LECTURE NOTES

On

Material Testing

Course

code:Th1

Semester: 4th

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Introduction:

Material testing is of 2 types.

i. Destructive testing

ii. Non-Destructive testing

i. Destructive testing: -

Testing up to failure & the sample will not be used further.
e.g. Hardness test, tensile test, Creep test, Fatigue test.

ii. Non-Destructive testing: -

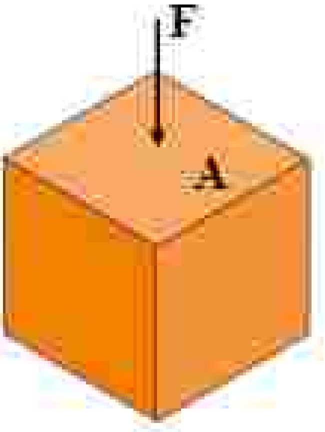
The sample doesn't damage during testing & can be used further.
e.g. Eddy current test, Ultrasound test, X-ray Radiography.
These tests are carried out on materials to determine the mechanical properties like: -

- Strength – Yield strength, Ultimate Tensile Strength
- Ductility
- Toughness
- Resilience
- Young's Modulus
- Hardness
- Impact toughness
- Creep strength
- Fatigue strength

1. TENSILE TEST

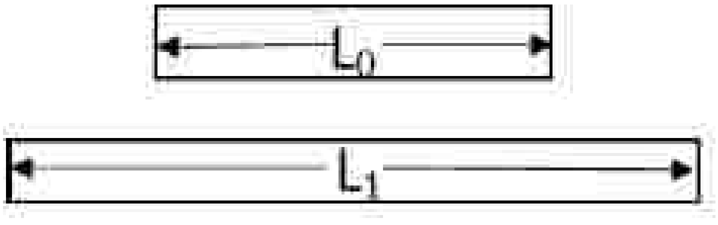
Stress: - Force acted upon unit area.

Stress = F/A = N/m^2 = Pa



Strain: Change in length to initial length. (Dimensionless)

Strain = $(L_1-L0)/L0 = \Delta L/L0$ (for expansion)



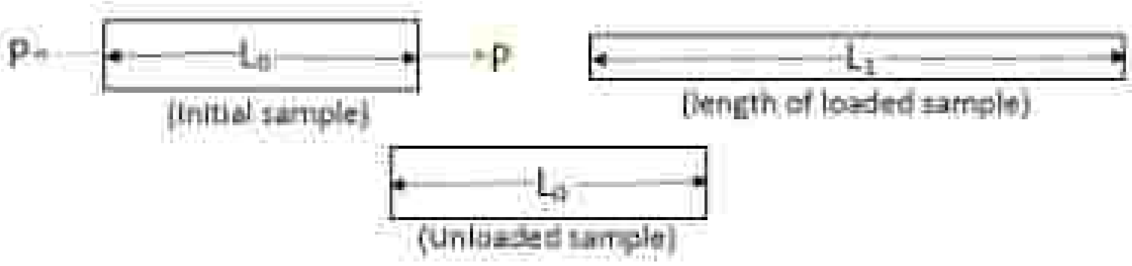
Deformation: - Change in shape of a material due to application of load.

It is of 2 types

a. Elastic Deformation

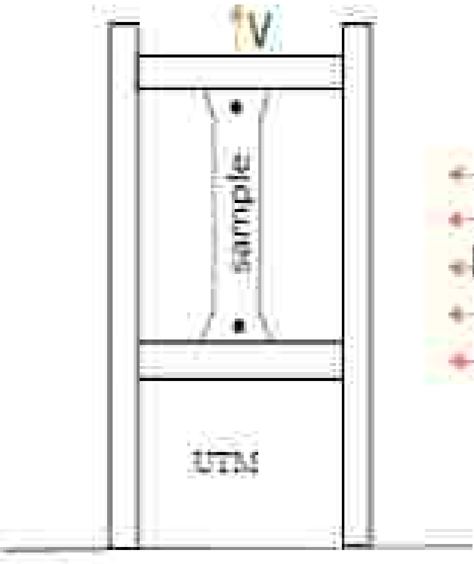
b. Plastic Deformation

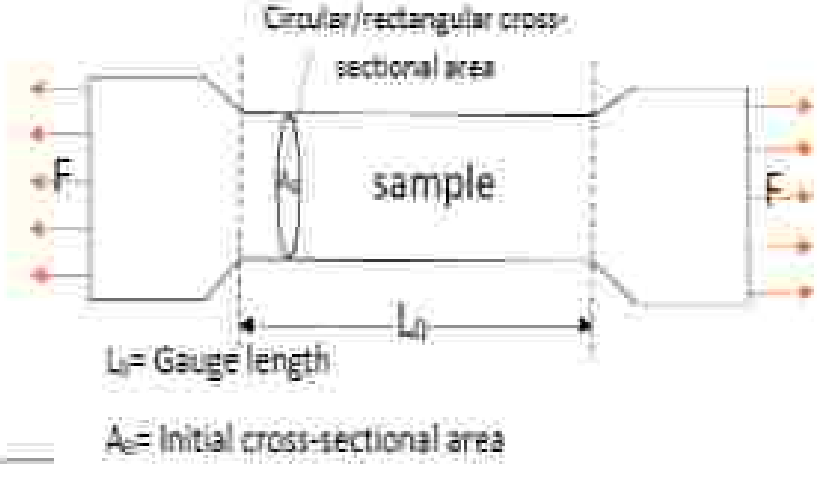
a. *Elastic Deformation:* - The sample is deformed on application of load but it comes back to its original shape once the load is removed. Hence, it's a temporary deformation.



b. *Plastic Deformation:* - The material doesn't come back to its original shape after removal of load. Hence, it's a permanent deformation.

Tensile Testing:





- It is carried out on universal testing machine (UTM).
- The tensile test sample is gripped at both ends as shown in the figure.

- The sample is loaded by moving the cross head at a constant velocity (strain rate).
- As the load F increases the length of the sample changes from L_0 to L.
- Change in length or elongation (ΔL) = L-L_0.

$$\text{Engineering stress } (\sigma) = \frac{\textit{Instantaneous load/force}}{\textit{Initial crosssectional area}} = \frac{F}{A0}$$

$$\text{Engineering strain } (e) = \frac{\textit{Change in length}}{\textit{Initial length}} = \frac{\Delta L}{L0}$$

Engineering Stress-Strain Diagram: -

The stress strain diagram provides valuable information like how much force/load a material can withstand before permanent deformation or failure.

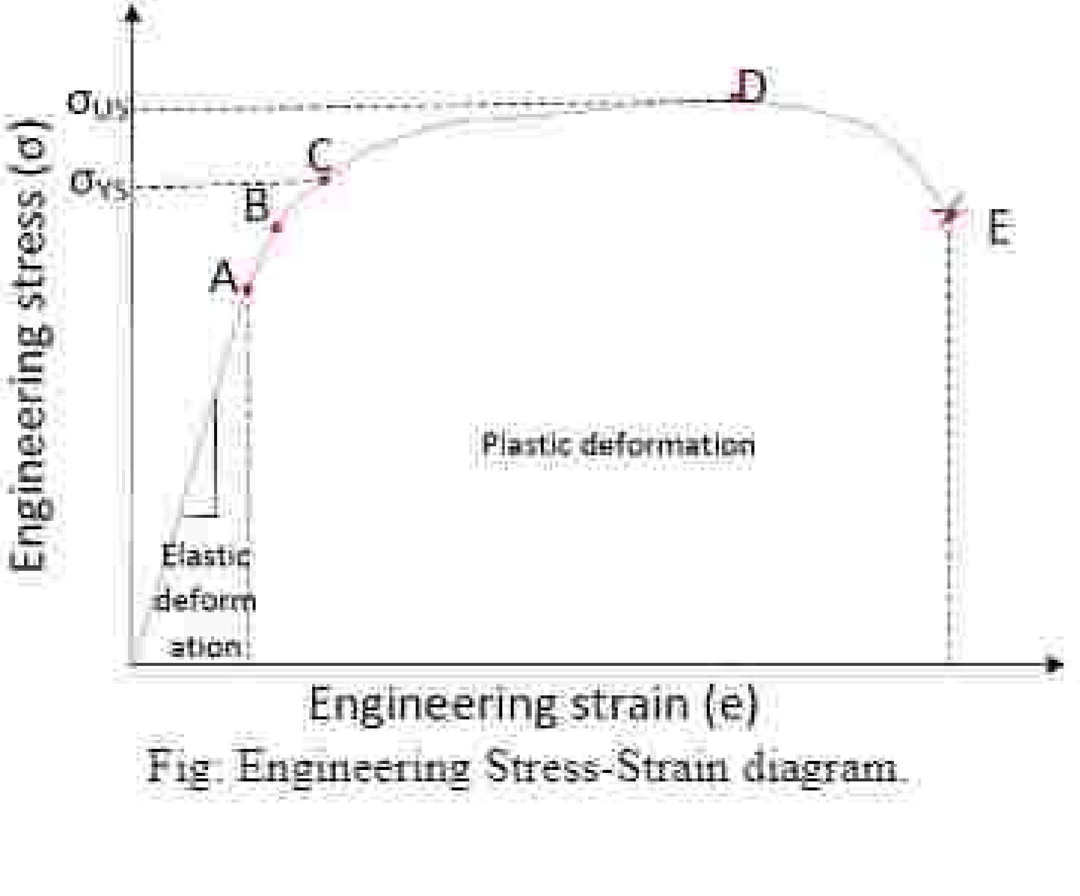


Fig. Engineering Stress-Strain diagram.

HOOKE's Law: -

It states that stress is directly proportional to strain within the elastic limit.

$$\sigma = E.\epsilon$$

Where, σ = engineering stress

ϵ = engineering strain

E = Young's modulus

- Here the proportional limit is shown as point A.

- Young's modulus or modulus of elasticity shown stiffness or resistance to elastic deformation of a material.

- Just beyond proportional limit, there is the elastic limit which shows that the deformation transition from elastic to plastic.

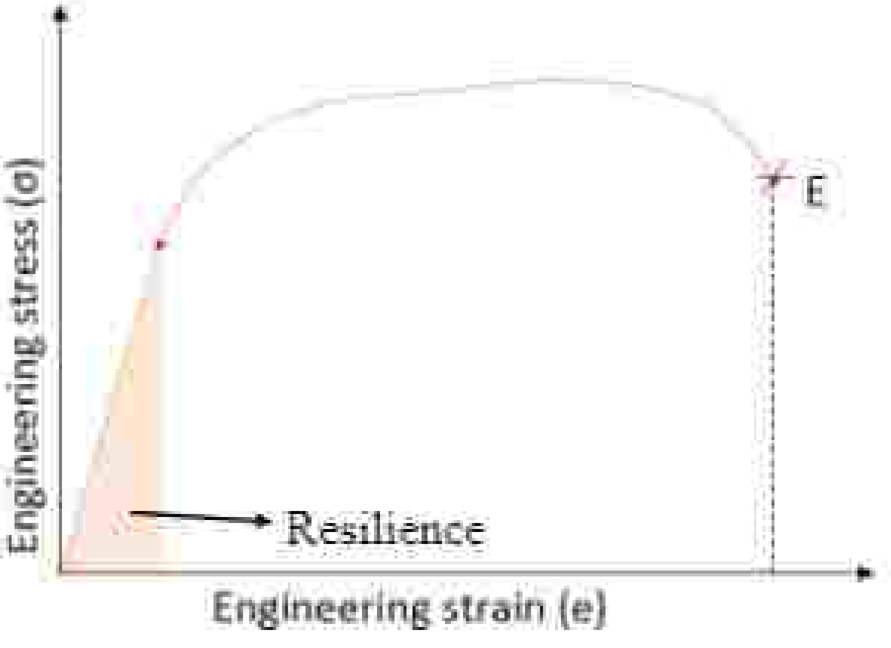
- Point C is the yield point or 0.2% proof stress or offset yield strength which shows the material has been deformed plastically by 0.2%.

- Point D is the maximum stress beyond which the stress decrease is known as Ultimate tensile strength UTS. It denotes the maximum stress the material can withstand.
- Yield strength = the value of stress at which a material starts to deform plastically.
- UTS = it is the maximum value of stress a material can withstand.

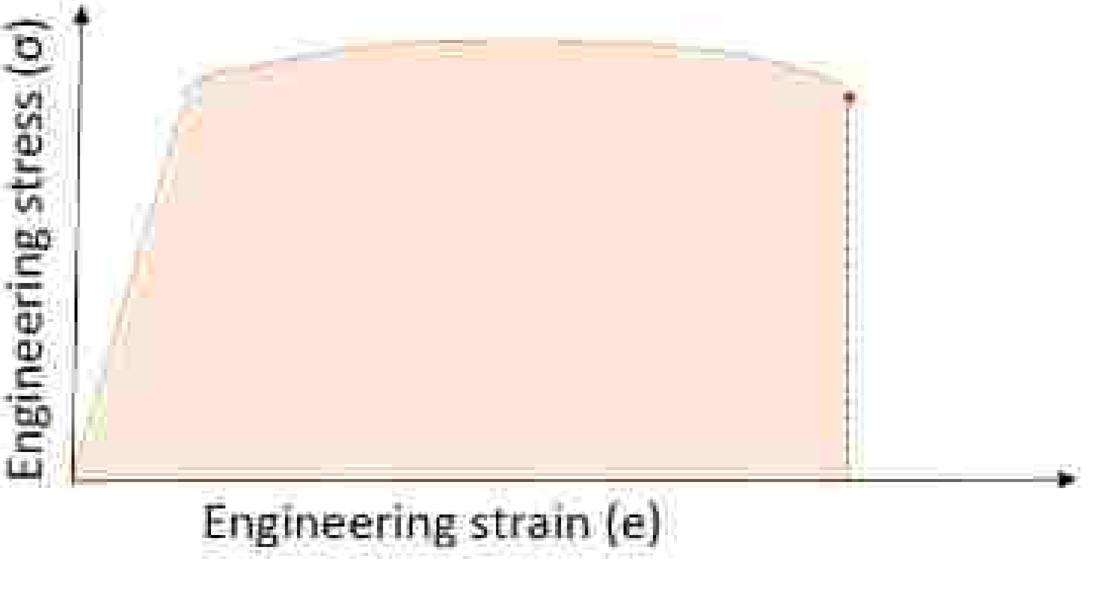
Properties:

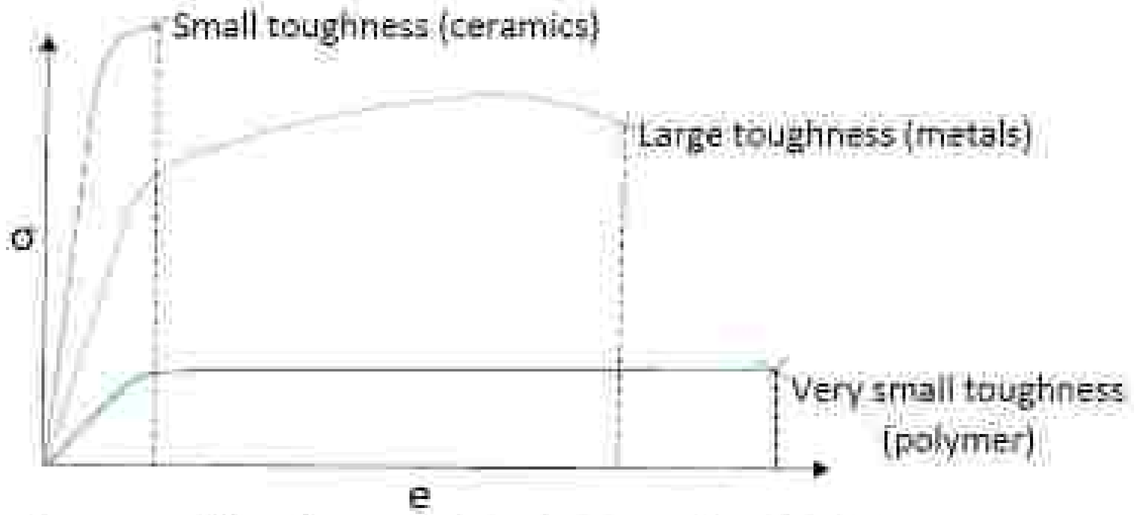
Ductility: - It is the ability of a material to deform plastically.

Resilience: - It is the energy absorbed by a material during elastic deformation. It is represented by the area under the elastic part of the stress-strain curve.



Toughness: - it is the energy absorbed by a material during deformation before failure. It is represented by area under stress-strain diagram.





Brittle fracture – small toughness, Ductile fracture – large toughness

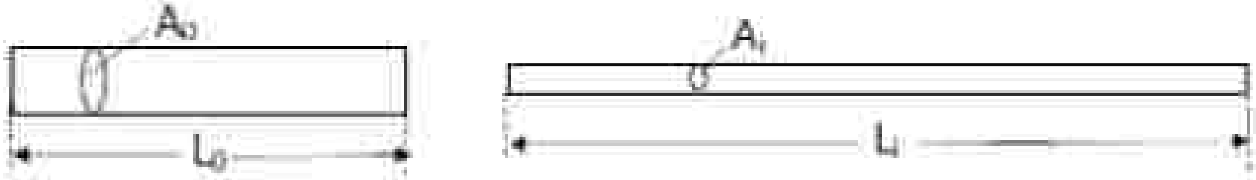
True stress (σ_t): -

- It is defined as the load divided by the actual cross-sectional area (instantaneous) as of the specimen at the load.

$$\boxed{\sigma_t = \frac{P}{A_i}} \quad \text{——(1)}$$

A_i = Instantaneous cross-sectional area

P = Load



$A_0 . L_0 = A_i . L_i$ (volume constant)

$$\Rightarrow A_i = \frac{A_0 L_0}{L_i}$$

Now on putting the value of A_i in equation (1), we get,

$$\Rightarrow \sigma_t = \frac{P L_i}{A_0 L_0}$$

$$\Rightarrow \sigma_t = \frac{P}{A_0}\left(\frac{L_0+\Delta L}{L_0}\right)$$

$$\Rightarrow \sigma_t = \sigma.\left(\frac{L_0}{L_0} + \frac{\Delta L}{L_0}\right)$$

$$\Rightarrow \boxed{\sigma_t = \sigma.(1+e)}$$

True strain (e_t):

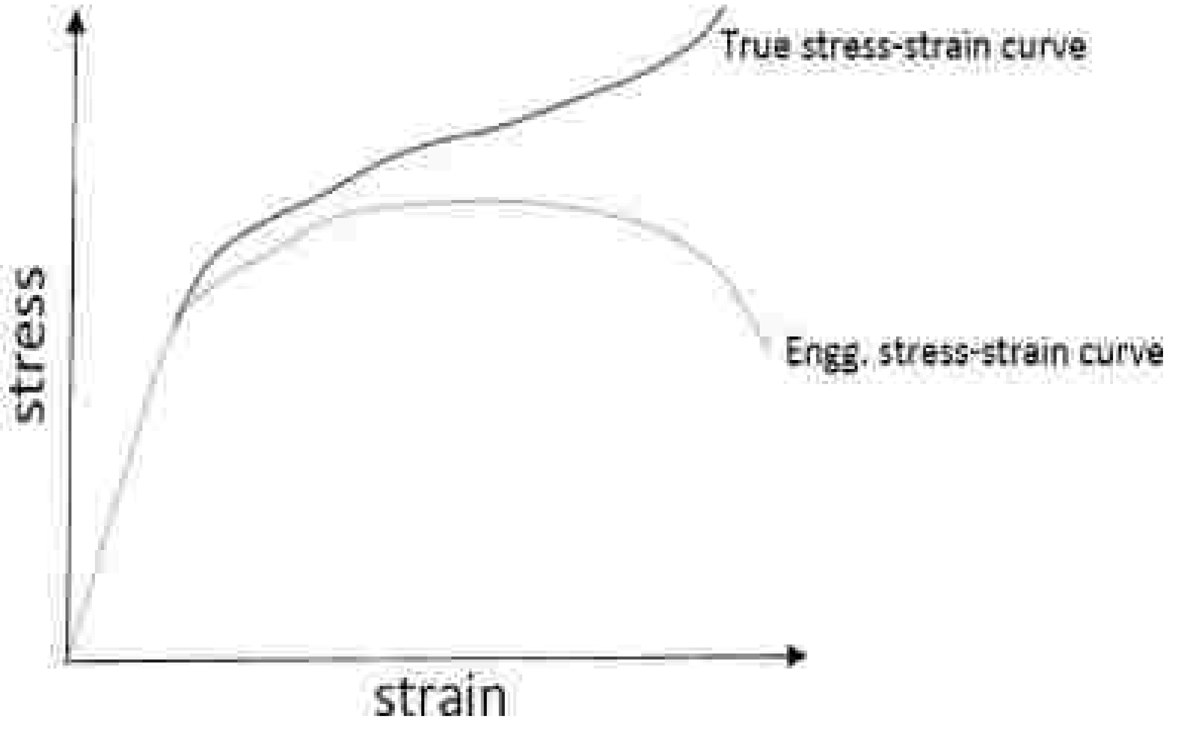
- It is defined as the change in length divided by the current length

True incremental strain = $de_t = \frac{dL}{L}$

$$\Rightarrow \int_0^{e_t} de_t = \int_{L_0}^{L} \frac{dL}{L} = [\ln L]_{L_0}^{L} = \ln(\frac{L}{L_0})$$

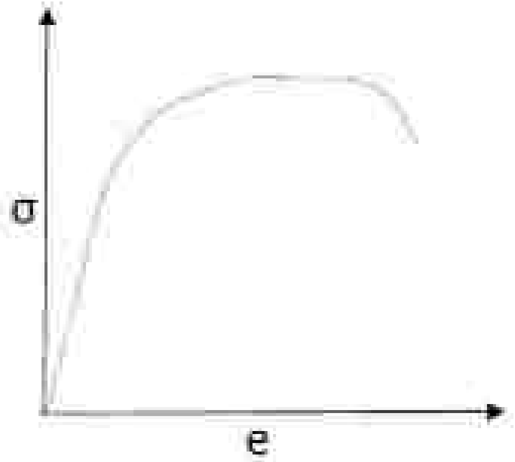
$$\Rightarrow e_t = \ln(\frac{L_0+\Delta L}{L_0}) = \ln(\frac{L_0}{L_0} + \frac{\Delta L}{L_0}) = \ln(1 + e)$$

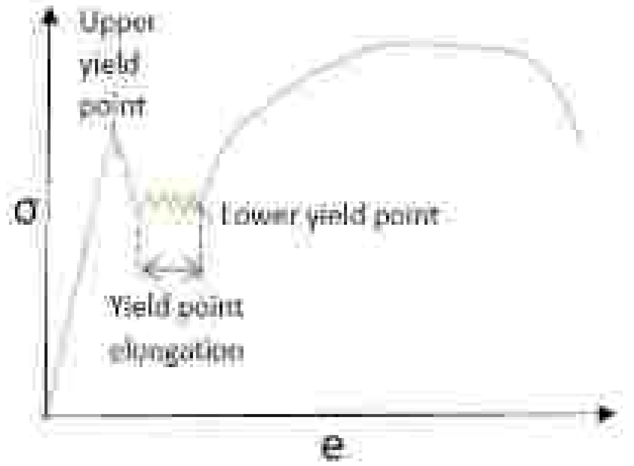
$$\Rightarrow \boxed{e_t = \ln(1 + e)}$$



Yield point phenomena:

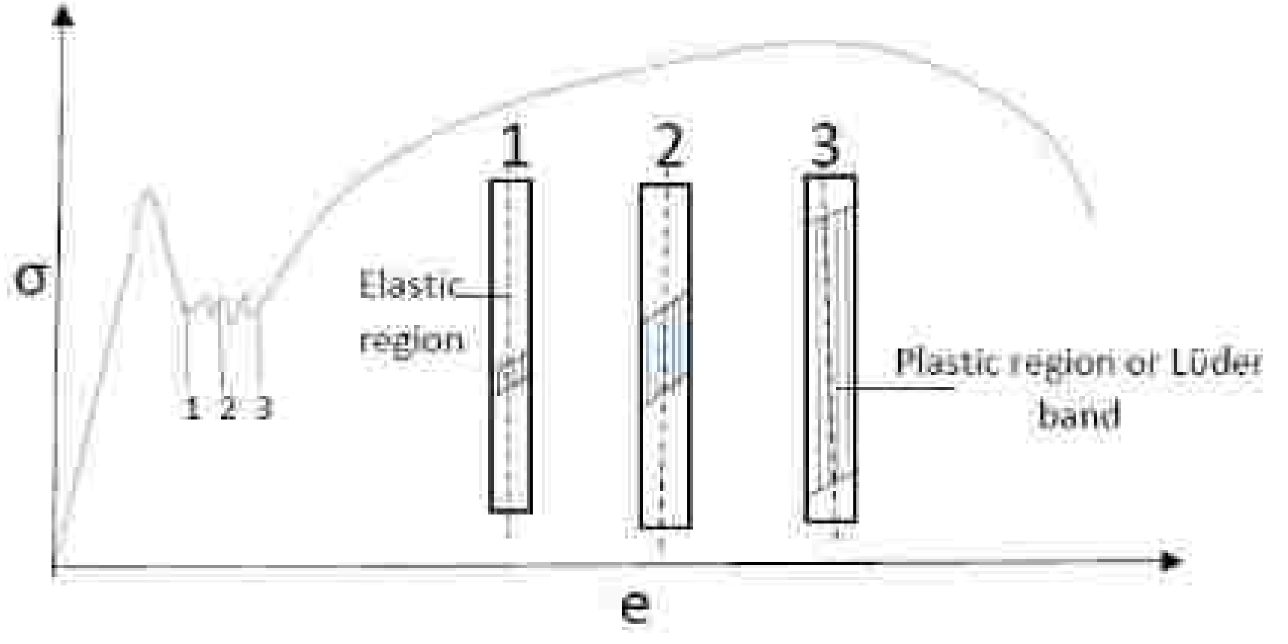
- During tensile deformation materials initially deforms elastically & the yield point mark the start of plastic deformation.





- For most of the material, the transition from elastic to plastic deformation is gradually s it is observed in the figure 1.
- But in some materials like, mild steel the transition is sharp and exhibited a phenomenon termed as yield point phenomena shown in figure 2.
- Metal particularly low carbon steel, Mo, Cd, Zn, Al alloys shows a localized heterogeneous transition from elastic to plastic deformation which is called yield point elongation.
- In such materials plastic deformation starts locally in some parts of the sample at a stress known as upper yield point.
- The load after upper yield point suddenly drop to a constant value known as lower yield point & then rise with further stress.

- The elongation which occurs at constant load is called as yield point elongation, which are heterogeneous deformations.



- This yield point elongation s appears as Lüder band stretcher strain on sample surface.
- Lüder band are formed at approximately 45° to tensile axis during yield point elongation & slowly propagates over the specimen.

1.HAREDNESS TEST

Hardness:

- It is the resistance to localised plastic deformation (indentation).

  Or

- It is the ability of a material to resist scratch or indentation.
- Hardness value can't be directly used for designing activities as like tensile test value.
- However, it is important to evaluate hardness value as its related to elastic & plastic properties of material (Young's modulus, yield stress, ductility, UTS etc.).
- Hardness test is very rapid & easy to conduct.
- Hardness value is very sensitive to the surface of the material.
- Depending upon the type of test, hardness of material is categorised into 3 types.

  - Elastic/rebound hardness
  - Scratch hardness
  - Indentation hardness

Elastic/rebound hardness: -

- The resistance offered by a material to impact and resultant rebound of the impact is termed as elastic or rebound hardness.
- The device used to measure this type of hardness is called Scleroscope and the test is known as Shore's hardness test.

Shore hardness test/ Scleroscope test: -

- The basic principle of this test is to measure relative hardness rom the rebound height from the surface of the material under consideration.
- In this case the metal plug that holds a diamond indenter (sharp pointed object) is dropped from a certain height is measured and accordingly hardness of the sample is determined.
- In general, softer the material the indentation size will be more & rebound height will be less & vice versa.

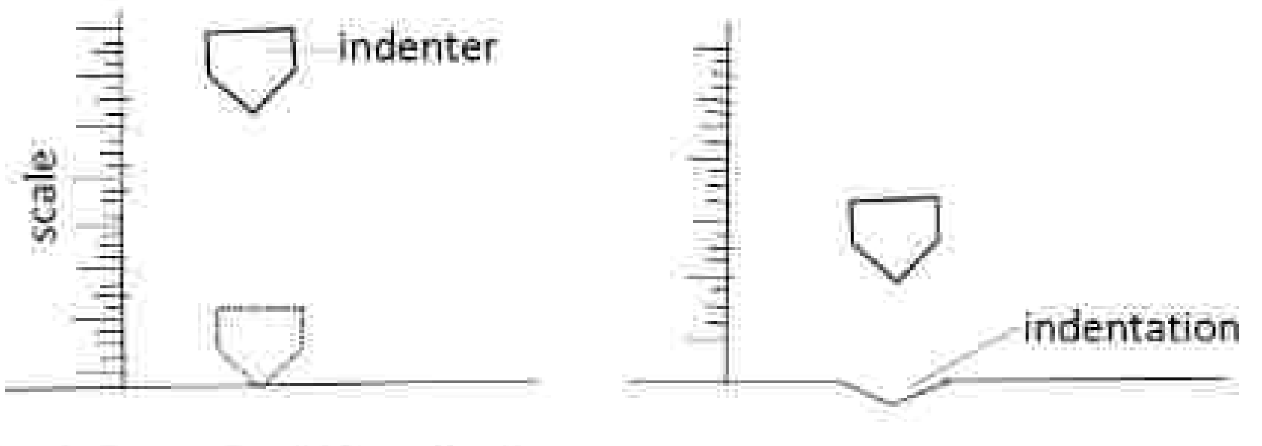


Fig: Schematic of Shore hardness test.

Application:

This is a portable device and very easy to use. This is used to measure

1. Hardness of pipeline & heavy machinery.
2. It can be used to measure thin section like razor blade & thick section as well.
3. It is used to measure the compressive strength of concrete surface.

Precaution:

1. Surface must be smooth, flat, and clean.
2. Proper clamping should be done to avoid vibration.
3. Multiple test should not be conducted at one region.
4. Number of tests should be carried out to get accurate hardness value.

Scratch hardness test: -

- This harness test determines the resistance of a material to scratch or abrasion.
- In this test, the material under observation is scratched by several series of standard materials for determination of hardness.
- This hardness test was developed by "Friedrich Moh". So, the hardness results from this test is expressed by Moh scale.
- In Moh scale, 10 standard materials are arranged in the order of increasing hardness value starting from softest talc (1) to hardest diamond (10).

- Suppose in the test the material is scratched by diamond but couldn't be scratched by corundum at a standard load. Then the scratch hardness of the material will be in between 9-10.

Application: -

- This test is widely used in the field of mineralogy for finding relative hardness of rocks, materials etc.

Advantages: -

1. It is extremely simple, low cost and required no technical skill.
2. This test is rapid and quick.
3. The hardness scale is only from1-10.

Disadvantages: -

- The hardness scale is highly limited to find out the exact hardness & find very little use with metallurgist.

Indentation Hardness Test

Introduction:

- Hardness is a measure of material's resistance to localized plastic deformation. In this case it is the resistance to indentation or penetration by an indenter.
- Indentation hardness test is widely used by metallurgist due to certain relation between hardness no. and tensile strength of metals.
- Hardness techniques by indentation have been developed over the years in which a small indenter is forced into the surface of a material to be tested.
- In this test an indenter of known geometry and defined applied load is impressed upon the sample surface.
- The test result is expressed by a number which determined from the depth of penetration of indenter or the applied stress, depending upon the type of test.
- In general, softer the material, higher will be the depth of penetration of indenter or higher indentation area and represented by a lower hardness number and vice versa.
- The major indentation hardness tests are:

  a) Brinell Hardness Test

  b) Rockwell Hardness Test

  c) Vickers Hardness test

a) Brinell Hardness Test

- Dr. J. A. Brinell invented the Brinell test in Sweden in 1900.
- This test uses a spherical indenter which is forced into the surface of the test sample at a certain load.
- Due to the action of load a circular impression is created on the sample surface.
- The diameter of the indentation is of prime importance in measuring the hardness number.

Types of indenter:

1. Hardened steel ball of 1, 2.5, 5 and 10mm size diameter.
2. For very hard material, Tungsten carbide ball is used.

Principle:

- The Brinell hardness testing consists of indenting the test material with a 10 mm diameter hardened steel or carbide ball subjected to a load of 500 to 3000 kg for 10 to 30 second.
- The full load (3000 Kg) is normally applied for iron and steel for 10 to 15 seconds.
- The load can be reduced to 1500 kg or 500 kg for 30 second to avoid excessive indentation for softer materials.
- When the indenter is impressed into the test sample surface it creates a circular impression after its removal.

- The diameter of the indentation is measured by a microscope. For better accuracy at least two readings of the diameter is measured.
- The Brinell hardness number is calculated by dividing the applied load with the curved surface area of the indentation.

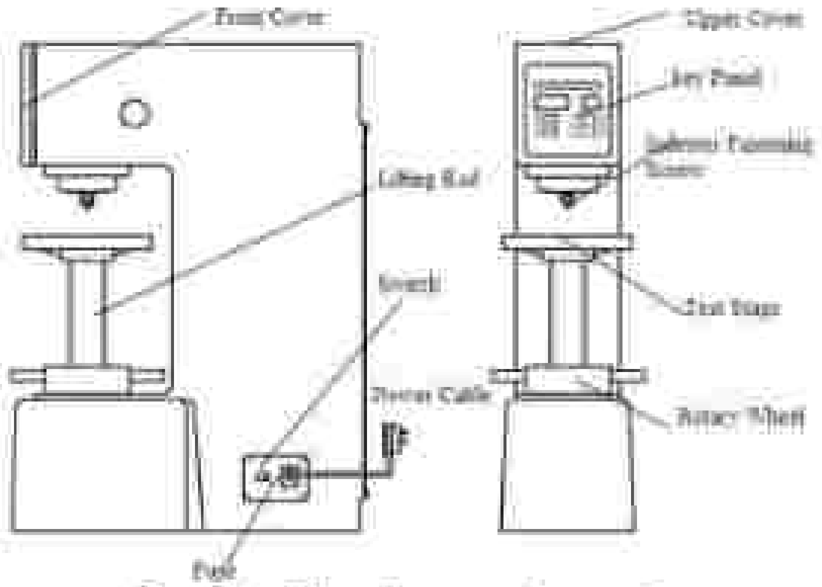
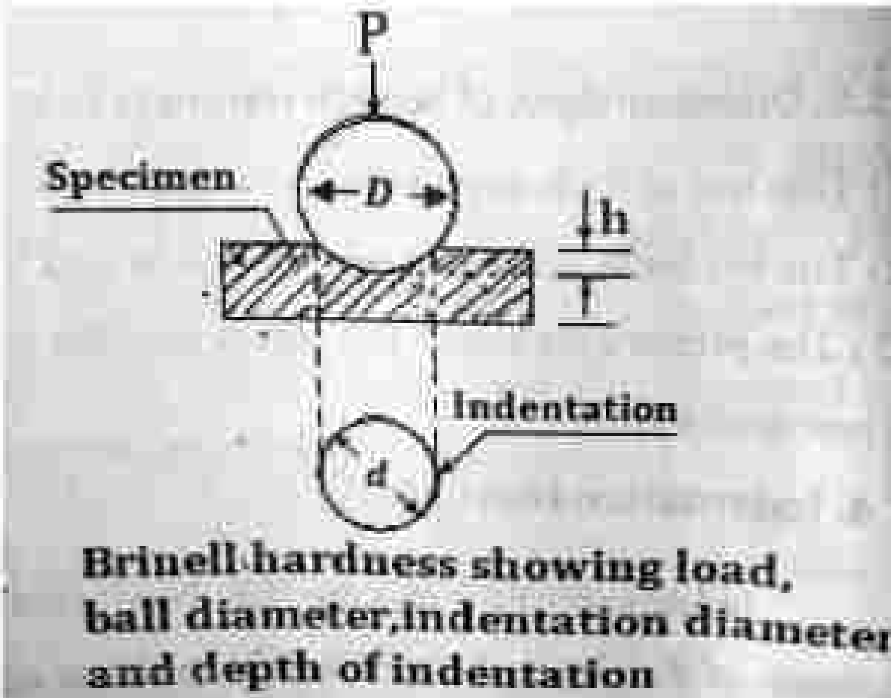
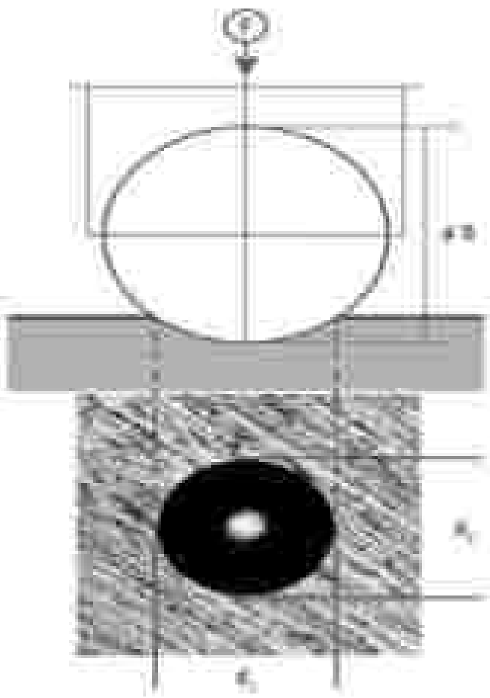


Fig: Brinell hardness testing machine



Brinell hardness showing load, ball diameter,indentation diameter and depth of indentation



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

where

- HB = Brinell Hardness Number (kgf/mm^2)
- P = applied load in kilogram-force (kgf)
- D = diameter of indenter (mm)
- d = diameter of indentation (mm)

- A well-structured Brinell hardness number reveals the test conditions, and looks like this, "75 HB 10/500/30" which means that a Brinell Hardness of 75 was obtained using a 10mm diameter hardened steel with a 500 kilogram load applied for a period of 30 seconds.

Advantages:

- This method is the best for achieving the bulk or macro-hardness of a material, particularly those materials with heterogeneous structures.
- Due to large size of the indenter the local inhomogeneity is averaged out.
- It is less influenced by the surface, so extensive surface preparation is not required.

Disadvantages:

- As, the Brinell impression is large so sometimes it act as a potential site for failure.
- Higher technical skill is required to perform the test.
- Relatively slow process.

Precautions:

- Hardness of the steel ball must be sufficiently more than specimen otherwise the ball itself may get deformed (sinking in).
- Depending upon material under the test the combination of the load and ball material is chose :
  - 500 kilograms for soft metals such as copper, brass and thin stock.
  - 1500 kilogram load is used for aluminium castings.
  - 3000 kilogram load is used for materials such as iron and steel.
- Surface of the material (specimen and ball) must be smooth & free from dirt or scale.
- Indentation mark should be avoided at the edges and corners of the materialis difficult to measure.
- The thickness of the metal under test should be at least 10 times of the depth of indentation.
- The load must be applied for specific time period.

Rockwell Hardness Test

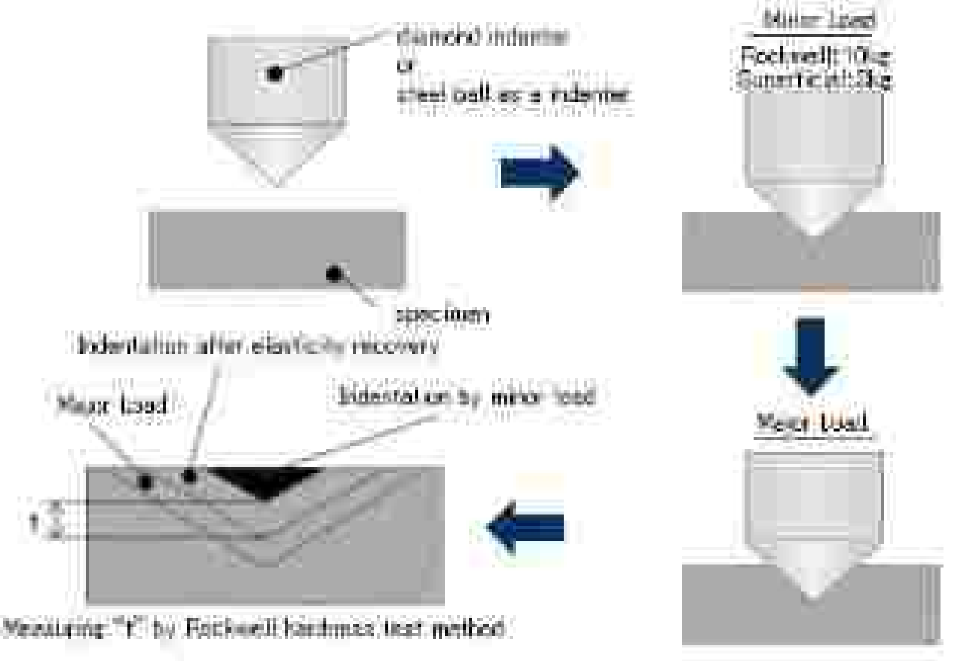
- Hugh M. Rockwell and Stanley P. Rockwell co-invented the "Rockwell hardness tester in 1919.

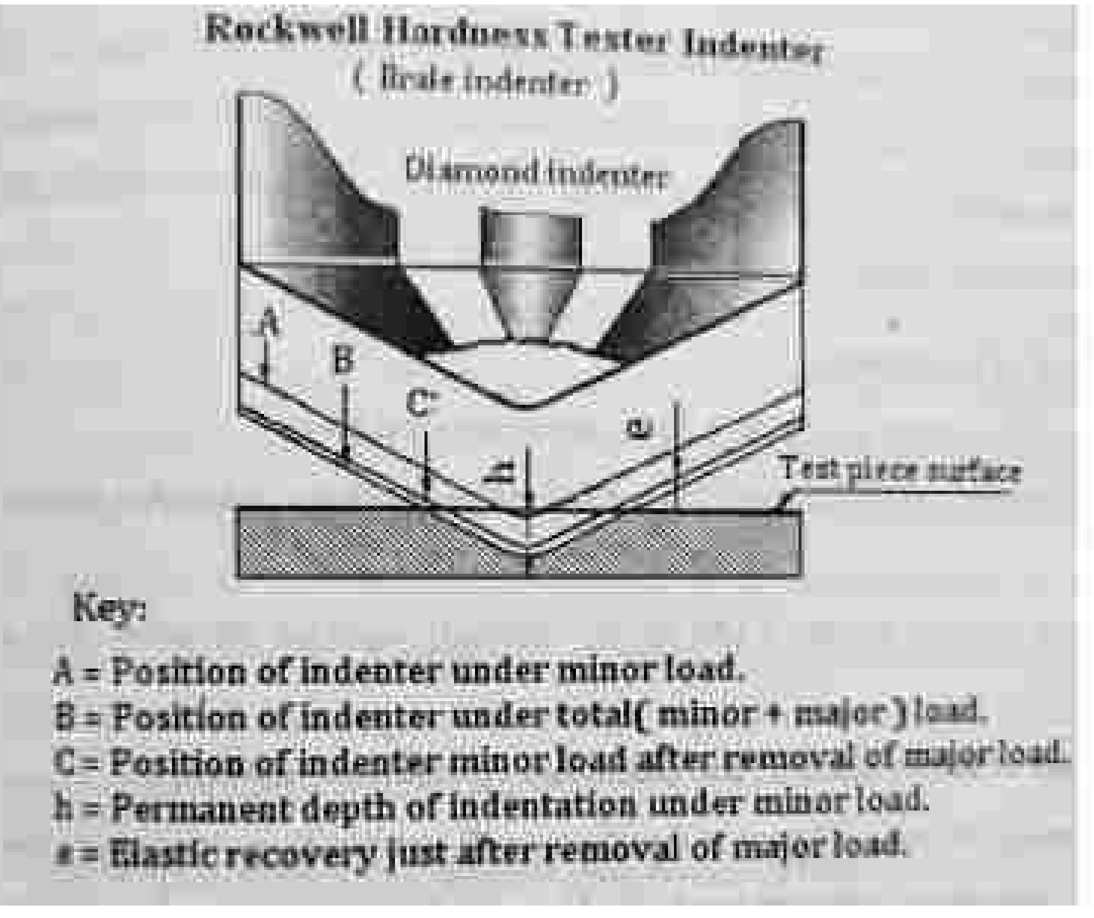
Principle of testing

- It is an indentation harness measurement method.

- In this test a diamond cone having an included angle 120° and 0.2mm radius of curvature or hardened steel ball of diameter 1.6mm or 3.2mm is forced into the test surface.

- In this test the load is applied in two steps i.e. minor load and major load.





- The determination of the Rockwell hardness of a material involves the application of a minor load of followed by a major load.

- The minor load establishes the zero position. The major load is applied, then removed while still maintaining the minor load.

- The depth of penetration from the zero is measured from a dial, on which a harder material gives a higher number. That is, the penetration depth and hardness are inversely proportional.

- In Rockwell testing the minor load is 10 kg and major load (60, 100, or 150 kg) is used regardless of the type of indenter.

Test method:

- Apply a minor load of 10 kg.
- Then the dial is set to zero and then major load is applied.
- Then apply major load of 60,100 and 150 kg according to the scale used for 6 seconds.
- Release the major load only, machine will show the Rockwell Hardness Number HR on the machine.
- The Result is written as ex: 60HRC.

Types of indenter and load:

- A 120° diamond cone with slightly rounded tip called brale indenter is used for hard materials.

- Hardened steel ball of diameter 1.6mm or 3.2mm.

- A major load of 60,100 and 150kg is used along with a minor load of 10kg.

  - The application of minor load in Rockwell machine ensures proper seating of indenter on the specimen and also removes any surface irregularities (Minimize surface preparation).

Type of Scale:

A Scale: This scale corresponds to brale indenter with 60Kg major load. This scale can major hardness of extremely soft material like brass as well as hard cemented carbides.

B Scale: This scale corresponds to brale indenter with 100Kg major load. This scale can major hardness of soft material like non-ferrous metals, low and medium carbon steel.

C Scale: This scale corresponds to brale indenter with 150Kg major load. This scale is mostly used to measure the hardness of hardened steel.

Representation of Rockwell hardness:

The hardness value is written as: 70 HR C

Hardness value   Rockwell Hardness   Scale

Precautions:

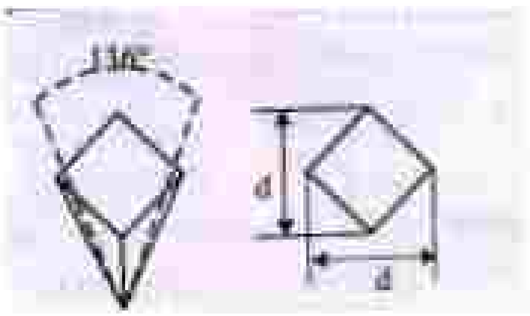
- The indenter should be clean.
- The test surface should be oxide free, clean, flat and smooth.
- The thickness of the specimen should be 10 times of the depth of penetration.
- Spacing between two indents should be 3-5 times the diameter of indenter.

Vickers Hardness Test

- The **Vickers hardness test** was developed in 1921 by Robert L. Smith and George E. Sandland.

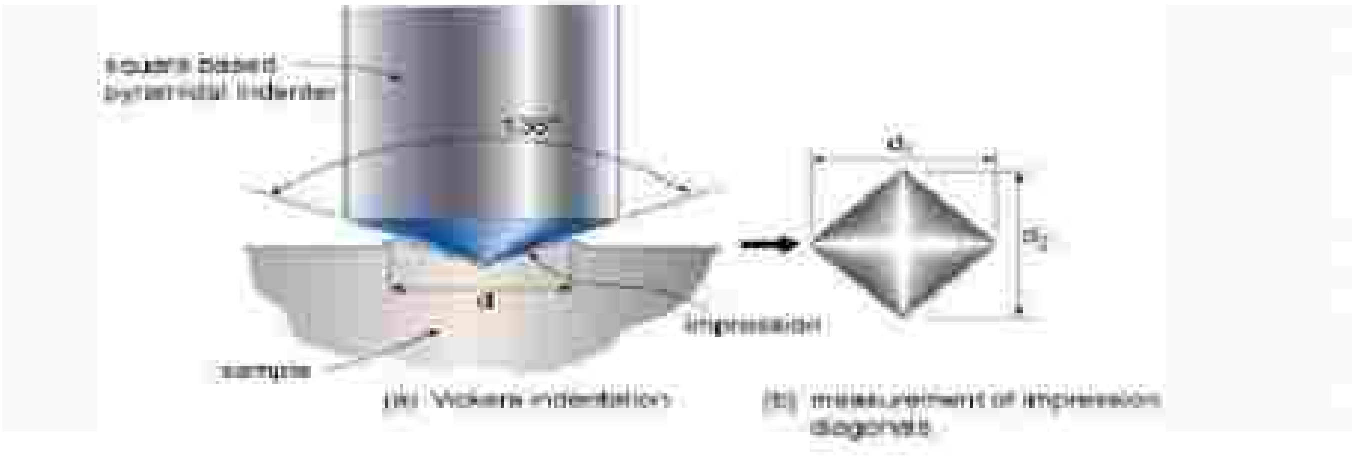
Principle of testing

- The test makes the use of a square-based diamond pyramid indenter with 136^0 angles between the opposite faces is impressed into the test sample.



Vickers hardness testing machine

Indenter



- The length of the two diagonals are measured after removal of load to calculate hardness.

Vickers hardness number

$$V.H.N = \frac{P}{A}$$
$$= \frac{2\,P\,Sin\theta\,/2}{d^2}$$
$$= 1.8544\,\frac{P}{d^2}$$

Where,

P= applied load in kg

A= surface area of indentation in sq.mm.

d= Average length of diagonal in mm.

θ= angle between opposite faces of diamond pyramid (136°).

Test Procedure

- Select the appropriate test load.
- The test sample should be placed tightly. And the area to be tested should be in focused condition.
- Then the indenter is brought into contact of the sample surface and the sample is loaded for 10-30 sec.
- The force is removed, and length of the diagonals are measured and averaged out.

Representation of Vickers hardness:

- Vickers hardness numbers are reported as e.g. 440HV30/20.

Where:

440 is the hardness number,

HV gives the hardness scale (Vickers),

30 indicates the load used in kg.

20 indicates the loading time

Precautions:

- The indenter should be cleaned.
- The test surface should be oxide free, clean, flat and smooth.
- Spacing between two indents should be 3-3.5 times the diameter of indenter.

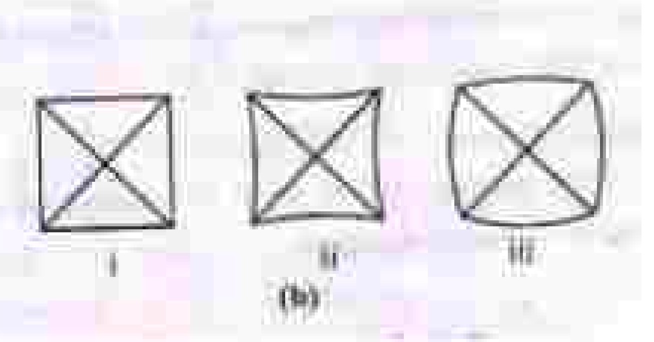
Advantages:

- The hardness of hardened steel or soft materials can be determined using large or small load respectively.
- This test is very useful for testing hardness of polished or nitrides surface due to small impression made on the test.
- This test is accurate and is suitable for metals as thin as 0.15mm.
- Hardness at elevated temperatures can be determined.

Disadvantages:

- It is a relatively slow process.
- It requires extensive surface preparation.

- In place of square impression sometimes Pin-cushioned or barreled indentation may form.



> First figure b (i) shows the perfect indentation which is in the form of a square.

> Figure (ii) shows Pincushion indentation, this is observed in soft materials. This results in overestimation of dimension of diagonals and shows lower hardness.

> Figure (iii) shows barrel type indentation, this is observed in hard materials. This results in underestimation of dimension of diagonals and shows higher hardness.

<u>Relationship between Hardness and Strength</u>

- As we can observe both BHN and VHN measures force/load require for indentation (plastic deformation). Which is similar to the task we do in case of tensile test.
- So, there exist a relationship between these hardness value and UTS of that sample.
- Hardness of a material is **2.5-3** times higher than the UTS of that material.

Chapter 03

IMPACT TESTING

Impact or Impact Force?

- An impact is a high force or shock applied over a short time period when two or more bodies collide.

  Example: car crash, wind force, earthquake etc.



Impact strength: It is the resistance to fracture or failure of any materials under sudden/high strain rate loading.

Or

It is the toughness of a material (energy absorbed) under sudden/shock loading.

- **Impact testing** measures the resistance to fracture or deformation of a materials during sudden loading.
- This test is mostly used to determine impact strength and behavior of materials at low temperature.
- These values are important for the selection of materials that will be used in applications that require the material to undergo very rapid loading processes such as in vehicular collisions, including steel hull plate for ships, nuclear plant pressure vessels, Aerospace, Automotive, Nuclear etc.

Types of Impact Testing

- The most common methods of performing impact test are –

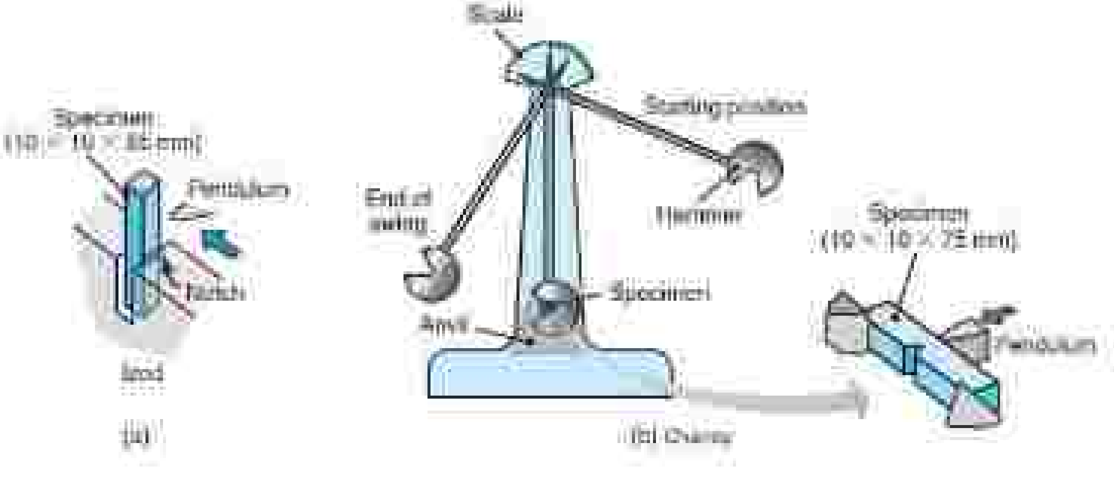
  1. Charpy Test Method
  2. Izod Test Method

- These tests are all essentially determine the same characteristics of the material but differs in the orientation of the test sample.

- In this test, a sample of material is held in rigid fixture and struck with a hammer with predetermined potential energy. The energy absorbed is measured by measuring how far the hammer swings in the opposite direction after the impact.

- Initial potential energy can be varied by positioning the hammer at different heights as well as varying the mass of the hammer.

- This is a very simple test to conduct and provides valuable information regarding fracture resistance, energy absorbed during fracture, ductile to brittle transition by varying test temperatures.

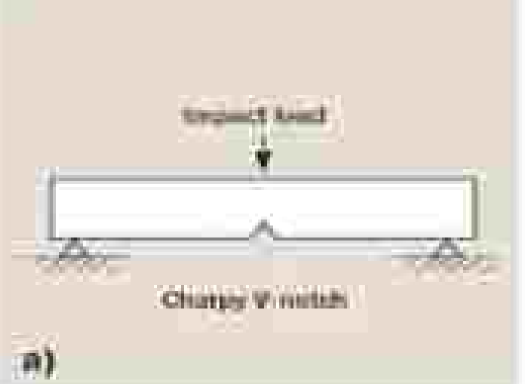


1. Charpy Test Method

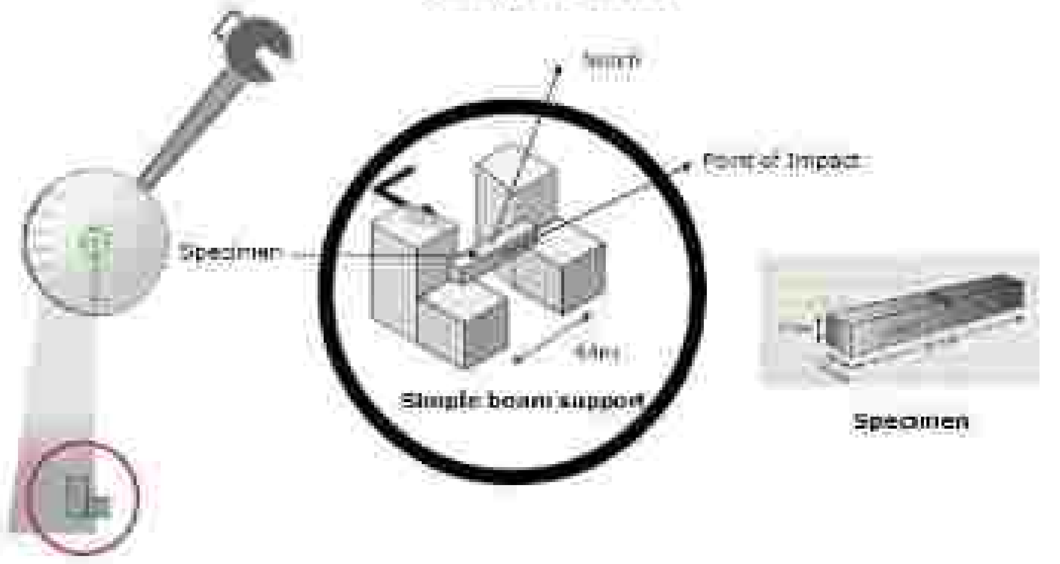
- The Charpy impact test, also known as the Charpy V-notch test, is a standardized impact test which determines the amount of energy absorbed by a material during fracture. This absorbed energy is a measure of a given material's impact toughness and acts as a tool to study.
- It is widely applied in industry, since it is easy to prepare and conduct and results can be obtained quickly and cheaply.

Charpy Impact Test Specimen:

- Charpy test specimens normally measure 55x10x10mm with 2mm deep notch at the middle of a specified surface.
- The notches may be: V-shaped notch, 2mm deep, with 45° angle and 0.25mm radius along the base.
- U-notch or keyhole notch – A 5mm deep notch with 1mm radius at the base of the notch.



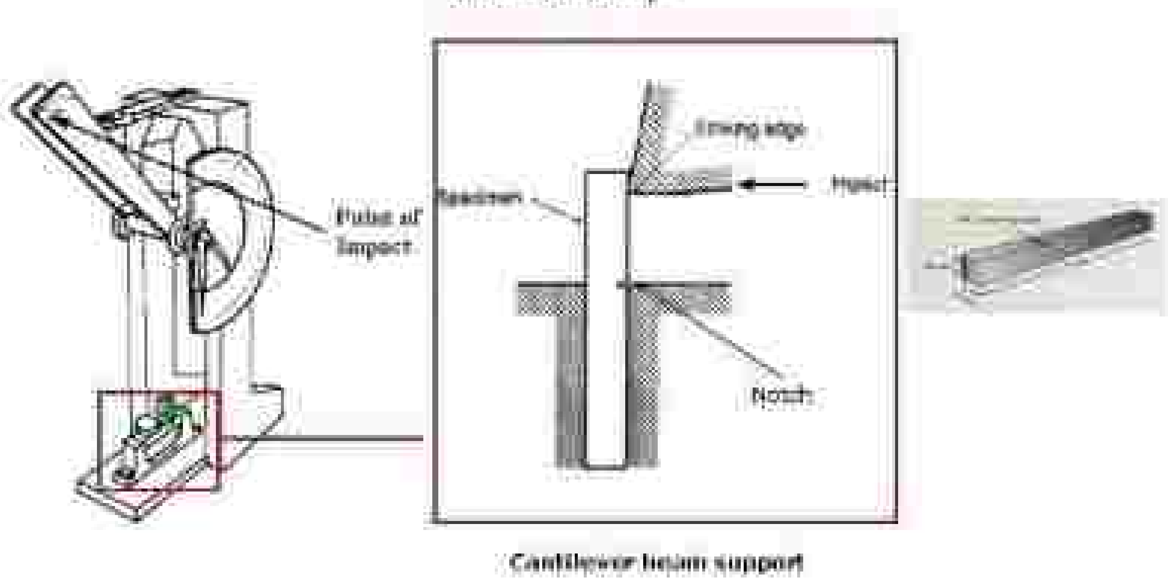
Charpy Test Setup



Izod test Method

- The test piece is a cantilever, clamped upright in an anvil, with a V-notch at the level of the top of the clamp.
- The test piece is hit by a striker carried on a pendulum which is allowed to fall freely from a fixed height.

Izod Test Setup

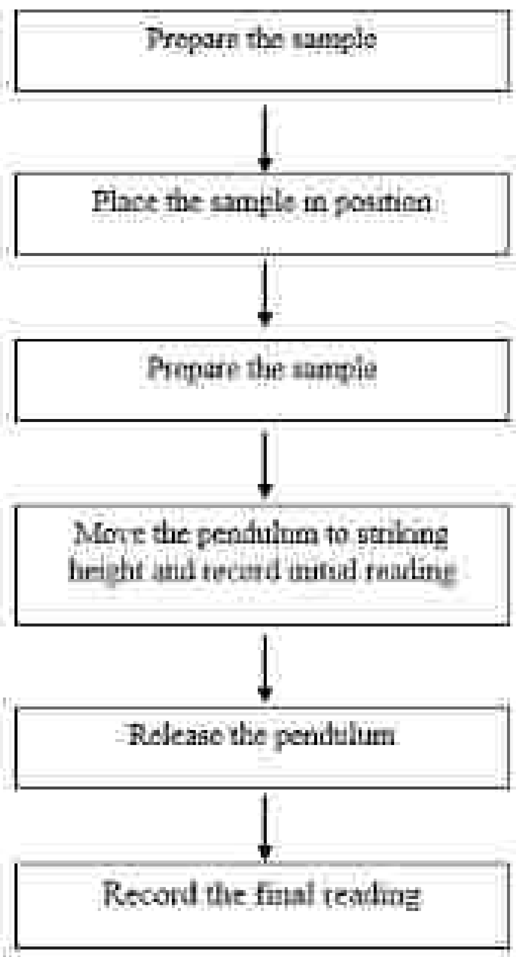


Cantilever beam support

Izod Impact Test Specimen

- The Standard Size of Izod impact test Specimen is (64mm x12.7mm x 3.2mm).
- The V notch Shaped bar is also used here.
- The Izod specimen is held rigidly in a vice type fixture with the notched side facing the direction of impact. The centreline of the notch must be in the plane of the vice top.
- Once the specimen is in place the hammer is released from a pre-set height and allowed to strike the specimen thus fracturing it at the v-notch.

Procedure of impact test



Difference between Charpy & Izod test

- In Charpy method the Specimen set is like a simply Supported beam. On other hand in Izod method the Specimen set is like a Cantilever.

- The notch in the izod test is facing the striker, fastened in pendulum, while in the Charpy test, the notch is positioned away from the striker.

- In the Charpy method, there are two kinds of notches, the V-notch and the U-notch, while in the Izod method; there is only one kind of notch.

Failure of Materials

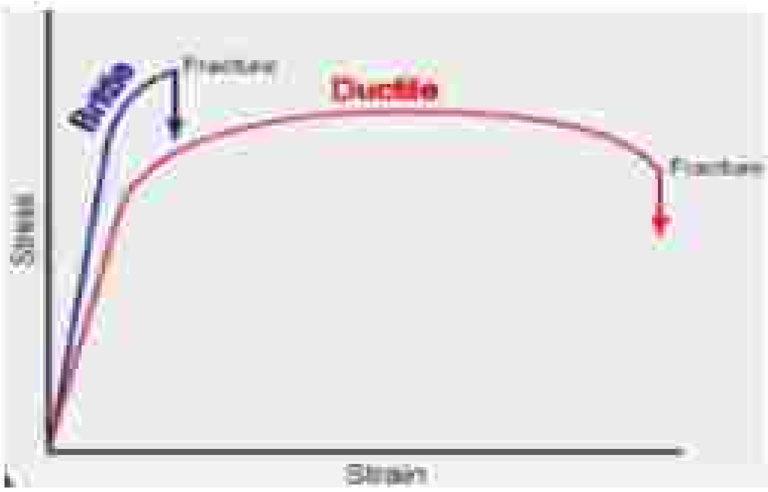
Brittle Materials: - A material is said to be brittle, when subjected to stress, it breaks without significant deformation (strain).

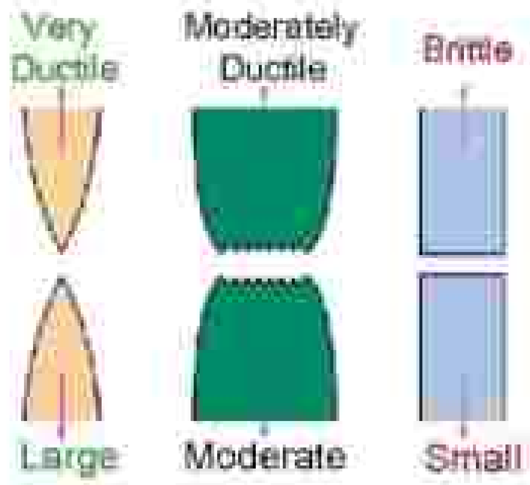
Examples: glasses and ceramics materials.

Ductile materials: - A material is said to be ductile, when subjected to stress, it shows significant amount of deformation (strain) before failure.

Examples: Nickel, Copper, Carbon Steel etc.

Ductile Fracture	Brittle Fracture
1. It involves large plastic deformation. 2. It is always preceded by the localized deformation called necking. 3. Ductile fracture normally observed in FCC metals. 4. The fracture surface of ductile material is rough and looks dull. 5. It occurs slowly with tearing of the metal with expenditure of considerable energy.	1. It is associated with very little or no plastic deformation. 2. It doesn't involve necking. 3. Brittle fracture is normally observed in BCC and HCP metals. 4. The fracture surface of brittle material is flat and shiny. 5. It occurs suddenly without any warning.



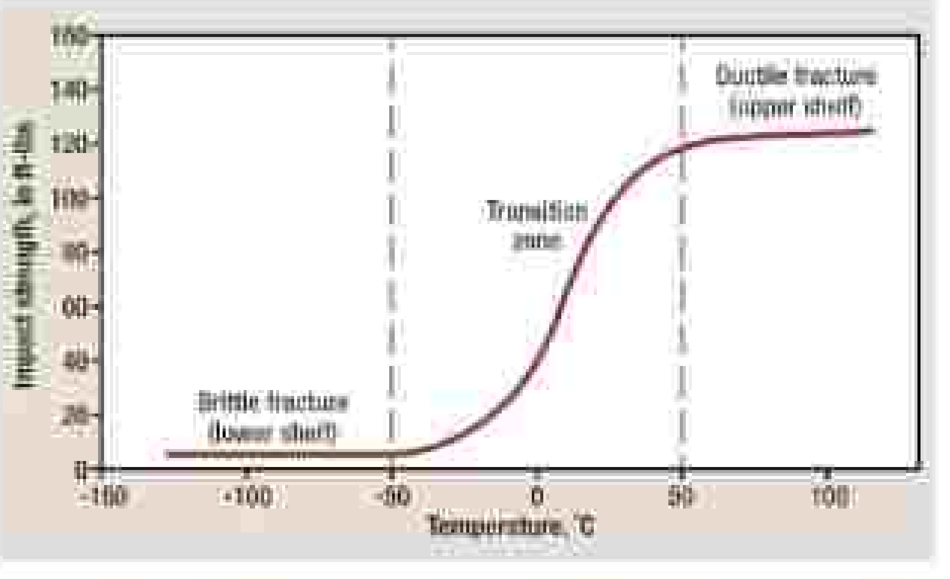


Ductile to brittle transition

- Toughness of metallic materials depends on temperature. Generally toughness increases with increase in temperature as plasticity of material increases and vice versa.

- However, in some materials such as carbon steels undergo what is known as a 'ductile to brittle transition'. In this phenomena the toughness decreases suddenly with decrease in temperature.

- When impact energy is plotted as a function of temperature. The resultant curve will show a rapid dropping off of impact energy as the temperature decreases.



(The curve represents a change in fracture behaviour from ductile at high temperature to brittle at lower temperature)

- If the impact energy drops off very sharply, a transition temperature can be determined. The temperature at which the material changes from ductile nature to brittle nature is termed as "Ductile to Brittle transition temperature" (DBTT).

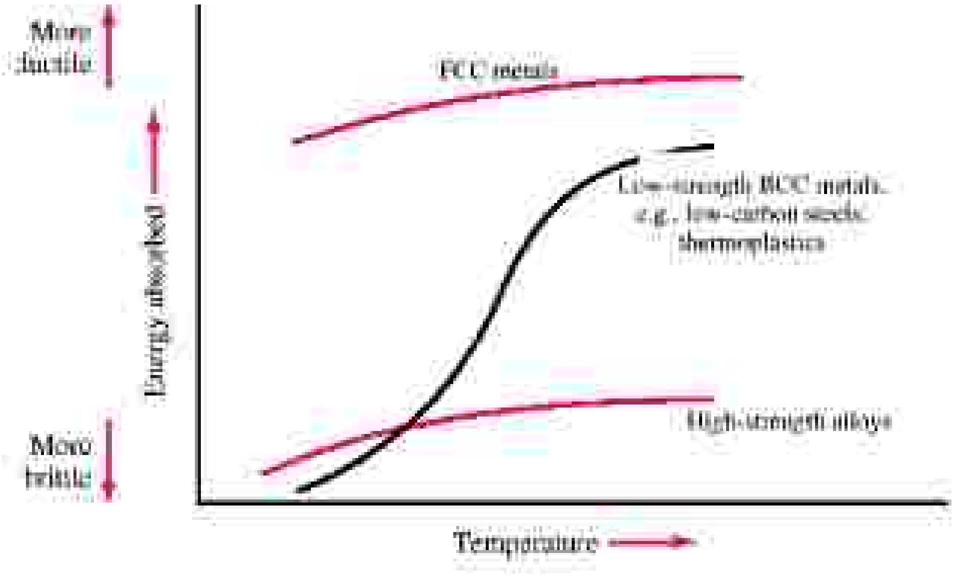
- This is often a good indicator of the minimum recommended service temperature for a material. The impact tests are very useful in determining the transition temperature while conducted over a range of temperature.

- To estimate the DBTT of the given material. The material is undergone notched impact testing over a range of temperatures.

- At high temperatures impact energy is relatively large. As temperature drops the impact energy drops suddenly over a very narrow temperature range.

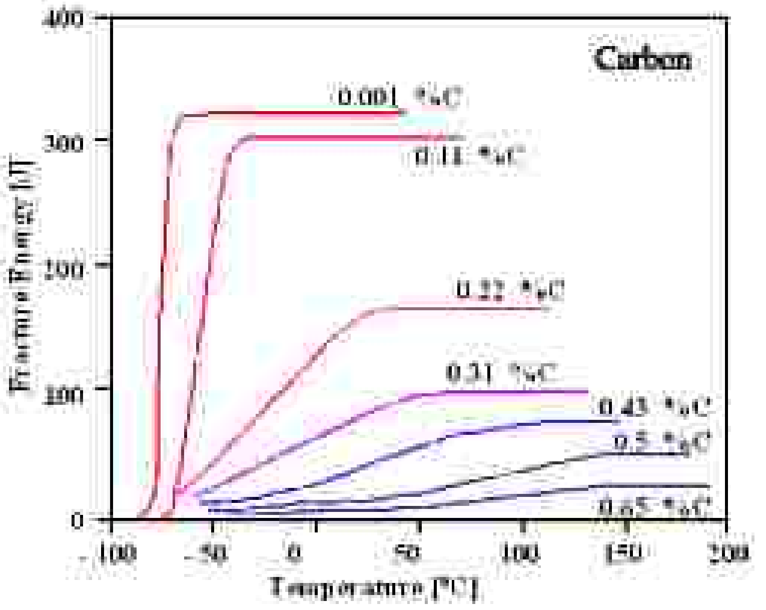
- Below that temperature, impact energy has almost constant but very small value. Ductile – brittle transition takes place over a range of temperature instead of a sharp value of temperature.

- Therefore it is difficult to define a single temperature. Usually DBTT is taken that temperature at which Charpy V notch energy value is 20J.



- BCC metals have transition temperature, but most FCC and HCP metals do not undergo this transition.

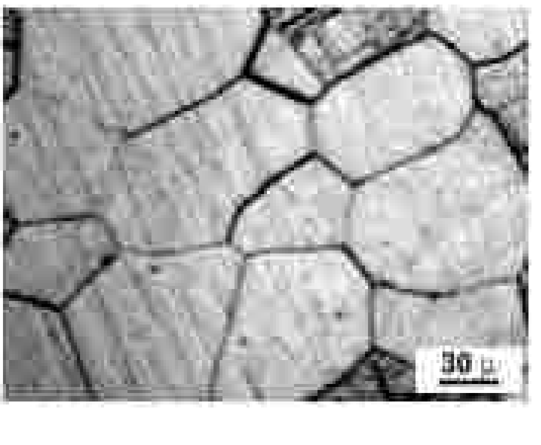
Factors affecting Transition temperature



- Largest change of DBTT in steel can be observed by changing percentage of C and Mn. The transition temperature is raised by 14°C for each 1% increase in C and lowered by 50°C for each 0.1% increase in Mn.

- Presence of P, Mo increases DBTT of steel whereas Ni decreases DBTT.

- Grain size has a strong effect on DBTT. Decrease in grain size increases DBTT of low C steel.



Fatigue Test

Definition: Fatigue is the type of test that is carried out under fluctuating stress or vibration.

Ex: Automotive, aircraft, compressor pump, turbine blade etc.

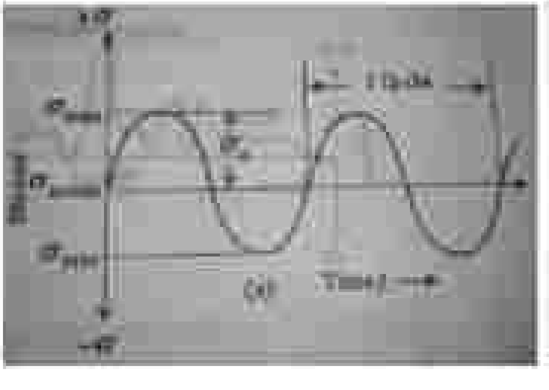
- The maximum load during fluctuation is well below the ultimate tensile strength or even yield strength. Failure occurring under fluctuating load is called fatigue failure.

Different Stress Cycles:

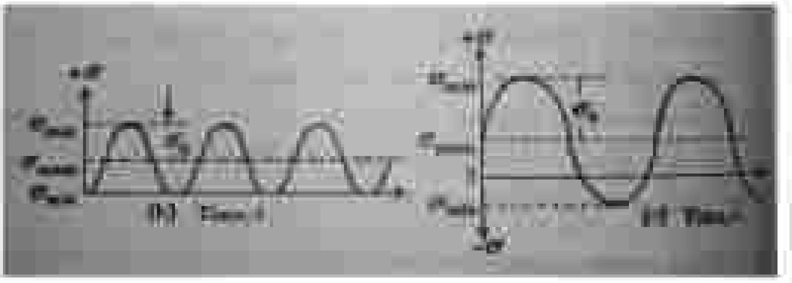
There are various types of load that is being experienced by an engineering material during its service period. In case of fatigue the load could fluctuate in regular or irregular manner. If the load varies in regular manner, then it is called as stress cycle.

Various type of load that could cause fatigue are:

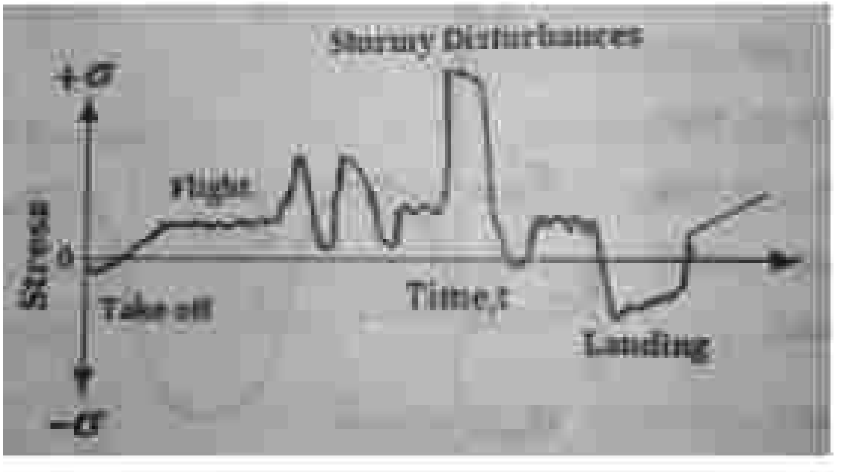
I. *Completely reversed cycle of stress (sinusoidal form)*
   In this type of stress cycle the maximum and minimum stresses are equal and are repeated with definite time interval (as shown in Fig.), making the stress cycle completely sinusoidal.



II. In this type of stress cycle, the cycle is repeated in regular time interval. But the maximum and minimum levels of the stress are different.



III. This type of stress cycle is the most complex one as there is no particular trend that is being followed. That means the maximum and minimum stress is not constant with respect to time. This type of stress cycles are observed in the aircraft wing and automobile parts where the components are subjected to unpredictable overloads due to various reason during their service life.



The representative cyclic loading curves are characterized by following parameters:

1. σ_{min}: Minimum stress
2. σ_{max}: Maximum stress
3. σ_m: Mean stress; $\sigma_m = (\sigma_{min} + \sigma_{max})/2$
4. σ_a: Stress amplitude; $\sigma_a = (\sigma_{max} - \sigma_{min})/2$
5. R: Stress ratio; $R = \sigma_{min}/\sigma_{max}$
6. $\Delta\sigma$: Stress range; $\Delta\sigma = \sigma_{max} - \sigma_{min}$
7. A: A-ratio; $A = \sigma_a / \sigma_m$

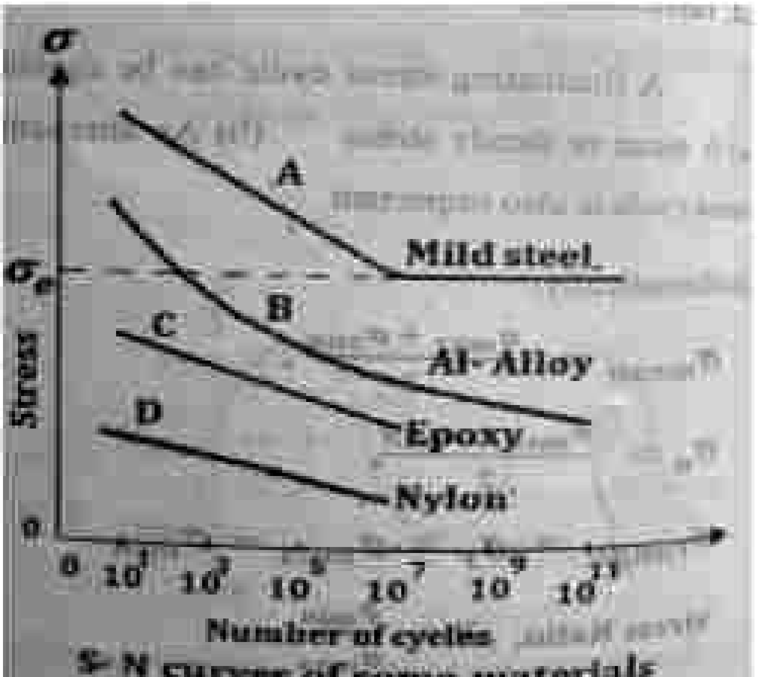
S-N curve

Presentation of Fatigue Data:

In general fatigue test results are presented by means of S-N curve (i.e. Stress- number of cycles to failure).

Procedure to plot S-N curve:

- To plot S-N curve for a material, several samples are prepared from the same material.
- The first sample is tested at relatively higher stress, as expected the sample fails at less number of stress cycle.
- The next sample is tested at a stress lower than the stress value of the previous test. This is continued till one or two sample doesn`t fail with in the specified no. of cycle.
- Then stress (σ) is plotted against the number of cycles to failure (N) of the test specimen. The general shape of the plot for different materials is shown below.



S-N curves of some materials

Endurance limit

- The concept of an endurance limit is used for safe stress designs.
- From the above plot it can be observed that, the number of cycle a material can sustain is increasing with decrease in the applied stress.
- Out the above four curve the curve A (Mild steel) shows a distinct feature. The curve is getting parallel to X-axis. That means below certain stress level mild steel can with stand infinite number of stress cycle without fracturing.
- A stress level below which the material does not fail and can be cycled infinitely is called ***endurance limit***. If the applied stress level is below the endurance limit of the material or the structure is said to have an infinite life.
- Many non-ferrous metals and alloys, such as aluminium, magnesium, and copper alloys, do not exhibit well-defined endurance limits. These materials instead display a continuously decreasing S-N response, similar to Curve B in Figure.
- In such cases a fatigue strength for a given number of cycles must be specified. An effective endurance limit for these materials is sometimes defined as the stress that causes failure at $1x10^8$ or $5x10^8$ loading cycles.

Fatigue testing

Fatigue test can be classified into two types:

(i) High Cycle Fatigue (HCF)
(ii) Low Cycle Fatigue (LCF)

(i) High Cycle Fatigue (HCF):

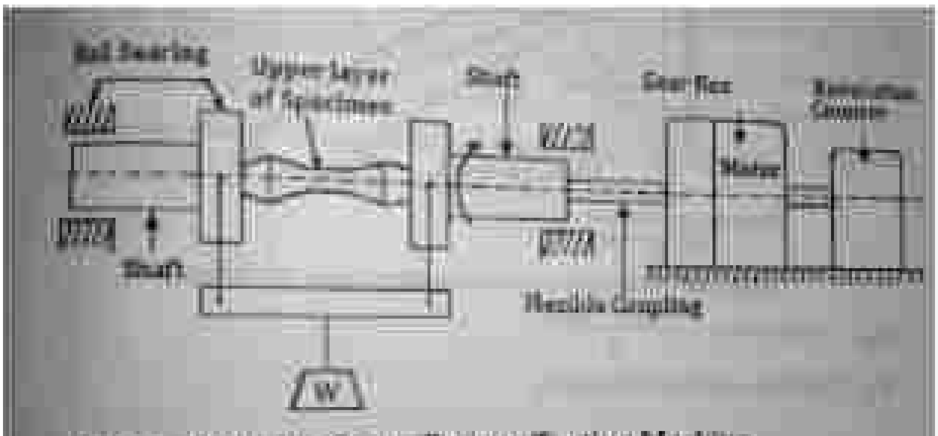
- If the test is conducted for 10^5 cycles or more then it is termed as High Cycle Fatigue test.
- The stress on the test sample is within the elastic limit.
- It is said to be load/stress controlled test. That is the test is conducted for specified load/stress.

(ii) Low Cycle Fatigue (LCF):

- If the test is conducted for less than 10^5 cycle, it is termed as Low Cycle Fatigue test.
- The stress on the test sample is beyond yield stress.
- It is said to be strain controlled test. That is the test is conducted for specified strain or deformation.

Fatigue testing machine

- Fatigue testing mostly done on rotating beam fatigue testing machine developed by Moore.
- In this machine, a polished specimen (beam) is placed as simply supported beam & loaded in pure bonding by a dead weight (W). This beam rotates in a ball bearing at a speed ranging from 3000 to 10,000 rpm. A variable speed motor/constant speed motor with a gear box is used for this purpose. The top mast layer of the rotating specimen remains in compression while bottom most in tension. Thus, sinusoidal alternating stress is produced on the surface of the specimen during each revolution. A mechanical revolution (counter) recorded the number of cycles of stress reversal the machine automatically went off after the specimen broken.



Moore Rotating Beam Fatigue Testing Machine.

Factors affecting fatigue behaviour

Experimentally it has been observed that fatigue crack usually nucleates/initiate at the surface of the material under cyclic loading. So, in general the factors which helps in formation of surface crack will decrease the fatigue strength and vice versa. Following factors greatly affect fatigue property of metal and alloys:

(a) composition
(b) stress concentration
(c) size effect
(d) surface condition
(e) residual stress
(f) Metallurgical factors
(g) Temperature

(a) <u>Composition</u>: The alloying elements which increase the tensile strength of a material are observed to increase the fatigue strength as well.

(b) <u>Stress concentration</u>: Presence of stress raisers like notch, holes decrease the fatigue strength. This stress raisers are the location from which a fatigue crack starts.

(c) Size effect: As the size of the component increases the fatigue strength decreases. It has been evident that as the size increases the number of crack and the size of pre-existing crack increases.

(d) Surface condition: Fatigue strength of a material strongly depend upon surface condition. As the fatigue crack always start from the surface. Therefore, for better fatigue strength the surface of the material should be smooth.

(e) Residual stress: Presence of compressive residual stress on the surface of the sample increases fatigue strength as it closes the initiating cracks and vice versa.

- Compressive stress on the surface of a component can be formed by: shot peening, surface rolling etc.

(f) Metallurgical factors :

- Solid solution alloying increases the fatigue strength.
- Finer/smaller the grain size higher the fatigue strength.
- Hardening increases the fatigue strength as the martensite percentage increases.
- Tempering after quenching increases the fatigue strength.
- Carburising, nitriding, case hardening or any surface hardening technique increases fatigue strength. While decarburising decreases the fatigue strength.

(g) Temperature: Fatigue strength increases with decrease in temperature unlike impact strength. However, there is no sudden increase in fatigue strength with fall of temperature.

Creep Test

Introduction

- The deformation behaviour of a material at room and at high temperature are not same.

- In general, a material becomes comparatively softer when deformed at elevated temperature.
- Now a day's several metal components have found their use at high temperature application like: jet engine, power plants, automobiles, chemical plants etc.
- Hence it is therefore necessary to study the deformation behaviour of materials at high temperature.

Definition and importance

- *Creep is defined as, a time-dependent plastic deformation under a certain constant applied load or stress.*
- Generally, occurs at high temperature (thermal creep), but can also happen at room temperature in certain materials (e.g. lead or glass).
- As a result, the material undergoes a time dependent increase in length, which could be dangerous while in service in places like: Industrial belts, turbine blades, pistons, rockets etc. and may lead to failure. So, it is necessary to study the creep behaviour of materials which are being used at elevated temperature.
- The term high temperature cannot be defined universally because for material like lead room temperature is also high temperature.

- In order to take care of this anomaly temperature is often expressed as **homologous temperature**. *It is the ratio of working temperature of a material and it's melting temperature both in kelvin scale unit.*

Homologous temperature = T/Tm

Where, T = working temperature in kelvin
Tm = Melting temperature in kelvin.

- Creep deformation generally occurs when Homologous temperature ≥ 0.5.

Creep Curve

- As Creep deformation is a time dependant process, so the total creep test may take few hours, few days, few months or even few years according to the importance and need.

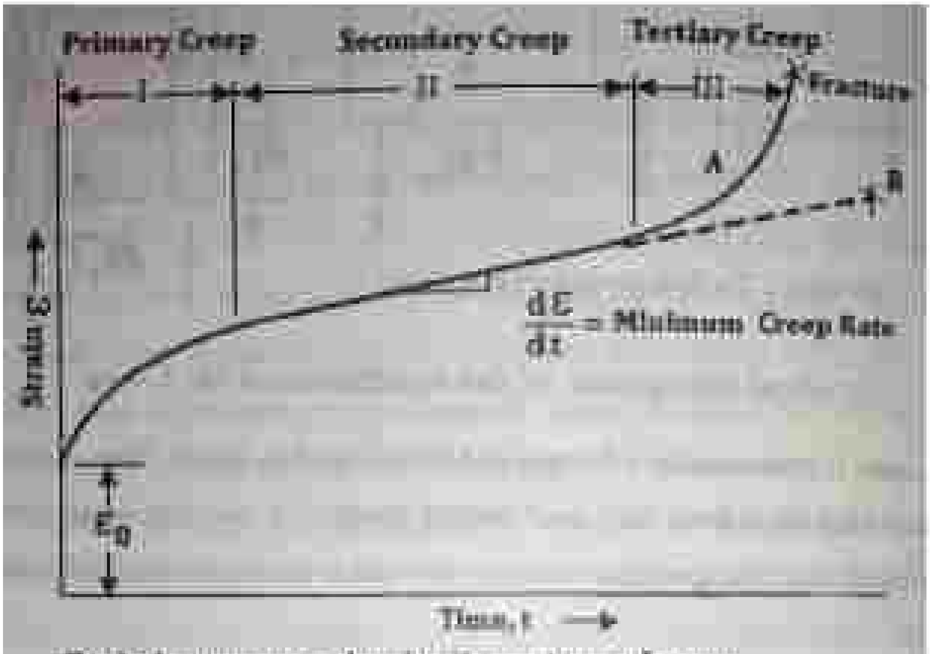
- The total creep or elongation or strain (ε) is measured for the entire duration of the test. *The plot of strain (ε) versus time (t) as shown in figure below is known as creep curve.*

- The curve A in the figure below represents an idealized creep curve. The slope of the curve is termed as creep rate.
- After an instantaneous elongation, the creep rate decreases with time, then reaches a steady state during which there is very little change in creep rate with time.

- Finally, the creep rate increases rapidly with time till fracture occurs. This phenomenon is divided into three distinct stages such as:

1. Stage I: Primary Creep.
2. Stage II: Secondary Creep.
3. Stage III: Tertiary Creep.

1. Stage I:
The first stage of the creep is known as primary creep or this shows a region of decreasing transient creep rate. During this stage, the creep resistance of the material increases due to strain hardening. At low temperature and stress, Stage I creep is significant while this zone vanishes as temperature & stress increases.



Typical creep curve showing three stages of creep.
Curve A: Constant load test ; Curve B : constant stress test

2. Stage II:
The Stage II creep is known as secondary creep. This is the period of nearly constant creep rate and is of great engineering importance. This constant creep rate results from the balance between the two competing processes that is strain hardening & recovery. For this reason secondary creep is known as Steady Creep.

3. Stage III:

Third stage of the creep curve is known as Tertiary Creep. Tertiary creep occurs when there an effective reduction in cross-sectional area of the specimen either due to necking or due to formation of internal voids. This leads to ultimate failure of the material.

Andrade's analysis of creep Curve

- Andrade was the first to examine the creep curve in detail and published his results in 1951.

- According to him the constant stress steep curve represents the superimposition of two separate creep processes which occur immediate after sudden strain (ε_0) and results from applying the load.
- The first component of creep curve is 'transient creep' with a creep rate decreasing with time added to this is a constant rate 'viscous creep'.

Stage I:

- The Stage I of the creep curve is known a transient creep or cold creep. This even occurs at low temperature hence known as primary or cold creep.

Andrade's law for Transient Creep is:

Parabolic law: Transient creep for metals and alloys, ε_{tr}= $\mathbf{Ct^n}$.

Where, C= constant, n Power index whose value is 1/3, t= Time.

Stage II:

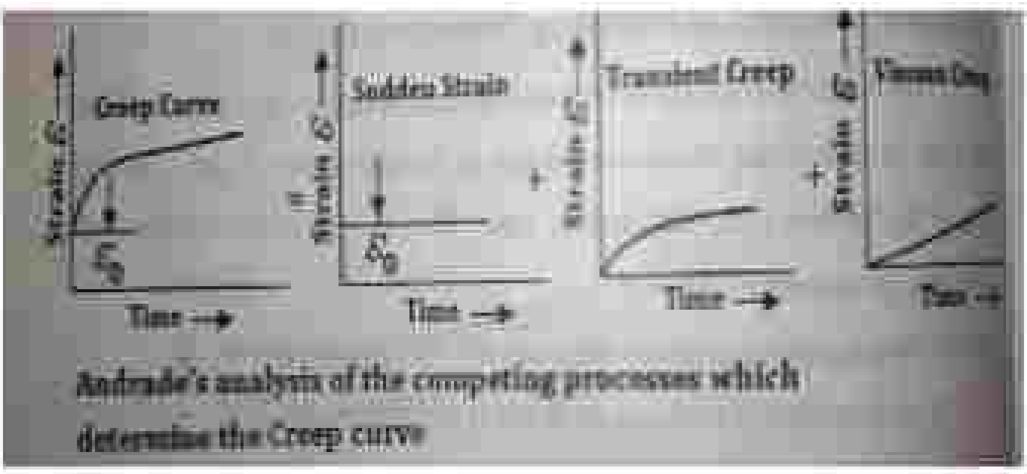
- This stage is known as secondary creep or steady state creep that result Creep from a balance between the competing processes of strain hardening and recovery.

- This stage of creep is also known as a viscous creep or hot creep.

Secondary creep law:
$\varepsilon_{cr} = \varepsilon_1 + v_{cr}t$
Where, $\varepsilon 1$=The strain intercept, v_{cr} = The minimum or viscous creep rate.

Stage III:

Third stage of creep is known as 'tertiary creep, during which the creep rate increase rapidly and finally results in failure of the material.



Andrade's analysis of the competing processes which determine the Creep curve

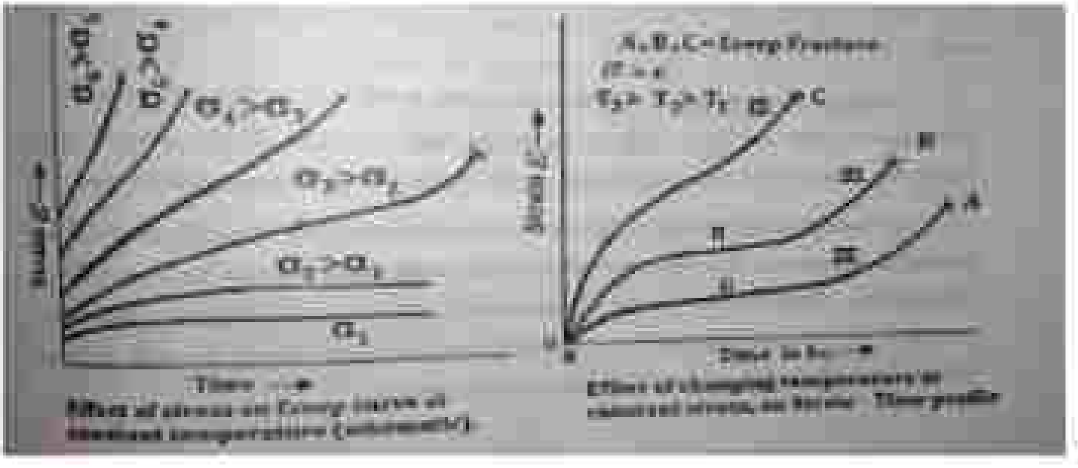
The total creep strain, $\varepsilon = \varepsilon_o + \varepsilon_p + \varepsilon_s$
ε_o = instantaneous strain at loading (elastic and plastic)
ε_s = steady-state creep strain
ε_p = primary or transient creep

Factors affecting Creep

- There are mostly three parameters which affect creep: stress, temperature and microstructure.

- Both increase in temperature and stress will increase creep rate and the failure will be early as shown in figure.

- However, we can tune the microstructure to get good creep resistance.



Creep testing machine

- Measures dimensional changes accurately at constant high temperature and constant load or stress.

- Useful for modelling long term applications which are strain limited.

- Provides prediction of life expectancy before service. This is important for example turbine blades.

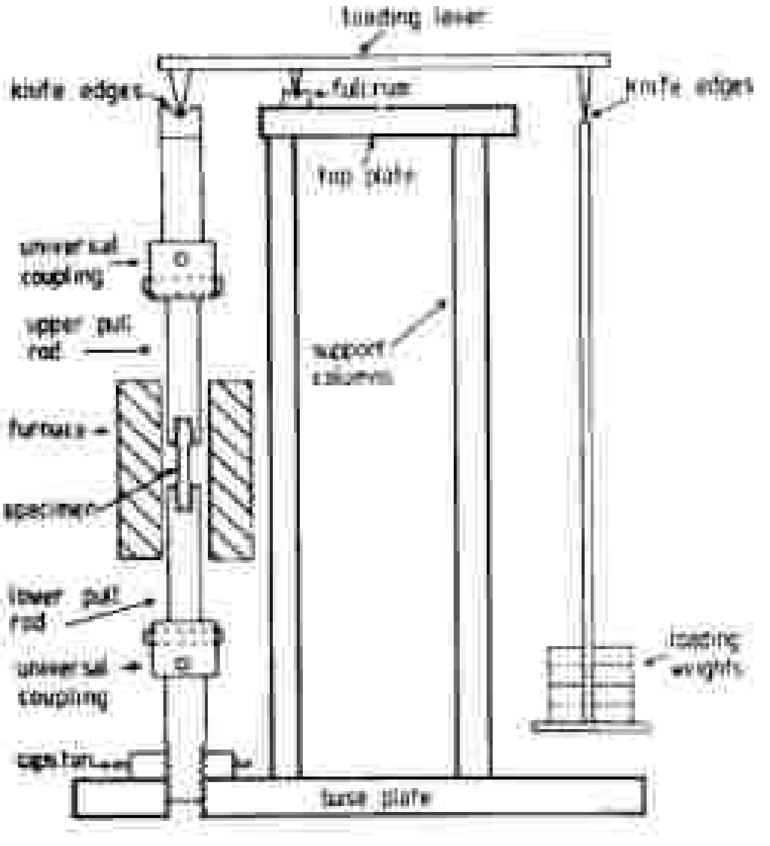


Fig: Creep test apparatus

- Measures strain vs. time at constant T and Load (Similar to graph seen previously).
- Relatively low loads and creep rate
- Long duration 2000 to 10,000 hours.
- Not always fracture.
- Strain typically less than 0.5%.

Stress Rapture Test:

- The stress rapture test is basically similar to Creep test. However, this test is always conducted at much higher loads and always continued up to the failure unlike creep test.

- As load is higher, the creep rates in case of stress rupture test are also higher compared to creep test.

- Usually the total strain during a creep test is often less than 0.5% while in a stress rapture test the total strain may be as high as 50%.

- The basic information obtained from the stress rupture test is the time taken to cause failure for a given nominal stress at a constant temperature.

Equicohesive temperature

- The temperature at which the strength of grain boundary equals to grain interior.

- Or the temperature at which the cohesive force at grain boundary becomes equal to grain interior.

It is the temperature at which there is transition of crack propagation from intergranular to transgranular occurs.