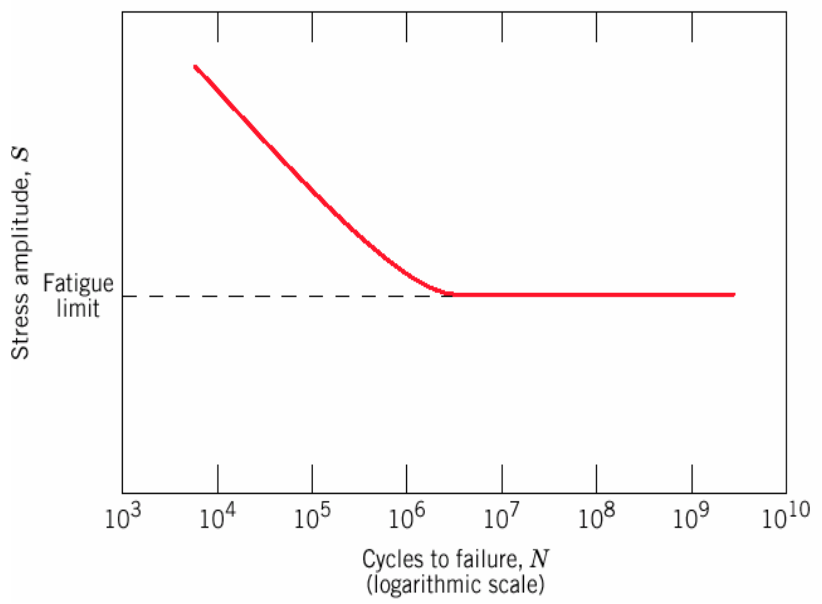


Fig.2.7.2 Fatigue curve

- In metals and alloys, the process starts with dislocation movements, eventually forming persistent slip bands that nucleate short cracks.

- Fatigue is a stochastic process, often showing considerable scatter even in controlled environments.

- The greater the applied stress range, the shorter the life. Fatigue life scatter tends to increase for longer fatigue lives. Damage is cumulative. Materials do not recover when rested. Fatigue life is influenced by a variety of factors, such as temperature, surface finish, microstructure, presence of oxidizing or inert chemicals, residual stresses, contact (fretting), etc.

- Some materials (e.g. steel and titanium alloys) exhibit a theoretical fatigue limit below which continued loading does not lead to structural failure.

- In recent years, researchers have found that failures occur below the theoretical fatigue limit at very high fatigue lives (109 to 1010 cycles). An ultrasonic resonance technique is used in these experiments with frequencies around 10-20 kHz
- High cycle fatigue strength (about 103 to 108 cycles) can be described byload- controlled servo-hydraulic test rig is stress-based parameters commonly

used in these tests, with frequencies of around 20-50 Hz. Other sorts of machines like resonant magnetic machines can also be used, achieving frequencies up to 250 Hz.

- Low cycle fatigue (typically less than 103 cycles) is associated with wide spread plasticity in metals; thus, a strain-based parameter should be used for fatigue life prediction in metals and alloys . Testing is conducted with constantstrain amplitudes typically at 0.01 -5 Hz

3.5 Fracture

Fracture: separation of a body into pieces due to stress at temperatures below the melting point.

Steps in fracture:

- crack formation
- crack propagation

Depending on the ability of material to undergo plastic deformation before the fracture. Two fracture modes can be defined - **ductile or brittle**

- **Ductile fracture** - most metals (not too cold):
  - Extensive plastic deformation ahead of crack
  - Crack is "stable": resists further extension unless applied stress is increased

- **Brittle fracture** - ceramics, ice, cold metals:
  - Relatively little plastic deformation

Crack is "unstable": propagates rapidly withoutincrease in applied stress

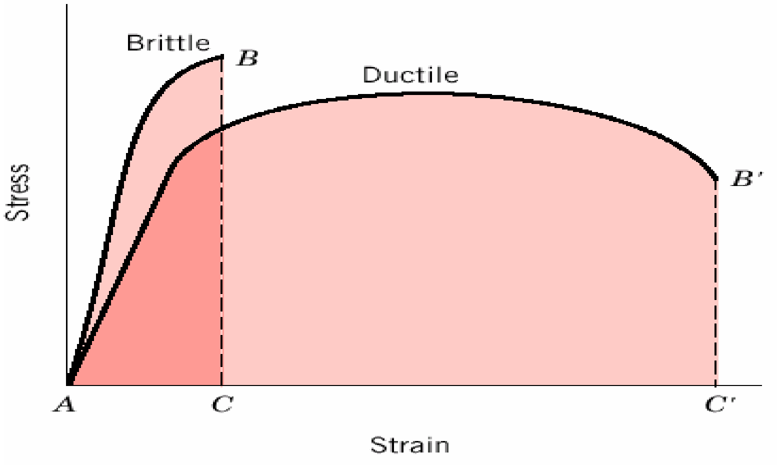
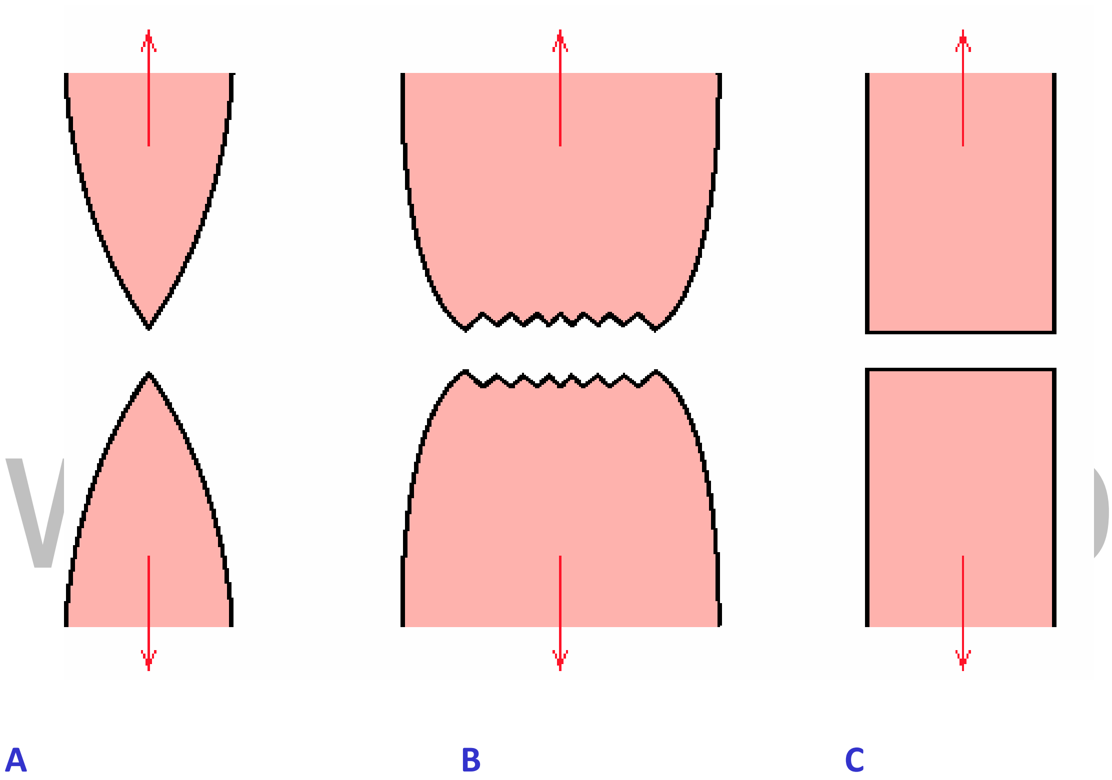


Fig 3.5.1 stress-strain curve

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

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



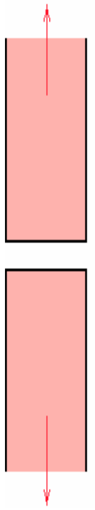
A. **Very ductile**, soft metals (e.g. Pb, Au) at room temperature, other metals, polymers, glasses at high temperature.

B. **Moderately ductile fracture**, typical for ductile metals

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

Brittle Fracture (Limited Dislocation Mobility)

- No appreciable plastic deformation
- Crack propagation is very fast
- Crack propagates nearly perpendicular to the direction of the applied stress
- Crack often propagates by cleavage - breakingof atomic bonds along specific crystallographic planes (cleavage planes).



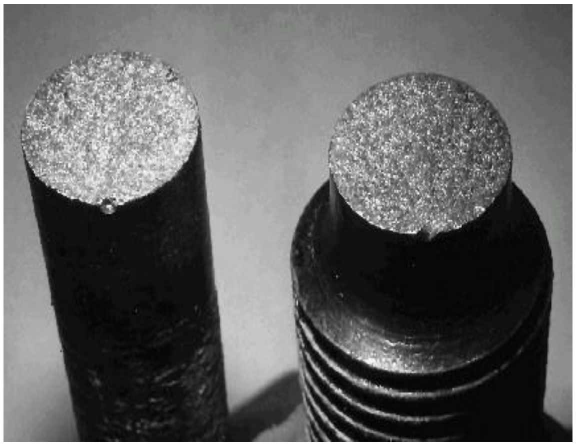
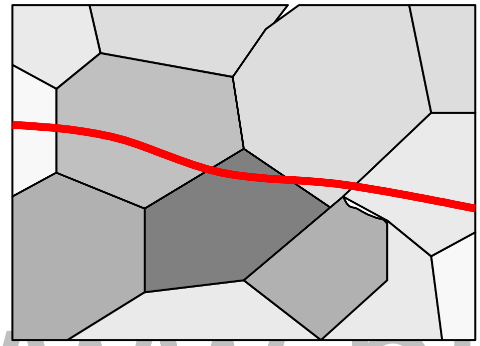


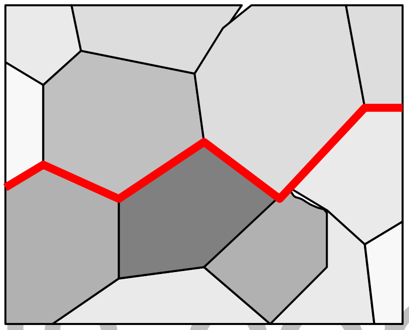
Fig 3.5. 2 brittle fracture in a mild steel

Brittle Fracture-Types

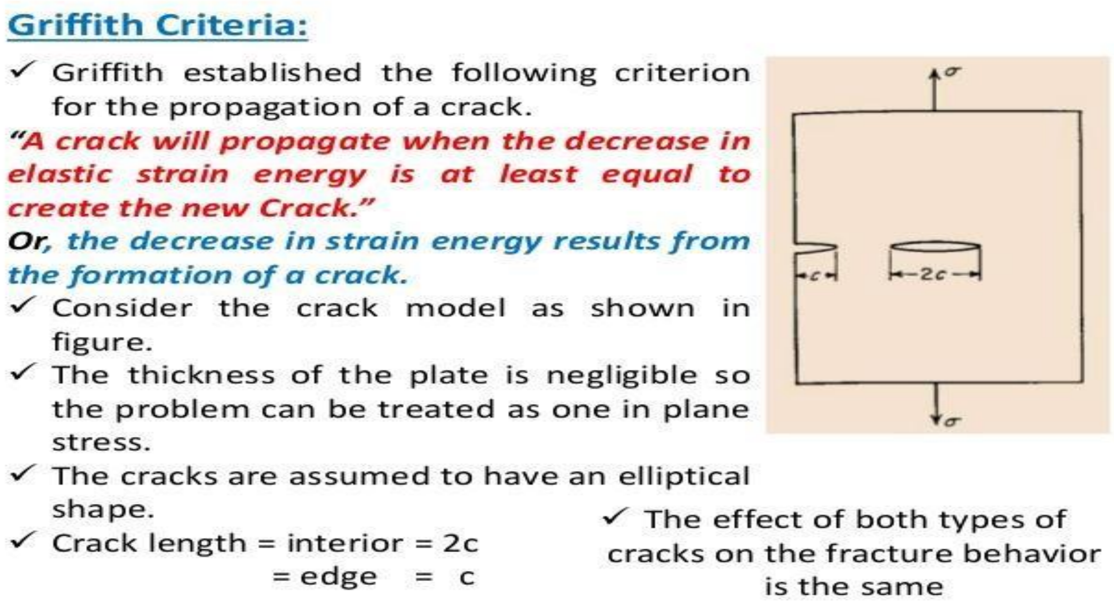
A. **Trans granular fracture**: Fracture cracks pass throughgrains. Fracture surface have faceted texture because of different orientation of cleavage planes in grains.

B. **Inter granular fracture**: Fracture crack propagation is along grain boundaries (grain boundaries are weakened by impurities segregation etc.)





3.6 Griffith Criteria



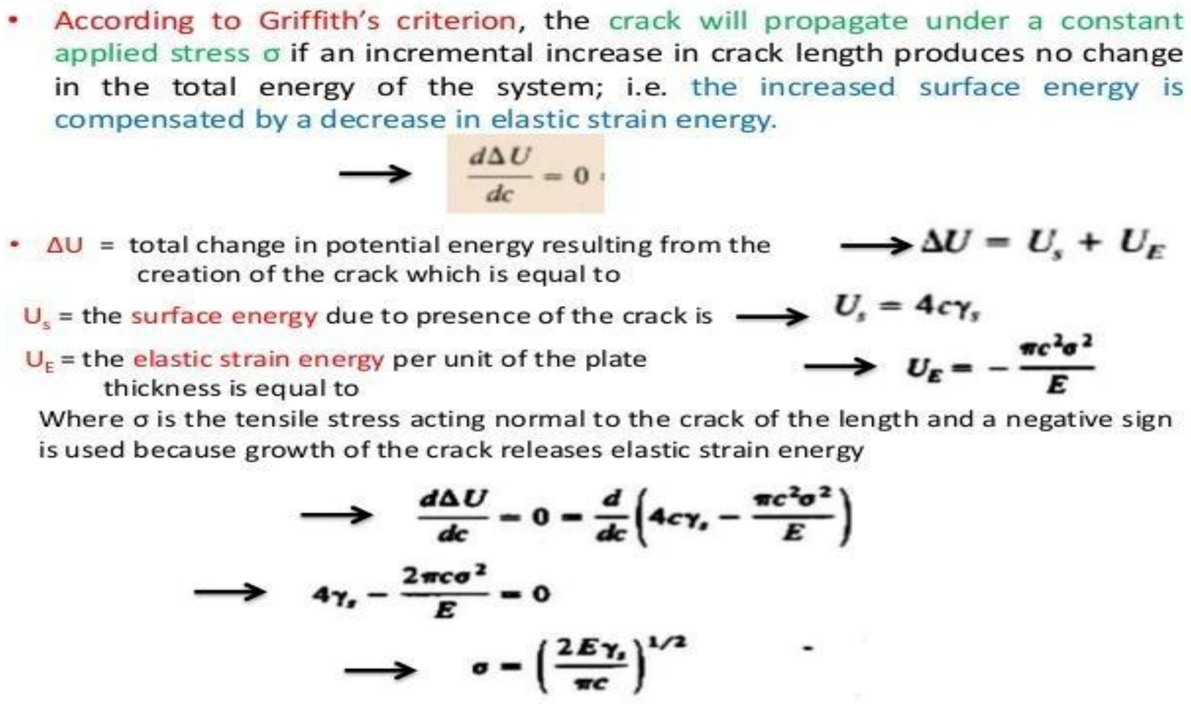
Griffith Criteria:

- ✓ Griffith established the following criterion for the propagation of a crack.

"A crack will propagate when the decrease in elastic strain energy is at least equal to create the new Crack."

Or, the decrease in strain energy results from the formation of a crack.

- ✓ Consider the crack model as shown in figure.
- ✓ The thickness of the plate is negligible so the problem can be treated as one in plane stress.
- ✓ The cracks are assumed to have an elliptical shape.
- ✓ Crack length = interior = 2c
  = edge = c
- ✓ The effect of both types of cracks on the fracture behavior is the same



- According to Griffith's criterion, the crack will propagate under a constant applied stress σ if an incremental increase in crack length produces no change in the total energy of the system; i.e. the increased surface energy is compensated by a decrease in elastic strain energy.

$$\longrightarrow \boxed{\frac{d\Delta U}{dc} = 0}$$

- ΔU = total change in potential energy resulting from the creation of the crack which is equal to $\longrightarrow \Delta U = U_s + U_E$

U_s = the surface energy due to presence of the crack is $\longrightarrow U_s = 4c\gamma_s$

U_E = the elastic strain energy per unit of the plate thickness is equal to $\longrightarrow U_E = -\frac{\pi c^2\sigma^2}{E}$

Where σ is the tensile stress acting normal to the crack of the length and a negative sign is used because growth of the crack releases elastic strain energy

$$\longrightarrow \frac{d\Delta U}{dc} = 0 = \frac{d}{dc}\left(4c\gamma_s - \frac{\pi c^2\sigma^2}{E}\right)$$

$$\longrightarrow 4\gamma_s - \frac{2\pi c\sigma^2}{E} = 0$$

$$\longrightarrow \sigma = \left(\frac{2E\gamma_s}{\pi c}\right)^{1/2}$$

3.8.4 Knoop Hardness Test

A rhombic pyramid as shown in the figure below is used as the indenter in this test. The included angle α of the pyramid is 72.5° and 130°.

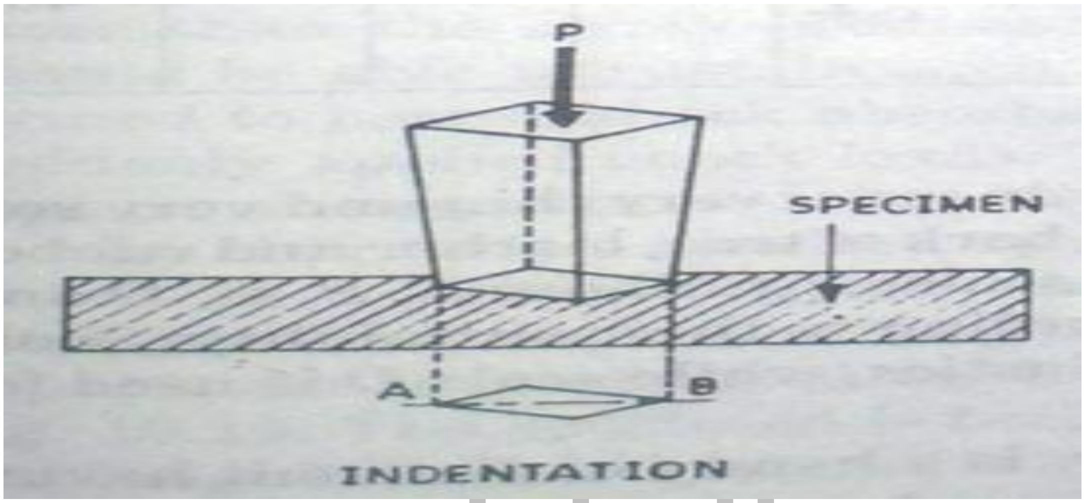


Fig3.8.4(a)b Rhombic pyramid indenter and its indentation in Knoop's test

Knoop hardness Number (KHN)

Knoop Hardness Number is determined from the following expression

KNP = $(14.229\ P)/d^2$

Where KHN – Knoop Hardness Number

P – Applied load (Kg)

D – Length of longer diagonal (mm)

Construction

Knoop Hardness Testing Machine consists of Knoop indenter tip ,anvil,high resolution optical microscope and other accessories to measure the impression.

Testing Procedure:

1.The diamond indenter is pressed into the surface of the sample.

2.The test load is maintained for a dwell period of time.

3.The indenter is removed after the dewell time.

4.The indenter produces an elongated diamond shaped image on the surface of the sample.

5.The hardness is determined by using

$$\text{KNP} = \frac{14.229\, P}{d^2}$$

Precautions:

1.Micro hardness require extra care in all stages of testing.

2.Good polishing of the surface is required.

Advantages:

1.The diagonals of the square indentation can be measured more accurately.

2.This method is suitable for hard materials as well as for soft materials.

Disadvantages and Limitations:

1.The accurate measurement of indenting size is very difficult and it requires high polished surface.

2.It consumes time for measurement.

3.The long diagonal of Knoop indentation is affected by elastic recovery for loads less than 300g.

Applications:

This hardness test is used for testing of materials such as wires ,springs, watches ,gears, tools ,tips ,plated surface, coatings, hardness of particular phase in micro structure etc.

3.2 **Plastic Deformation**

Permanent deformation of materials, on application of a load is called plastic deformation. If such a deformation takes place at elevated temperature (more than 40% of absolute melting point of the metal, $0.4T_m$), then it is call creep. Plastic deformation can occur under tensile, compressive or torsional stresses. Here engineering stress and strain are given by

$$\text{Stress, } \sigma = \frac{P}{A_o} \quad \text{Strain } \varepsilon = \frac{\Delta l}{l}$$

Where P is the applied stress

A_o is the initial cross-sectional area

Δl is the fractional change in the gauge length of the sample

l is the original length of the sample

Plastic deformation corresponds to the motion of a large numbers of dislocations. There are two types of fundamental dislocations, vis., edge dislocation (slip) and screw dislocation (twin). Slip deformation is the result of lattice distortion, which moves along dislocation line in a direction perpendicular to applied stress. Deformation due to twinning is a result of a shear distortion at the dislocation line passes through the center of a spiral plane.

Mechanism of plastic deformation by slipping

Slip mode of deformation is a shear deformation that moves atoms by many inter-atomic distances from initial position. The orientation of the all parts of the crystal remains the same before and after slip. Thus, even though imperfections are introduced during plastic deformation, X-ray diffraction pattern shows that the crystal structure remains same.

The slipping take place along the plane called ***slip plane***. The slip planes are closely packed atomic planes within the crystal with greatest atomic density (higher number of atoms per unit area). The direction along which slip occurs called slip directions are the closest packed planes in the crystal.

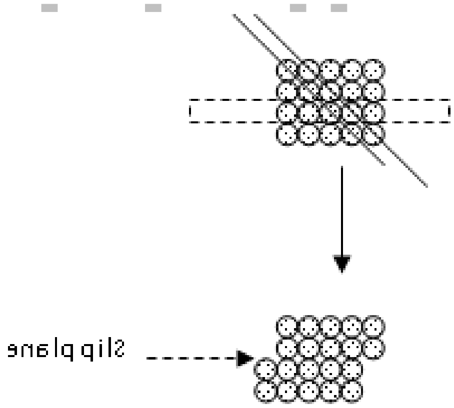


Fig.3.2.1 slip

In the case of ionic crystals, the slip planes and slip directions are such that the ions of the same polarity do not become juxtaposed as nearest neighbors during shear, since, this will increase potential energy of the crystal to a great extent.

Slip system

A slip plane and a slip direction that lies on to it together constitute a slip system. For example, in FCC system, a combination of (111) and [110] form a slip system, but not (111) and [110], as the direction [110] does not line on (111) plane. There are 12 slip systems in FCC and BCC crystals, while in HCP there are only 3 slip systems.

Critically resolved shear stress (CRSS)

CRSS is a parameter which decides whether the applied stress can cause slip or not in a particular plane.

Deformation by slip mode in the crystal takes place on application of shear stress through slip plane in slip direction. When the tensile or compressive stress is applied, the shear component exists in all directions. The shear component existing in a direction parallel and perpendicular to the applied stress, is called resolved shear stress. Their magnitude not only depends on the applied stress, but also on the orientation of both slip plane and slip direction within that plane.

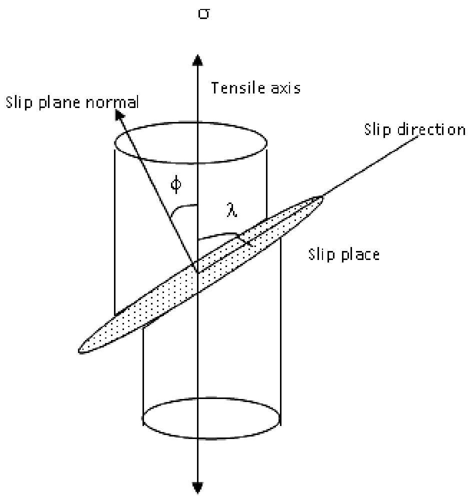


Fig 3.2.2 slip direction

Let ϕ represent the angle between normal to the slip plane and the applied direction, and λ be the angle between slip plane and stress direction, then the resolved shear stress, τ_R is

$\tau_R = \sigma \cos\phi \text{ cost } \lambda$

Where σ is the applied stress.

In the case of a metal single crystal, there are a number of slip systems that can lead to slip deformation. But they differ in a way that, the direction of applied stress, which may not be the same. Hence, the slip system, which is favourably oriented will have largest resolved shear stress ($\tau_{R(max)}$) which is written as

$\tau_{R(max)} = \sigma\, (\cos\phi \text{ cost } \lambda)_{max}$

Thus, when the resolved shear stress in the most favoured slip system reaches a critical value, then only the slip deformation takes place. This is called ***Critical resolved shear stress***, $\tau_{crss.}$ It is represents the minimum shear stress required to initiate the slip, i.e., when $\tau_{R(max)} = \tau_{crss}$**,** then deformation takes place, and this point is the yield strength σ_y and is given as:

$$\sigma_y = \frac{\tau_{crss}}{(\cos\phi\ \cos\lambda)_{\max}}$$

Mechanism of deformation by twinning

The second important mechanism of plastic deformation is twinning. It results when a portion of crystal takes up an orientation that is related to the orientation of the rest of the untwined lattice in a definite, symmetrical way. The twinned portion of the crystal is a mirror image of the parent crystal. The plane of symmetry is called twinning plane. Each atom in the twinned region moves by a homogeneous shear a distance proportional to its distance from the twin plane. The lattice strains involved in twinning are small, usually in order of fraction of inter-atomic distance, thus resulting in very small gross plastic deformation. The important role of twinning in plastic deformation is that it causes changes in plane orientation so that further slip can occur. If the surface is polished, the twin would be still visible after etching because it possess a different orientation from the untwined region. This is in contrast with slip, where slip lines can be removed by polishing the specimen.

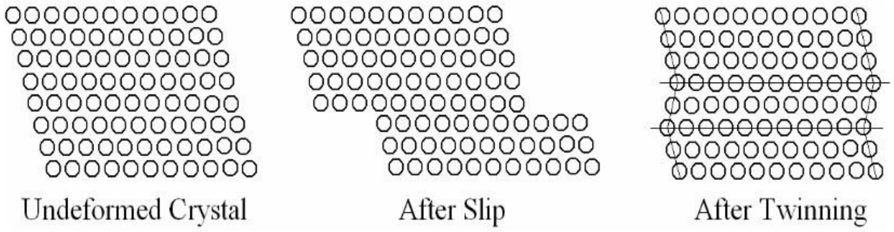


Fig 3.2.3 Twinning

3.8.2 Rockwell Hardness Test

This test is more common due to its quick and simple method. There is no need of any calculation because the Rockwell Hardness (HR) may be read directly on the dial. The test involves application of an initial load of 10 kg on the specimen so that the effects of dust, dirt, oil, etc., are nullified. This makes Rockwell test more accurate than Brinell test.

Scale	**Type of indenter**	**Initial load (kg)**	**Major load (kg)**	**Pointer position**	**Kind of material**
A	Cone, 120°	10	50	0	Much harder such as carburized steel, cemented carbides
B	Ball, 1.58 mm	10	90	30	Soft steels, copper, aluminium, brass, grey cast iron
C	Cone, 120°	10	140	100	Hard steels, Ti, W, V, Etc.
D	Cone	10	90	-	Thin ferrous metals
E	Ball, 3.0 mm	10	90	-	Very soft such as bearing metals, magnesium alloys, etc.
F	Ball, 1.58 mm	10	50	-	Soft such as babbitts, bronze, brass, etc.

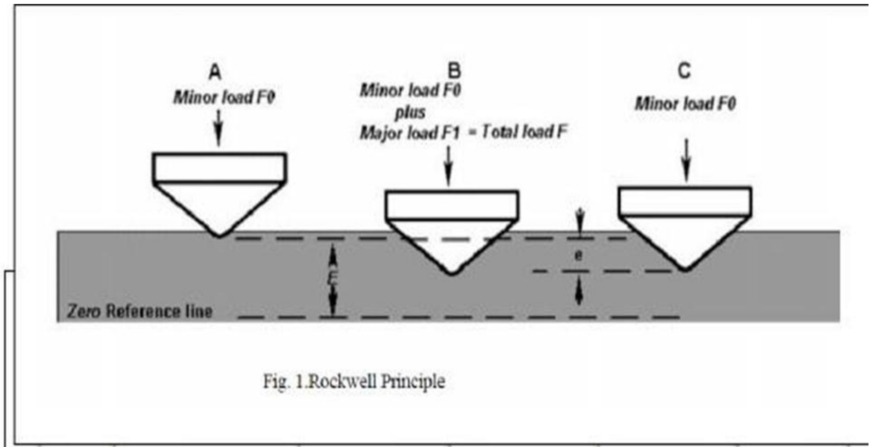
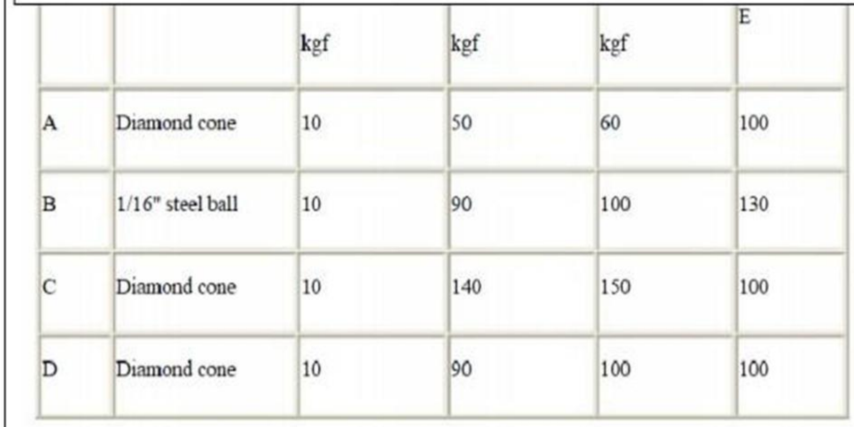


Fig. 1.Rockwell Principle



		kgf	kgf	kgf	E
A	Diamond cone	10	50	60	100
B	1/16" steel ball	10	90	100	130
C	Diamond cone	10	140	150	100
D	Diamond cone	10	90	100	100

Fig 3.8.1(b) Indentation due to load

This test employs a ball and a cone as indenters. The specimen is subjected to a major load for about 15 seconds, after the initial load. These scales are named as A, B, C, D, E, F, M, R, etc. Of these B-scale and C-scale are commonly employed.

B-scale is preferred for soft steels and aluminium alloys, while C-scale is chosen for titanium and hard steel. B-scale employs a ball of 1/16 inch (1.58 mm) diameter. A cone indenter is used in C-scale with an angle of 120° and point of radius 0.2mm. hardness value determined from B-scale is referred to as HRB and from C-scale as HRC.

Different scales, initial and major loads to be given on them, their suitability to kind of materials and other related details are given in the table. If the depth of penetration in mm is known then the hardness may also be calculated from the following relation.

$$\mathrm{HRA} = 100 - \frac{t}{0.002}$$

$$\mathrm{HRB} = 130 - \frac{t}{0.002}$$

$$\mathrm{HRC} = 100 - \frac{t}{0.002}$$

Rockwell hardness method may be used to determine hardness of wires, blades, inside and outside cylindrical surfaces such as in IC engine cylinder and piston. Finished components can also be tested by this method as the indentation made is small. This method is suitable for hardness beyond the range of Brinell hardness.

Precautions:

- Successive impressions should not be superimposed on one another, nor made too close.
- Thin specimen or edge should not be selected.
- Care should be taken for surface preparations, because small size impressions are made.
- The surface of specimen should be flat and free from spring action.

Advantages

- It is more flexible than Brinell test. Large combinations of indenters and loads are available.
- Rockwell testers are fitted with number of fixtures for testing different size and shapes.
- The measurement can be made quickly.
- Since, impressions made are small, it is considered as non-destructive.

Limitations:

- Requires great care for sample preparation.

3.3 Strengthening Methods

To meet the challenges of advanced technologies, new materials are need to be developed. The new and conventional materials desire their strengthening and hardening so as to withstand varying functional conditions. The behavior of a solid depends on its chemical composition, mechanical properties and thermal processing. Heat treatment, casting, hot-working, sintering, etc., are the thermal processes that influence the mechanical properties by changing grain sizes and phases. Accumulation of dislocations during plastic deformation also adds to the strength of a metal. Various strengthening and hardening mechanisms are

a) Strain hardening

b) Precipitation hardening (Age hardening)

c) Dispersion hardening

d) Solid-solution hardening

Cold Working

Working means processing or operations regarding fabrication of metals to some desired shapes. These processes may be rolling, forging, embossing, etc. When the processes are carried out below the re crystallization temperature ($0.3T_m$ to $0.5T_m$), these are known as cold working processes.

The advantages during cold working is given below:

i) Increase in the hardness

ii) Increase in the yield and ultimate strengths

iii) Decrease in ductility

iv) Slight decrease in density

v) Decrease in electrical conductivity

vi) Distortion in the microstructure of metals

vii) Formation of crystal defects

viii) Improved surface finish

ix) Closer dimensional tolerances

x) High mechanical energy required to cause plastic deformation

xi) Raising of re crystallization temperature of metals

The amount of cold working is expressed as percent of cold work. This indicates the percent reduction of thickness, or reduction in area of this metal. The percent cold working may be determined from

$$\%CW = \frac{t_o - t_d}{t_0} \times 100$$

or

$$\%CW = \frac{A_0 - A_d}{A_0} \times 100$$

Where t_o and A_o are the initial thickness and cross-sectional area; t_d and A_d are thickness and cross-sectional area after deformation, respectively. The effect of cold working on the hardness of some materials is shown in the figure below.

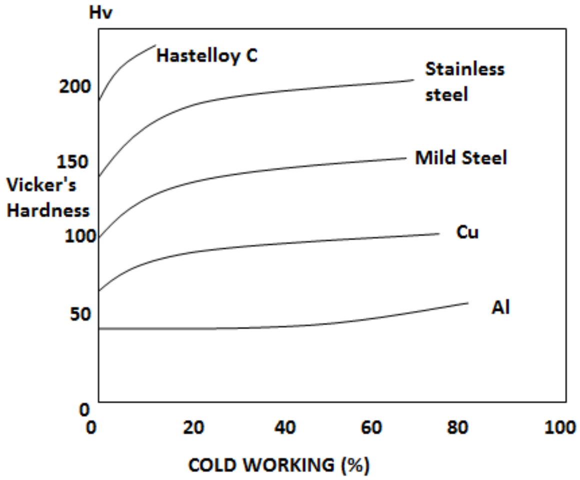


Fig 3.3.1 cold working

It indicates that the hardness increases with increasing cold working. Increase in tensile strength with a corresponding reduction in elongation due to enhancing amount of working in mild steel is depicted in figure below. The defects induced due to cold working is removed or minimized by ***annealing*** a heat treatment process.

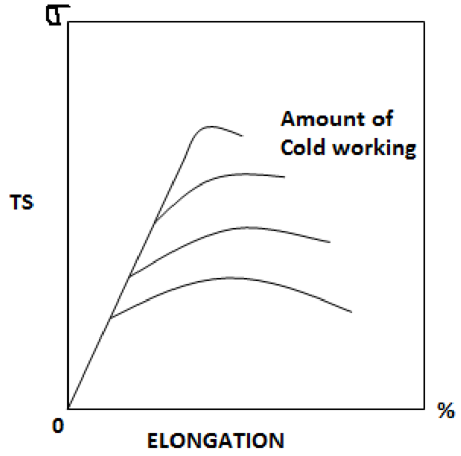


Fig 3.3.2 Annealing

Strain Hardening (Work Hardening)

Strain hardening (or work hardening) is a phenomenon in which steeply rising tensile stress-strain behavior is noticed after yielding. During strain hardening in ductile materials, an increase in stress is needed to produce further strain in the plastic region. Each increment of strain strengthens and hardens the material so that a larger stress is needed for further straining (deforming) of material. The stress-strain behavior during this phenomenon is shown in Figure below. Initially, the slope of curve is upward which gradually lowers down. The increasing stresses $\sigma_4 > \sigma_3 > \sigma_2 > \sigma_1$ are required to cause increasing strains $\varepsilon_4 > \varepsilon_3 > \varepsilon_2 > \varepsilon_1$.

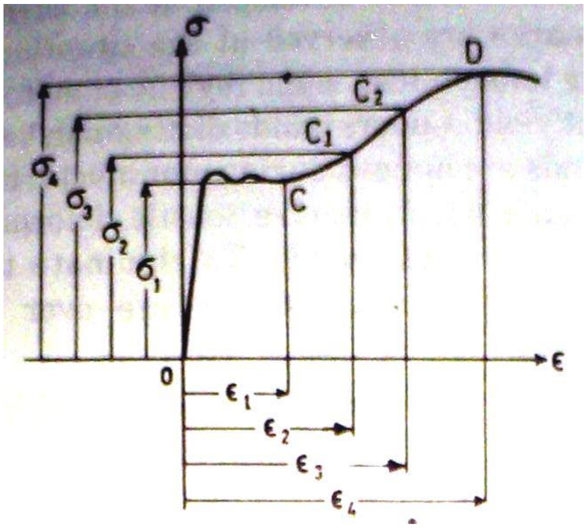


Fig.3.3.3 Strain hardening showing ever increasing stress required to cause increasing strain during CD part of stress-strain curve.

Mechanism of the Process

Strain hardening cannot occur if any one of the following situations are not present.

1. Dislocations
2. Obstacles and
3. Back stresses

Strain hardening is mainly accounted for by dislocations and their interactions. We shall first study the case of interaction of like and unlike dislocations existing on the same plane. If the Burgers vector of these dislocations is the same, the net effect will be annihilation of dislocations. Hence, no strain hardening will be produced in the material.

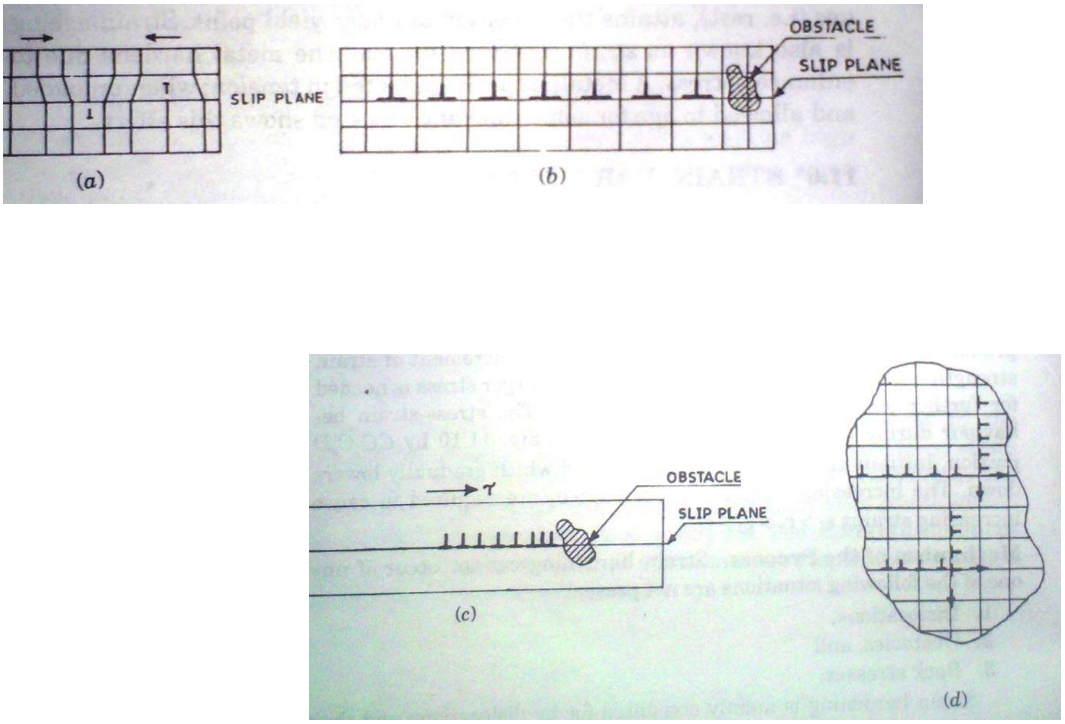


Fig 3.3.4 Mechanism of strain hardening showing (a) like and unlike dislocations annihilating each other (b) like dislocations on the same slip plane (c) crowded dislocations stopped by an obstacle, and (d) collision of dislocations on intersecting planes.

Consider the case of similar dislocations (Fig. b above). If for any reason, similar dislocations approach each other, they interact in such a way that the stress and strain field will cause increased strain energy. When these like dislocations lying on the same slip plane, move under the influence of shear stress τ, they are encountered by an obstacle lying within the material. The obstacle may be natural or manmade. Cementite in steel and oxides in non-ferrous metals are the examples of natural obstacles. Grain boundaries and other imperfections are manmade obstacles. The dislocations are stopped by the obstacle which they cannot break or by-pass and hence get crowded (Fig. c above). Now a back stress sets-up. The entire slip on that place is brought to halt. To produce further slip, τ has to be increased to overcome the obstacle. Stress required to move a dislocation in stress field of dislocation density ρ_d is given by

$$\tau = \tau_o + \lambda \sqrt{\rho_d}$$

where, τ_o is the stress to move dislocation with zero dislocation density and λ is a constant.

Initially, the slope of the curve CC_1C_2D is upwards. In due course of loading, it slops down when obstacle becomes weaker and dislocations move gradually. It is an indication of diminishing strain hardening.

In above discussion, we considered dislocations on a single slip plane. As there are several slip planes in most of the crystals, the dislocations interact on these intersecting slip planes and hinder the movement of each other. Consequently, they accumulate within the material and result into strain-hardening.

Effect of strain-hardening:Cubic crystals strain harden more than hexagonal crystals. Hexagonal crystals have only one set of slip planes whereas the cubic crystals have several slip planes. These are prone to multiple slip. Polycrystals have higher rate of strain hardening than the single crystal. It is because the dislocations find additional obstacles in the form of crystal boundaries.

Strain hardening occurs in all the metals and ceramics. To a material scientist, this phenomenon is good and bad both. It is useful in that this is a material strengthening method. It is not useful in a process like rolling of thin metal sheet where yield strength rises to a limit which is difficult to work. Rolling can proceed further by annealing the metal to remove accumulated dislocations.

UNIT-3

MECHANICAL PROPERTIES

Mechanical properties of materials play a vital role in the development of structures , machines and other products. Normally these constructions are subjected to natural and manmade loads under widely varying environments and temperatures.

STRENGTH OF ENGINEERING MATERIALS

3.1 TENSILE TEST

Tensile testing is one of the simplest and most widely used mechanical **tests**. By measuring the force required to elongate a specimen to breaking point, material properties can be determined that will allow designers and quality managers to predict how materials and products will behave in their intended applications.

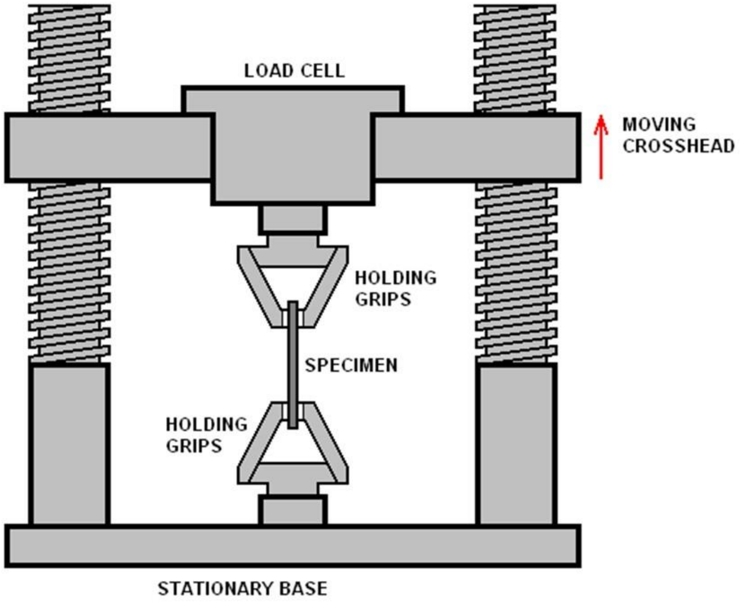


Fig.3.1.1 Tensile test machine

The permanent deformation of materials on the application of a load can be either plastic deformation or creep. In crystalline materials, at temperatures lower than $0.4T_m$, where T_m is the melting point in Kelvin, the permanent deformation is called ***plastic deformation***. In this temperature range, the amount of deformation that occurs after the application of load is small enough to be ignored. The rate at which the material is deformed may, however, play a role in determining the deformation characteristics. At temperatures about $0.4T_m$ permanent deformation continues as a function of time, following the application of the load. This behaviour is termed as ***creep***.

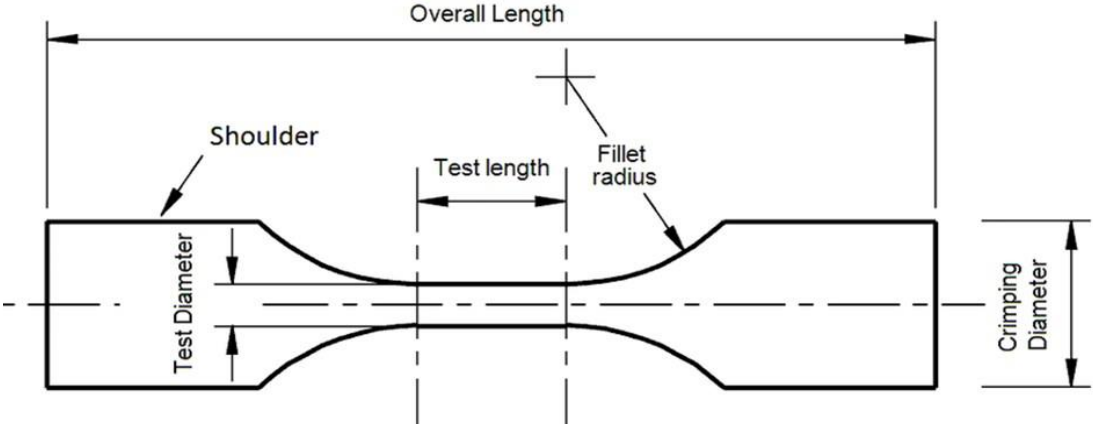


Fig 3.1.2 Tensile test specimen

Tensile Strength

Plastic deformation can occur under tensile, compressive or torsional loads. A typical tensile stress-strain curve is shown below. The applied load is plotted against the elongation or extension of the test specimen. The applied load P divided by the initial cross-sectional area A_o of the specimen gives the engineering stress:

Engineering stress = P / A_o

Engineering strain is given by the fractional increase in the gauge length l_o;

Engineering strain = $\Delta l / l_o$

Where, Δl is the increase in gauge length.

The deformation of the specimen is elastic up to the yield point, beyond which it becomes plastic. The load at the yield point divided by the initial cross-sectional area of the test specimen is called ***yield stress*** or ***yield strength*** of a material. Mild steel exhibits a clearly defined yield point, but a number of other materials do not have a clear demarcation between the elastic and the plastic regions.

Beyond the yield point, the linear elastic region is followed by a non-linear plastic region. In this region, the load required to cause further deformation increase with increasing strain. This phenomenon is called ***work hardening***. The slope of the load-elongation curve decreases, as the elongation increase. It becomes zero at some maximum load. The engineering stress corresponding to the maximum load is called the ***ultimate tensile strength*** (UTS) of the material. Beyond this maximum a neck forms in the middle of the specimen, where the cross-sectional area locally decreases. The applied load decreases up to the point of fracture, where the specimen breaks into two pieces across the reduced cross-section of the neck.

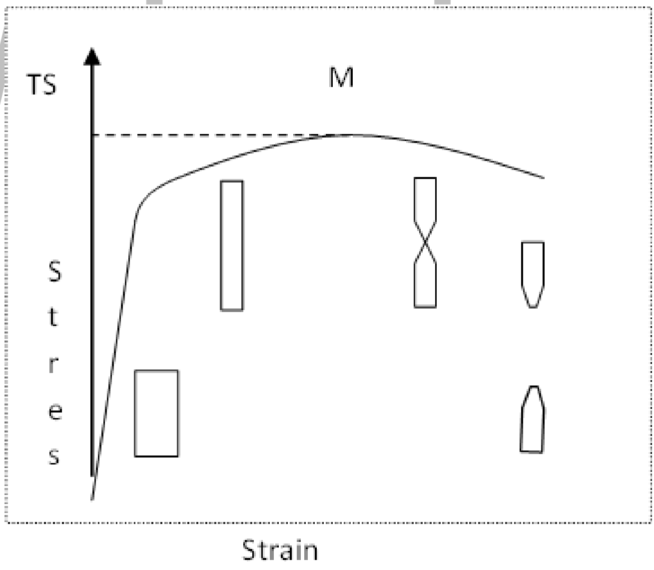


Fig3.1.3 The tensile load-elongation curve

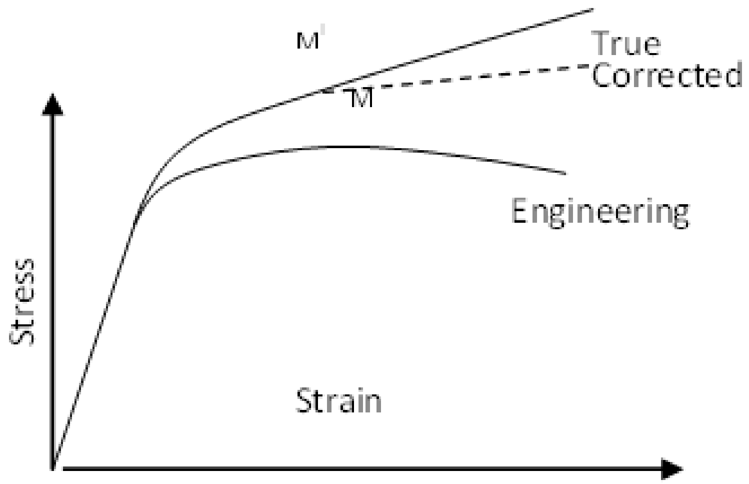


Fig.3.1.4Stress-Strain curve

It is observed from the above figure, that after the necking point, the strength of the deformed portion becomes weaker. The strength is calculated by load divided by original cross-section area. In the real sense, it is the reverse, after necking that portion becomes stronger. Since the cross-section area decreases rapidly after necking, the True stress is calculated as the applied load divided by the instantaneous cross-sectional area. i.e.,

$$\text{Truestress } \sigma_T = \frac{P}{A} \text{ and Truestrain } \varepsilon_T = \ln \frac{l_i}{I}$$

When the deformation of the specimen becomes non uniform after necking starts the true strain becomes a function of the length over which it is measured. In order to avoid ambiguity, it is specified as the integral of – dA /A, where, A is the cross-sectional area at the neck. The true stress-true strain curve is plotted and unlike the load-elongation curve, there is no maximum. The slope in the plastic region decreases with increasing strain, but does not become zero before fracture. This indicates that there is not work hardens continuously till fracture, although at a decreasing rate.

3.8.3 Vickers Hardness Test

This test is similar to Brinell test but uses a different type of indenter. A square based pyramid indenter of cone angle α = 136° between opposite faces of pyramid is used. The applied loads may be 5, 10, 30, 50, 100 or 200 kg. The Vickers hardness HV is calculated from the following equation.

$$H_V = \frac{P}{| d^2 / 2 \sin\alpha / 2]}$$

$$= \frac{1.8544P}{d^2} \text{ for } \alpha = 136^o$$

Where, P is the applied load in kg, d is the diagonal length in mm of indentation made by the pyramid. The indenter and the indentation are shown in the figure below.

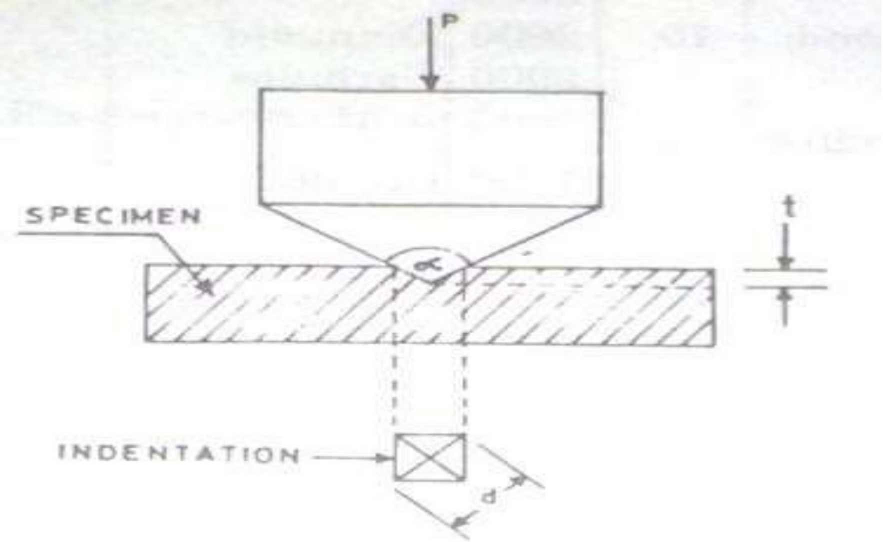


Fig.3.8.3(a) Square based pyramid indenter in Vicker's test

The test performed for similar cross-sections, very hard materials, polished and nitride surfaces, and very thin test pieces.

Testing Procedure:

1.The specimen is placed on the anvil.

2.Load is applied and then indenter is pressed on the surface of the sample.

3.Force is maintained for a period 10 t0 15 seconds known as dwell time.

4.The indenter is removed from the sample after the dwell time.

4. Indenter leaves a square indentation .

5.The two diagonal lengths of the square indenter on the sample is measured using optical microscope.

Advantages

- Greater precision in measurement compared to spherical ball in Brinell test.
- It can be used for test very hard materials, since diamond is used.

Limitations

- Complicated and expensive
- Can be considered for micro hardness testers, since, they cause small size impressions.