Module 6

Experimental Tools & Techniques II

Lecture 6

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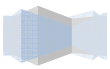


Keywords: Tensile test, elastic & plastic deformation, yield strength, ultimate tensile strength, % elongation, engineering / true stress, engineering / true strain, Hardness scales: Rockwell, Brinell, Vickers, Charpy notch impact test, Fracture toughness, Fatigue tests, and Creep tests

Introduction

Metals and alloys are commonly used as structural components. Ability to withstand load under a variety of user defined conditions is the major criteria of their selection. These are characterized by a set of mechanical tests. In this module we shall learn how these tests are performed, what types of equipments are needed and the properties obtained from such tests. Most of the properties depend strongly on how the product has been made. For example a cast product would have totally different set of properties than that of a forged product even if it is made of the same alloy. Many of these properties will often be referred to in subsequent modules. Therefore it would be good to have an elementary knowledge about these. This module gives a brief overview of following mechanical tests: tensile, impact, hardness, creep and fatigue.

Tensile Test

A specimen of a standard size and shape made of the material is pulled in tension while the load and elongation are continuously (or periodically) monitored. The data thus collected are used to generate stress strain curve. Figure 1 shows a sketch highlighting the important parts of the testing system used to perform a tensile test. Modern machines have an intelligent computer interface and have facility to perform tests under various user defined modes (for example load control, displacement control and strain control). Usually tensile tests are performed under displacement control mode where the moveable end of the grip is made to move at a constant speed. The load and displacement (strain) records are stored at specified intervals of time. Once the sample breaks the machine stops. The data can then be displayed on the computer screen. Figure 2 gives a typical load displacement plot which is converted to stress strain plots using the following expressions given after fig 1.

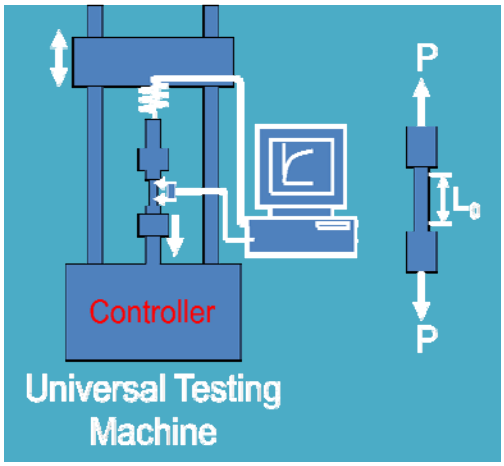


Fig 1: A sketch showing the main parts of a universal testing machine used for tensile test. It has a load frame with load cell and an actuator with suitable feedback control. Modern units are equipped with computer to store and analyze test data. An enlarged view of the test specimen is shown beside the UTM. L_0 denotes initial gauge length. The inputs from the load cell and extension gauge mounted on the specimen are fed to computer through a suitable intelligent interface. Such a unit with suitable grips and fixtures can be used to perform various other types of mechanical tests. This is why it is known as universal testing machine.

Stress = S = Load / initial cross sectional area = P/A_0 (1)

Stress = $\frac{4P}{\pi d_0^2}$ (for samples with circular cross section having d_0 as its initial diameter)

Strain = e = $\frac{L-L_0}{L_0} = \frac{\Delta L}{L_0}$ (where L is the length at any instant & L_0 is the initial length) (2)

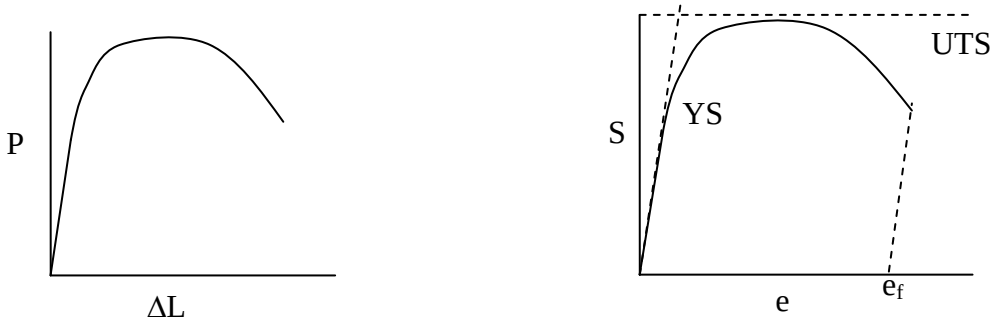


Fig 2: a) A schematic load displacement plot. b) A schematic stress strain plot obtained from fig 2a using equations 1 & 2 given above. The peak stress is known as ultimate tensile strength (UTS), the slope of the initial linear part of the plot is called Young's modulus, e_f is the strain at rupture (elongation if expressed as %) and the point at which the plot starts deviating from linear relationship is called yield stress (proportional limit). If the sample is loaded within the linear part of the plot and subsequently unloaded it comes back to its original shape and size. The specimen is said to have undergone elastic deformation. If the sample is loaded beyond YS and then unloaded it would not come back to its original shape and size. Deformation in this case is permanent (plastic deformation). Of the two types of deformation the former (elastic) is reversible whereas the latter (plastic) is irreversible (see table 1). At any stage beyond YS the total stain has both elastic and plastic components. Once the sample ruptures the elastic part recovers (it becomes zero) but the plastic part which is permanent remains unaltered. This is known as the strain at rupture. It is a measure of the ductility of the material.

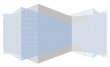
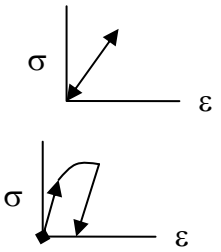


Table 1: Main characteristics of elastic and plastic deformation

Elastic deformation		Reversible Stress strain relation: Hooke's law: $\sigma = E\varepsilon$ Metals mostly exhibit linear elastic behaviour
Plastic deformation		Irreversible: leaves permanent strain Stress strain beyond YS: $\sigma = K\varepsilon^n$ K & n are constants. Slope of unloading step is same as that of the elastic part of the plot.

For most engineering applications the magnitude of tensile stress is defined as the load over the initial cross sectional area. However as strain increases the area decreases therefore the true stress at any given strain should be defined as the load over the instantaneous area. As long as the magnitude of strain is small the difference between the two is insignificant. When we talk of large strain well within the plastic regime it is more appropriate to consider true stress and strain (defined as the increase in the gauge length over the instantaneous gauge length).

$$True\ strain = \varepsilon = \int_{L_0}^{L} \frac{dL}{L} = ln\left(\frac{L}{L_0}\right) = ln\left(\frac{L_0+\Delta L}{L_0}\right) = ln(1+e) \qquad (3)$$

$$\text{True stress} = = \sigma = \frac{P}{A} = \frac{P}{A_0}\left(\frac{A_0}{A}\right) = S\left(\frac{A_0}{A}\right) = S\left(\frac{L_0}{L}\right) = S(1+e) \qquad (4)$$

Note that if the deformation is uniform and there is no change in volume due to plastic deformation A_0L_0 = AL. Using equation 3 & 4, the engineering stress strain curves can be converted to true stress strain plots (see fig 3). The relation between stress & strain beyond YS given in table 1 are valid for true stress and true strain.

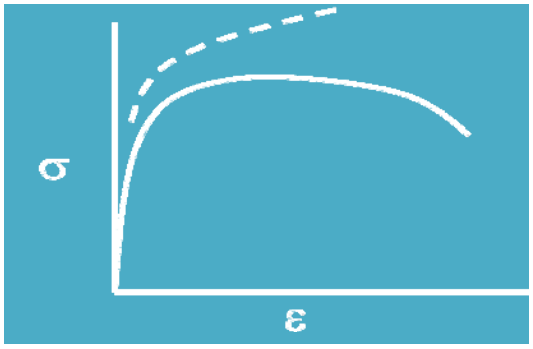


Fig 3: The firm line denotes engineering stress strain plot where as the dotted line is the true stress – strain plot. As long as the strain is small (<5%) the two are identical. Engineering stress strain diagram shows a peak at UTS. Until this point deformation is uniform and expression A_0L_0 = AL can be used to convert elongation to reduction area and hence it can be used to estimate true stress. Thereafter local deformation sets in and the state of stress is no longer uni-axial.

Figure 4 shows typical stress strain diagrams of a ductile and a brittle material. Most metals & alloys have excellent ductility whereas ceramics (or inter-metallic) have poor ductility. Apart from elastic modulus, YS, UTS, ductility (% elongation and % reduction in area) there are a large number of other properties that can be obtained from tensile tests. A few of these are listed in table 2.

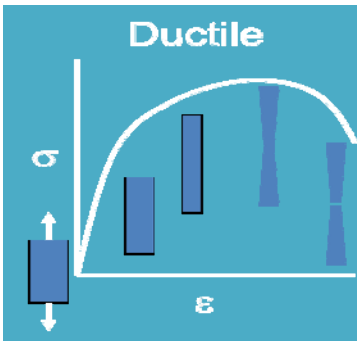


Fig 4a shows the stress diagram of a ductile material. Specimen shapes are also shown in the figure. Local deformation sets in when the stress reaches its maximum point. The area under the plots is large.

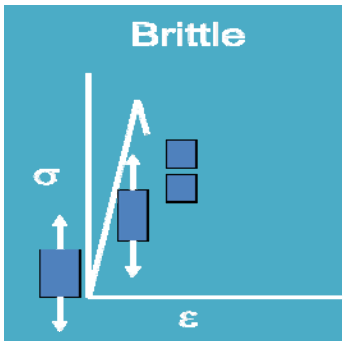


Fig 4b shows stress strain diagram of a brittle material. Note that the deformation along the length of specimen is uniform. Stress drops as cracks sets in. This may occur even before yielding. The area under the plot is small.

The local deformation or necking as it is more commonly known as is encountered during tensile testing of ductile material. This is also known as tensile instability. Assuming a simple relationship between stress and plastic strain as given in table 1 it is possible to derive the condition under which such instability is likely to occur. This is described below:

Applied stress = $\sigma = \frac{P}{A}$ 5

It can be also written as: $\frac{d\sigma}{\sigma} = \frac{dP}{P} - \frac{dA}{A}$ 6

When the load reaches its maximum value: $\frac{dP}{P} = 0$. $(-\frac{dA}{A})$ still represents incremental strain (d□). Therefore it is possible to derive the condition at which necking sets in. This is given by:

$\sigma = \frac{d\sigma}{d\varepsilon}$ 7

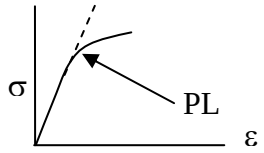
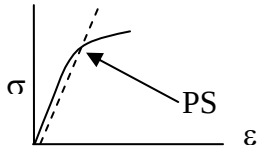
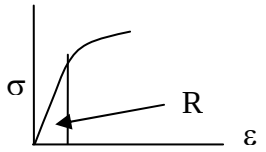
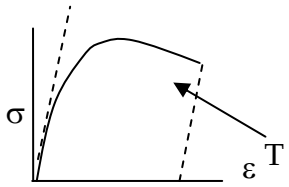
Note that in these equations □ & □ denote true stress and true strain. Equation 7 states that at necking the slope of the stress strain plot becomes equal to the stress itself. The slope of the stress strain plot gives an idea about the extent of strain hardening. Since the relation between stress and strain is given by:

$\sigma = K\varepsilon^n$; $\therefore \frac{d\sigma}{d\varepsilon} = Kn\varepsilon^{n-1} = n\frac{\sigma}{\varepsilon}$ 8

From equation 7 & 8 it follows that $\varepsilon = n$ 9

This shows that n is an indicator of the strain at necking. A large n means the material has good ductility. For most metals it is around 0.3.

Table 2: Shows how various mechanical properties of a material can be obtained from its stress strain plot

Proportional limit (PL)		Indicates the stress up to which it is directly proportional to strain.
0.2% Proof stress (PS)		Sometimes it is difficult to identify the yield point. Therefore the stress to reach a specified level of strain (0.002) is taken as the yield stress.
Resilience (RS)		A measure of recoverable stored energy, given by the area under the elastic part of the stress strain diagram. Useful property for the selection of material for spring.
Toughness (T)		The area under the total stress strain plot minus the amount of recoverable energy due to elastic deformation. This is a measure of energy absorbed due to plastic deformation.

Hardness

It is often defined as the ability of a material to resist scratch or indentation. Talc is known for its softness. You may be able to scratch it with your nail. In terms of Moh's scale (Oldest measure of hardness) hardness of talc is taken as zero and that of diamond (the strongest solid) as 10. All materials have hardness values in between these limits. However this is too qualitative a measure to be of practical significance for engineering application. Resistance to deformation or indentation is a more practical and popular measure of hardness. There are several different ways of estimating this by trying to force an indenter made of a hard non- deformable material of standard dimension. The hardness is defined on the basis of the type of indenter, load used and the size of the impression left on the material. Three most commonly used indentation hardness scales are known as Rockwell, Brinell and Vickers.

Rockwell hardness is a linear function of depth of indentation. Higher the depth of indentation lower is the hardness. The scale ranges between 0-100. It uses either a diamond 120° cone indenter or a

ball indenter made of hardened steel. Depending on the combination of indenter and load there are several Rockwell hardness scales. Three most commonly used Rockwell hardness scales are given in table 3. The tester consists of a moveable sample stand, a loading device connected to an indenter. The sample is placed beneath an indenter. A minor load of 10kg is applied. The position of the indenter is indicated on a dial gauge fixed on the loading device. The reading at this stage corresponds to zero. Subsequently the major load is applied. The indenter penetrates into the material. After a specified time interval the major load is withdrawn. The indenter moves up but does not come back to its original position. The scale is calibrated in a reverse fashion. The closer it comes back to its original position higher is the hardness. Each reading corresponds to a depth of penetration of 2□. The combination of indenter and load are so chosen that the reading lies between 20 and 80. R_c scale is used to measure hardness of heat treated steel whereas R_B scale is used for relatively softer materials like aluminium.

Table 3: Common Rockwell Hardness Scale

Rockwell Scale	Minor load, kg	Major load, kg	Total load, kg	Indenter
R_A	10	50	60	120° diamond cone
R_B	10	90	100	1/16" steel ball
R_C	10	140	150	120° diamond cone

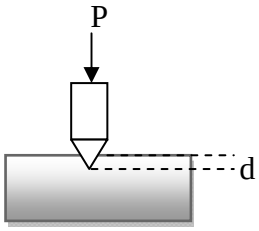
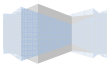


Fig 5: A sketch showing the extent of penetration by major load P in a Rockwell hardness tester. It measures d after the major load is withdrawn. H = K-d

Brinell hardness uses either 10 or 5mm diameter ball indenter made of either hardened steel or tungsten carbide. The applied load depends on the hardness of material. As a thumb rule the load used for measuring the hardness of steel = $30D^2$ kg; where D is the diameter of the ball. If D = 10mm the load to be used = 3000kg. The machine consists of a loading device connected to the indenter and a moveable stand to place the sample. The sample stand is raised so that it touches the indenter. Thereafter the specified load is applied. After a specified length of hold time (~10s) the load is withdrawn. This leaves an indentation mark. Its diameter (d) is measured using a graduated eyepiece. If P is the applied load the Brinell hardness number (BHN) of the material is given by load / area of the indentation. Unlike Rockwell hardness which is just a number BHN has a dimension of kg/mm^2. The expression to estimate BHN is as follows:

$$BHN = \frac{2P}{\pi D\left(D-\sqrt{D^2-d^2}\right)} \qquad 10$$



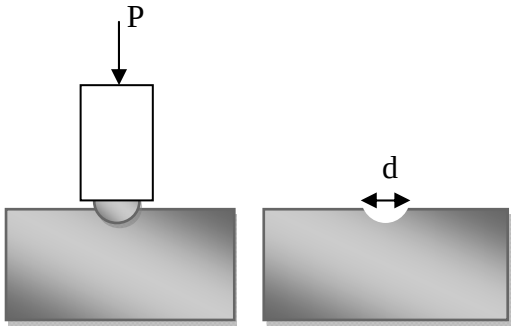


Fig 6: A sketch showing the extent of penetration by load P in a Brinell hardness tester. It measures diameter (d) of the indentation using a graduated eye piece after the load is withdrawn. Hardness is given by P divided by the surface area of the indentation.

Since the loads and the sizes of indenter are much larger than those used for Rockwell scale the impression left on the sample too is much larger. It is likely to give an average hardness over a larger area of the sample. BHN is a preferred scale if the material is heterogeneous (example cast iron).

Vickers hardness scale (number) is similar to that of BHN. The difference lies in the choice of indenter and the load. It uses square based diamond pyramid indenter with an apex angle of 136°. The loads used are in the range 1 to 120kg. This scale is independent of load. Since the load is much lower than that in Brinell, the size of indentation is much smaller. It needs a microscope to measure the size of the indentation mark. The commercial hardness measurement system is equipped with a loading device connected to the indenter; an adjustable specimen stage and a microscope with provision to measure the diagonal of the impression left behind or an imaging system than can magnify the indentation mark to facilitate measurement. Hardness is defined as load over the area of the indentation. If the diagonal of the square shaped indentation is d and □ is the apex angle of the indenter; Vickers Hardness Number (VHN) is given by:

$$VHN = \frac{2P}{d^2} Sin\left(\frac{\theta}{2}\right) = 1.8534\frac{P}{d^2} \qquad 11$$

Both BHN & VHN use the similar concept for the measurement of hardness. Therefore for most materials the hardness values are nearly the same up to 500BHN (approximately). Since indentation hardness measures the resistance to deformation it has a direct correlation with tensile strength of the material. The hardness number is approximately 3 times the UTS (□$_0$) in MPa. (BHN = VHN = 3□$_0$). Measurement of hardness is extremely simple and easy. It does not need elaborate sample preparation or machining. A flat surface is good enough. Only VHN needs a little better surface finish with fine emery paper. Hardness measurements using these three scales are very popular for engineering applications. It (Rockwell & VHN) is nearly a non-destructive method of estimating the strength of a material. Whatever technique you use for hardness measurement there are standard conversion tables to help you convert hardness measured on one scale to another.

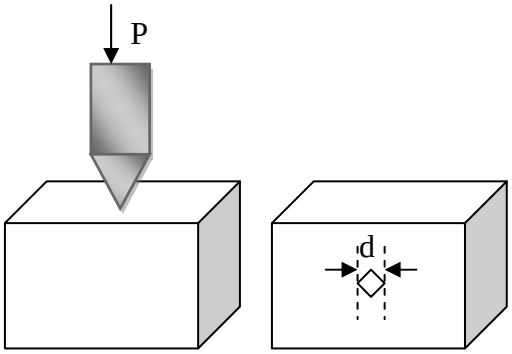
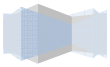


Fig 7: A sketch showing the extent of penetration by load P in a Vickers hardness tester. It measures diagonal (d) of the indentation using a graduated eye piece after the load is withdrawn. Hardness is given by P divided by the surface area of the indentation.

Impact

Often materials known to be ductile and tough under normal rate of loading is found be brittle if it is subjected to impact or sudden loading. Impact testing helps us assess the ability of a material to withstand such loading. There are several methods of testing impact resistance. However we shall try to give an idea about one of the most common techniques known as Charpy V Notch (CVN) test. This uses a standard 10mm square 55mm long specimen with a 2mm deep V notch located half way between the two ends. It is placed horizontally on two supports at either ends so that the V notch is vertical. A hammer having a specified shape and size mounted on fixture that can be made to swing like a pendulum is used to strike the specimen on the face opposite the one having the V notch. The hammer can be raised to different heights as necessary. The height gives the net potential energy stored in the hammer (= mgh; where m is the mass of the hammer in kg, h is the height in meter (m) and g is acceleration due to gravity in m/s^2). When it is released this gets converted into kinetic energy. When the hammer is in its lowest position, its kinetic energy or its velocity attains its maximum value ($=\frac{1}{2}mv^2$). This is when it strikes the sample. As a result the sample breaks and the hammer still continues to swing. The height to which it rises immediately after it breaks the sample gives an estimate of the energy of the hammer after the sample is broken. It breaks through initiation and propagation of a crack from the notch root. The difference between the two gives a measure of the energy absorbed by the sample. Higher the amount of energy needed to break the specimen higher is its impact resistance. It is expressed in terms of Joule. When it absorbs a large amount of energy to break there are signs of large local deformation near the notch root. The fractured surface is rough. Such materials are said to be tough. A brittle material on the other hand absorbs little energy for crack initiation and propagation. There is hardly any sign of notch root deformation. The fractured surface is nearly flat. CVN is found to be a function of materials, its microstructure and the test temperature. Metals by and large have CVN. However steel is known to exhibit transition from ductile behaviour at room (and high temperature) to brittle behaviour at low temperature. Figure 8 shows a typical CVN versus temperature plot of steel. The temperature at which there is a sharp change in CVN value is known as its transition temperature.



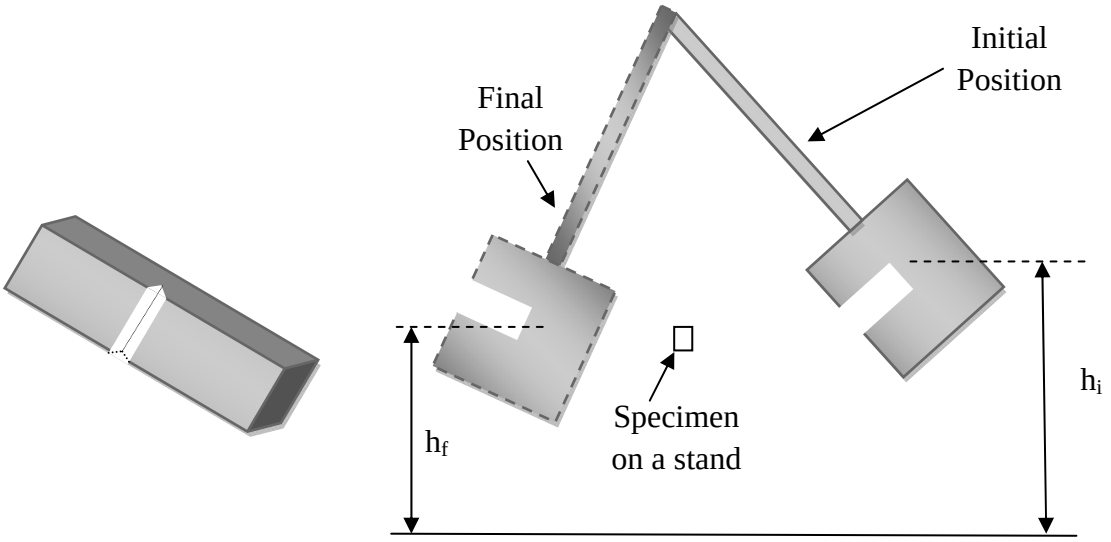


Fig 8: a) A sketch of the standard CVN test piece (55mm long 10X10mm cross section) with a 2mm wide v shaped notch on one face as shown. The hammer strikes the face opposite the one having the notch. b) A sketch showing the position of hammer just before and after the test. The hammer can swing like a pendulum. When released from a height of h_i it goes to other side to the same height if there is no specimen. If there is a specimen on the stand as shown it absorbs a part of the energy of the hammer. Let the height the hammer rises to now be h_f. Therefore CVN = mg (h_i-h_f).

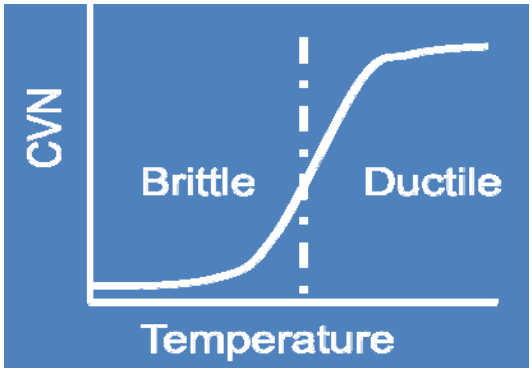


Fig 9: Shows CVN of steel tested at different temperatures. At lower temperatures material is brittle but at higher temperatures it is ductile. The temperature shown with dashed line is known as transition temperature. Brittle fracture shows little notch root contraction whereas ductile fracture is fibrous with significant notch root contraction.

Limitation of CVN as a measure of toughness: It only gives a qualitative index of the ability of a material to resist unstable growth of a notch that represents a defect under impact loading. Unlike properties such as yield strength it does not allow estimation of the load a component could withstand from the CVN data. This is because in the presence of a defect the local state of stress near the defect is more complex than that in the case of a uniformly stressed sample. The stress that helps the crack to open up or propagate is perpendicular to the plane on which it lies. Figure 10 represents the orientation of a crack of length equal to *a*, in a sample supported at two ends and loaded at the

centre. This is commonly known as 3 point bend loading. This is the way a sample is loaded during Charpy V-notch impact testing. It also gives the nature of the stress distribution near the crack tip. The concept of K_{1C} which is known as the fracture toughness of the material has also been explained.

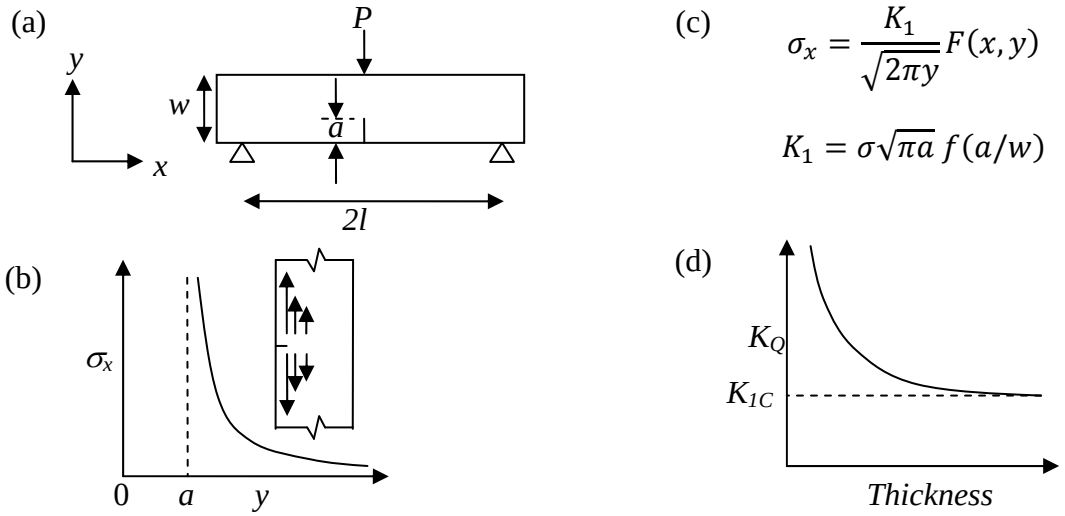


Figure 10: (a) A sketch showing how a sample of width *w*, thickness *B* and length *2l* is loaded in bending. The load *P* is applied at the centre of the span. The sample has a crack of length *a* as shown. (b) Shows how the stress acting along *x* axis varies with the distance from the crack tip (*y*). (c) Gives the dependence of stress σ_x on stress intensity factor (SIF) K_1 and a geometric function *F*. SIF gives the amplitude of the stress distribution near the crack tip. The expression for K_1 has a term *f(a/w)*. This depends on the loading and geometry. Unstable crack extension occurs as it approaches K_{1C} representing the fracture toughness of the material. (d) Shows the effect of sample thickness on the magnitude of the SIF at which unstable crack growth occurs in a specimen of thickness *B*. This is denoted as K_Q. It shows that beyond a specific thickness it becomes independent of B. This is defined as K_{1C} which is a material property. It is independent of loading, specimen size and

The critical size of a defect or the length of a crack (a_c) for a given stress , specimen geometry and the nature of loading can be estimated using the expressions given in fig 12(c). For simplicity let us assume *f(a/w) = 1*. This gives the following expression for the stress at which a crack of length *'a'* would grow in an unstable manner.

$$\sigma_f = \frac{K_{1C}}{\sqrt{\pi a}} \qquad 12$$

Equation 4 suggests that in the presence of a crack the stress at which fracture takes palce could be substantially low. Expressions for *f(a/w)* for various types of specimen and loadings are available in any books on mechanical behavior of engineering materials or fracture mechanics (Hertzberg, R.W; (1983) Deformation and Fracture Mechanics of Engineering Materials, John Wiley, New York).

Fatigue

When a material is subjected to cyclic loading it fails after a certain number of cycles of loading even if the load much lower than its yields strength. This phenomenon is known as fatigue. Many engineering components are subjected to cyclic loading (for example any rotating shaft, connecting rod, rails, wheels etc). The resistance of a material to withstand such a failure is a function of loading and material characteristic. Fig 11 shows the type of loading. Fig 12 shows sample geometry and a rotating beam fatigue testing machine. The samples are mounted on the shaft of a motor as shown.

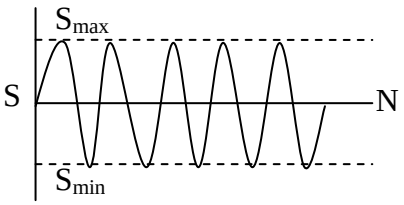
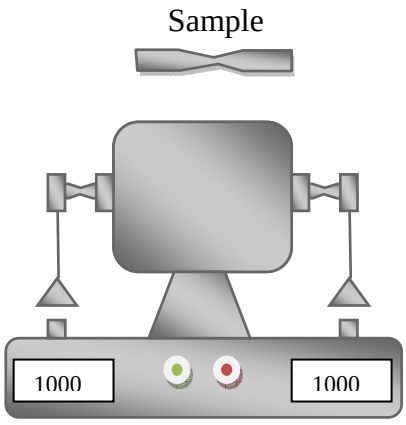


Fig 11: A diagram showing a sample being subjected to cyclic loading. The stress keeps changing between two limits Smax & Smin. The stress amplitude S = (Smax-Smin) / 2. The test continues till failure. Such tests are carried out at different stress amplitude to generate S versus N (number of cycles to failure) plot. This is known as S-N plot.



Fatigue testing unit

Fig 12: Shows the sketch of a rotating beam fatigue testing unit with two samples mounted on it with the loading train. An enlarged view of test specimen made from cylindrical rod is shown just above the testing unit. The sample is loaded as a cantilever. Therefore it has a reduced section at the centre to ensure that the central portion of the test piece is subjected to maximum stress (bending moment). Two samples can be mounted on the machine. Each has separate loading pan fixed with the help of bearing. The top half of the sample is subjected to tension whereas the bottom half is subjected to compression. As the sample rotates the stress at point keeps changing. This is how it is subjected to cyclic loading.

As the sample rotates the stress at a point keeps changing. One rotation corresponds to one cycle of loading. The machine has a counter to count & display the number of cycles of loading. When the sample breaks the loading pan falls on a limit switch that stops the machine and the counter. The number of cycles to failure is noted. Tests are conducted at different stress ranges. The stress (S: the peak stress when the mean load is zero) versus number of cycles to failure plot is popularly known as S-N curve. Such data help in estimating fatigue lives of engineering components subjected to cyclic loading. A typical plot is shown in fig 13. For materials like steel the S-N curve slope becomes zero below a specific value of stress S. This is called the endurance limit. Within this stress range the component is expected to have infinite life. However there are a host of other metals & alloys that do not show a definite endurance limit. These are the materials that do not have infinite fatigue life at any stress range.

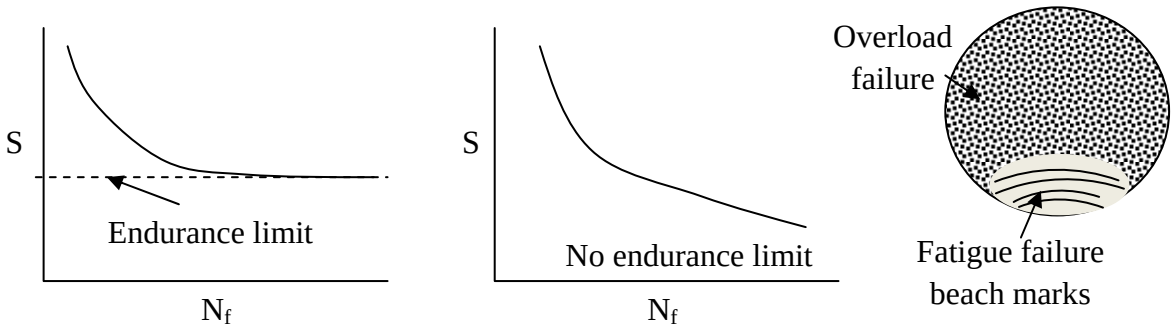


Fig 13: a) A typical S-N curve for steel showing a definite endurance limit. It is a plot of stress amplitude versus the number of cycles to failure ($2N_f$). Below the endurance limit the sample can withstand infinite numbers of cycle. b) A typical S-N curve for Al alloys. It has no definite endurance limit. In such cases 10^7 cycles is taken as the limit. c) A typical appearance of fatigue fracture the curved lines denote beach marks. Fatigue failure takes place by initiation and propagation of crack. Once a crack develops the two faces that come in contact during subsequent stages of loading get rubbed by each other. This results in beach marks. When the remaining area becomes too small to support the load rapid fracture takes place. This may have features of normal tensile failure. The fractured surface thus has two distinct regions one having beach marks characteristic of fatigue loading and the other relatively rough face typical of overload failure.

Beach mark as shown in fig 13c is the characteristic signature of fatigue failure. It suggests that under cyclic loading failure does not take place all on a sudden. It has two distinct stages: nucleation and growth. A tiny crack first nucleates (often at the exposed surface of the specimen or a component) and later it propagates leaving behind such beach marks. Examination of the plastic replica taken from the beach marked region of a fractured surface under TEM (Transmission Electron Microscope) suggests that these are made of several striation marks consisting of a set of parallel lines. The distance between two consecutive striations denotes crack extension during each cycle of loading.

S-N curves are usually obtained from fatigue tests performed on rotating beam fatigue testing units. The stress over the entire cross section of the specimen is not uniform. Once a crack initiates the peak stress at the crack tip too increases significantly. This would result in an ever increasing crack growth rate. Therefore it is more likely to give an estimate of fatigue crack initiation life. The S-N curve can be represented by Basquin equation. It is given by

$$\sigma_a = \sigma_f (2N_f)^b \qquad 13$$

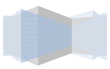
□□$_a$ is the stress amplitude (peak stress), □$_f$ is the fracture stress, $2N_f$ is the number of cycles to failure and b is a material constant. It means if a failure takes place during the first half cycle when the load is tensile the stress amplitude corresponds to the fracture stress of the material. The magnitude of b

is often in the range of 0.1 – 0.2 for most metals and alloys. It gives a conservative estimate of the fatigue life of an engineering material.

Over the last 5 decades there has been a significant progress in our understanding of the fatigue crack growth behaviour. This has been facilitated by the availability of servo-hydraulic and servo-electric material testing system where standard samples having pre-existing cracks can be subjected to user defined uniaxial fatigue loading. Figure 14 shows a schematic representation of the results obtained from a test performed on a centre cracked tension panel having a crack of length *2a* at its centre. In the presence of a crack the stress at the tip of a crack is best described by stress intensity factor (*K*). The relation between fatigue crack growth rate $\left(\frac{da}{dN}\right)$ and stress intensity range (*K*) is best described by the following equation which is commonly known as Paris law.

$$\frac{da}{dN} = c(\Delta K)^n \qquad 14$$

In this expression c and n are material constant. The magnitude of n is 4 for several commercial structural materials.



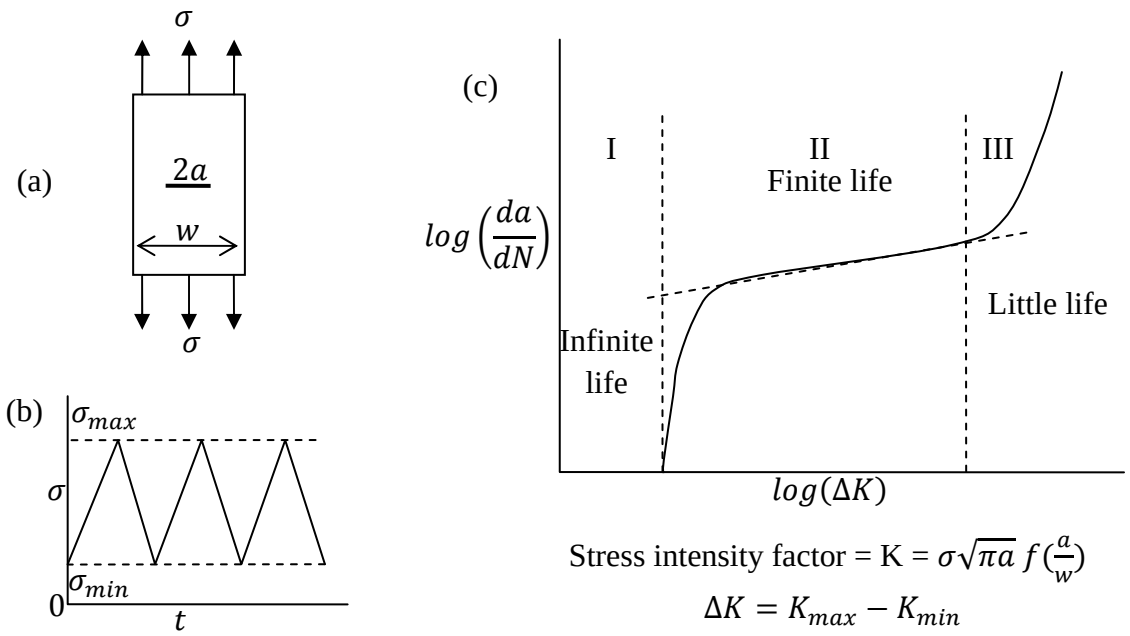


Fig 14 (a) Shows a test specimen of width *w* having a crack of length *2a* at its centre. Such specimens are commonly known as centre cracked tension panel. It is subjected to uniform tensile stress σ as shown. (b) Shows how the stress keep changing with time between two limits σ_{max} and σ_{min}. (c) Shows how the rate of crack extension per cycle of loading increases with an increase in the stress intensity range (ΔK). It has 3 distinct stages. The stage I has infinite life. In stage II the crack growth rate can be expressed as a function of ΔK. In stage III the crack growth rate keeps increasing rapidly. For all practical purposes it has limited life. The expressions estimating K & ΔK are given beneath the plot.

The comparison of the two methods of estimating fatigue life suggests that the endurance limit in the case of the S-N curve approach corresponds to the first stage of the fatigue crack growth behaviour. The magnitude of ΔK below which a material has infinite life is known as $\Delta K_{thresold}$. It depends on the microstructure of a material. It also gives a measure of the size of the defect that does not grow under a given fatigue loading.

Creep

When a material is subjected to load at an elevated temperature it undergoes a slow time dependent deformation even if the stress is much lower than its yield strength. This phenomenon is known as creep. This is measurable at temperatures T°K > 0.4 T_M°K where T_M denotes melting point in °Kelvin. Figure 15 shows a sketch showing important parts of a creep testing unit. It has a loading device connected to a set of pull rods with grips to hold the sample, a furnace having a sufficiently long heating zone with temperature controller, and a strain measuring system. The sample is kept under constant load at a constant temperature and the strain is measured as a function of time. Figure 16 shows a typical strain time plot at a given stress and temperature. This has three distinct stages apart

from the instantaneous strain on loading. Stage I where the strain rate keeps decreasing, stage II where strain rate is nearly constant and the stage III where the strain rate keeps increasing with time.

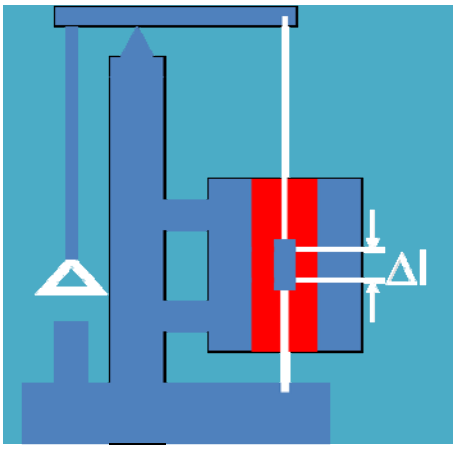


Fig 15: Shows the sketch of a typical constant load creep testing unit. It has a loading system based on a lever resting on a knife edge, pull rods with grips to hold the specimen, a furnace with suitable controller capable of maintaining sufficiently long uniform temperature zone and strain measuring device mounted on the specimen. There is a motor connected to the bottom pull rod and a sensor mounted on the lever. If the lever gets tilted beyond a limit the sensor detects it and switches on the motor. It pulls the rod until the lever becomes nearly horizontal. This is called automatic lever levelling system.

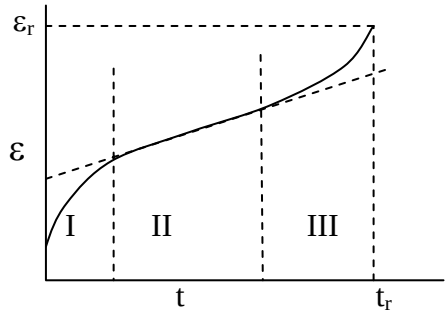


Fig 16: A typical strain time plot at a constant temperature and load. This is known as creep curve. It has three stages: I called primary where strain rate keeps decreasing, II called steady (secondary) state and III called tertiary stage where creep rate keeps increasing with time. Time at which rupture takes place (t_r) & strain (ε_r) at rupture, steady state creep rate $\dot{\varepsilon}_s$ are some of the important parameters obtained from the test. These are functions of load (initial stress) and temperature. Since load remains constant as strain increases with time stress would continue to increase.

Creep behaviour of engineering materials is a strong function of stress, temperature and the internal structure of materials. Figure 17 shows the effects of stress and temperature on the shape of the strain time plots. Creep strain accumulation increases significantly with stress and temperature. All high temperature components are subjected to creep. Therefore it becomes a major consideration for the selection of materials for such applications. There are a few simple relations derived from the analysis of experimental data that are generally applicable for most materials. A few of these are given below.

Minimum (steady state creep rate) = $\dot{\varepsilon}_s = A\, exp\left(-\frac{Q}{RT}\right)\sigma^n$ 15

$\dot{\varepsilon}_s t_r =$ Monkman Grant constant 16

Note that $\dot{\varepsilon}_s$ & R in equation 13 denote steady state creep rate, and universal gas constant, Q = activation energy and A and n are material parameters (constants). In equation 16 tr denote rupture life (time to failure).

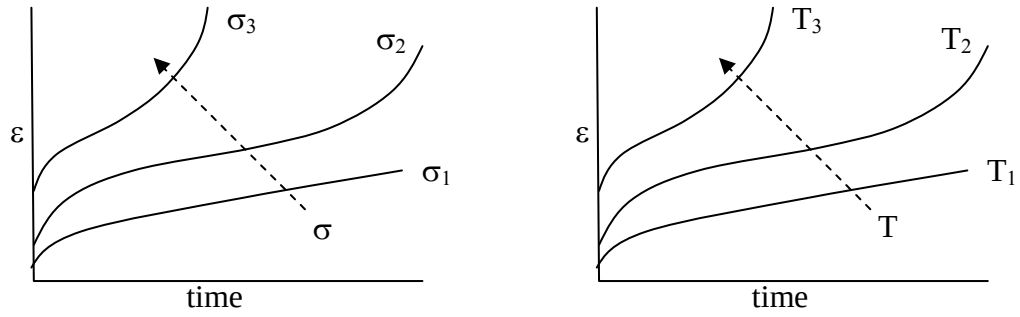


Fig 17: a) effect of stress b) effect of temperature on the shapes of creep strain time plots

Clearly it appears that a large volume of data needs to be collected (some of the tests may continue for enormously long periods of time e.g., 10 years) and analysed for describing load bearing capacity of materials at elevated temperatures. This problem is overcome for most engineering applications by looking at the times to rupture (failure). Figure 18 (a) shows the effects of stress and temperature on times to rupture. It is also possible to find or evolve suitable time temperature functions so that one could have master rupture plots as illustrated in figure 18(b).

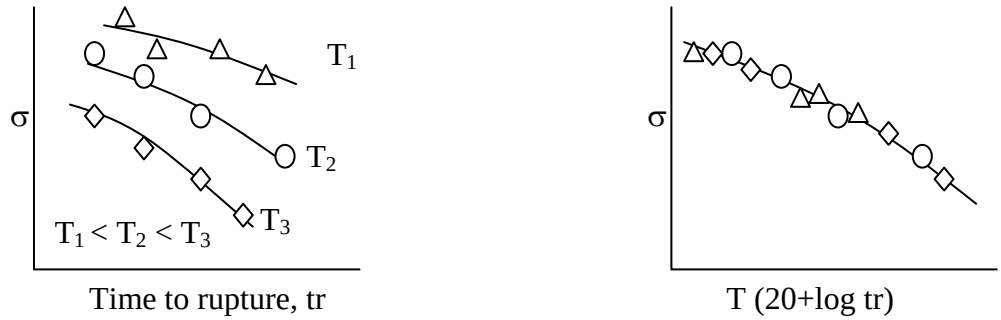
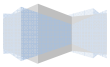


Fig 18: Sketches showing effects of stress and temperature of time to rupture. Such curves are known as stress rupture plots. (a) Shows rupture plots at three different temperatures. The lines show trend whereas symbols experimental points. (b) If these data are plotted as the function of a combined time temperature parameter as shown one gets a common master rupture plot. Note that irrespective of test temperature all data fall on the same trend line. The parameter used here {T(20+log tr), where T is in °Kelvin} is commonly known as Larson Miller parameter. There are a large numbers of similar parameters used in estimating stress rupture lives. The master rupture plot sometime may appear to have two distinct lines with different slopes. One at higher stresses has a relatively lower slope and the other at lower stress has a higher slope. The failure at higher stress level is due to trans-granular fracture whereas that at lower stress is due to inter-granular fracture.



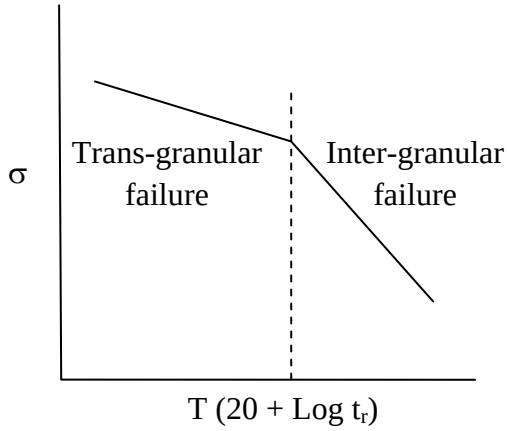


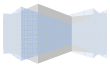
Fig 19: Stress rupture plots of most engineering materials may have two distinct regions. At higher stresses the failure is due to trans-granular fracture whereas at lower stresses failure is due to inter-granular fracture

Summary

In this lecture an attempt has been made to tell you about various types of tests that are conducted on materials to assess its load bearing ability. Unlike other physical properties of materials the load bearing capacity is found to be most sensitive to its internal microstructure. For example by controlling the composition and processing steps the strength of common structural steel can be raised from 100MPa to 3000MPa. The main focus of this course on physical metallurgy is to understand the evolution of structures in metals as it cools from liquid state and passes through subsequent transformation processes. This is done to make the materials more durable and suitable for a variety of applications. Since bulks of materials are used for load bearing applications it is necessary to have some idea about how these are evaluated.

Exercise:

1. If tensile stress strain plot beyond elastic limit is given by □ = k□^{n} show that necking (plastic instability) sets in when true strain exceeds n.
2. Derive a relation between true strain and engineering strain.
3. The size of Brinell indentation taken on a steel specimen was found to be 5mm. Diameter of the ball indenter is 10mm. Estimate its hardness.
4. Does necking take place during compressive loading?
5. Estimate the size of Vickers indentation on a specimen taken with 10kg load if its hardness is 200VHN. What will be the size of indent if load used were 30kg?
6. At what temperature does time dependent deformation become measurable?
7. What problem do you anticipate in measuring hardness of lead?
8. A specimen having initial length l_o is deformed under tension in two stages. In stage I it is deformed to a length of l_1 and subsequently it is deformed to a length l_2. Find out engineering and true stain in each of these stages. Which of these follows additive rule if you have to estimate final strain? Assume that deformation is uniform.

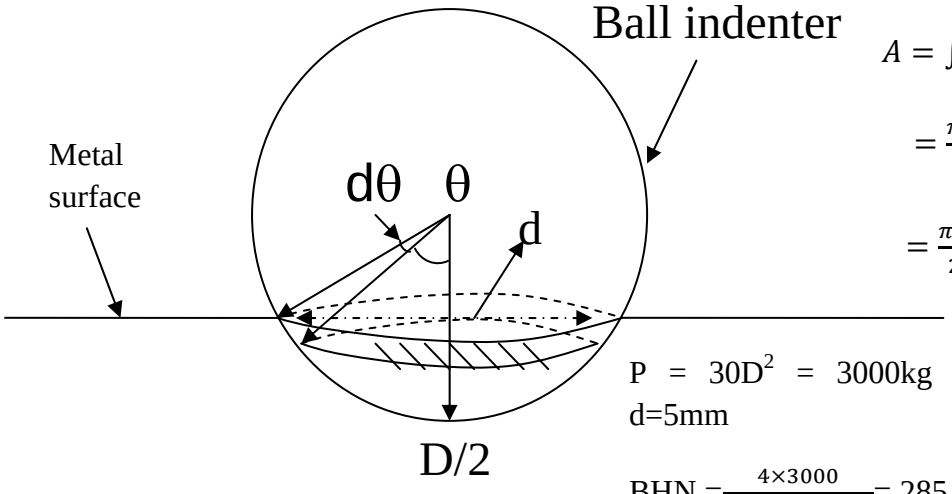


Answer:

1. Necking sets in during tensile test when the load (P) reaches its peak value. This is given by P = ??A where ? is the stress and A is the cross sectional area. Take log & differentiate to get $\frac{dP}{P} = \frac{d\sigma}{\sigma} + \frac{dA}{A}$. This becomes zero when P is maximum. Since reduction in area (-dA/A) is equal to true strain increment (d?) it gives: $\frac{d\sigma}{d\varepsilon} = \sigma$. Since ? = k?^{n} it can be shown: $\frac{d\sigma}{d\varepsilon} = k\,n\,\varepsilon^{n-1} = k\varepsilon^n\, n/\varepsilon = \sigma$ Therefore: strain at which necking sets in is given by ?= n.

2. True strain (d?) is defined as change in length (dl) over instantaneous length (l). Let initial length be l_o and final length l so that engineering strain (e) is = $(l-l_0)/l_0$. Therefore to obtain true strain one has to integrate the following equation between limits l_o & l.
$$\varepsilon = \int_{l_0}^{l} \frac{dl}{l} = \ln\frac{l}{l_0} = \ln\left(\frac{l+dl}{l}\right) = \ln(1+e)$$

3. Relation between indenter & indentation mark is shown in the following figure. Area of the annular strip on the surface of the indenter = dA



$$A = \int_0^{\theta} \frac{\pi D^2}{4} \sin\theta\, d\theta$$

$$= \frac{\pi D^2}{4}(1 - \cos\theta)$$

$$= \frac{\pi D}{2}\left(\frac{D}{2} - \sqrt{\frac{D^2}{4} - \frac{d^2}{4}}\right)$$

P = $30D^2$ = 3000kg since D=10mm & d=5mm

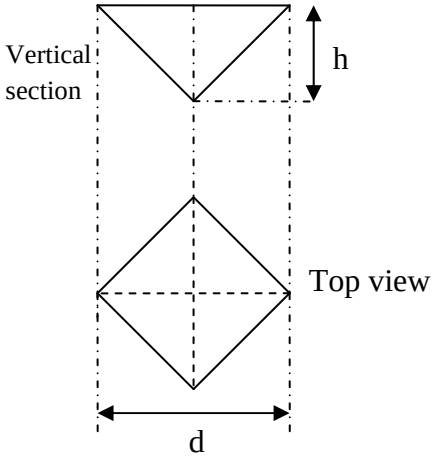
BHN = $\frac{4\times3000}{10\pi\,(10-\sqrt{75})}$ = 285

4. Necking does not occur under compressive load because stress decreases with strain (note that in this case cross section area increases with deformation). There may be instability of another kind. This is known as buckling. It is determined by length to

diameter ratio. Cylindrical test piece with higher height to diameter ratio is prone to such instability.

5. Vickers hardness VHN = P/A where P is load and A in area of indentation mark. The indenter is a square based pyramid with apex angle =136°. If the diagonal of the indentation is d the area of indentation can be obtained as follows:

6.



Length of one side of indentation = d/√2 if the apex angle = θ using simple trigonometric relation the area of one of the triangular faces of the indentation can be shown to be = $\left(\frac{d}{2\sqrt{2}}\right)^2 \frac{1}{\sin\frac{\theta}{2}}$. There are 4 such faces. Therefore VHN defined as P/A is given by: $\left(2\sin\frac{\theta}{2}\right)\frac{P}{d^2} = \frac{1.854P}{d^2}$. If P =10kg d = 0.304mm & if P=30kg d=0.527mm

Creep is a time dependent deformation. It is a strong function of temperature. It becomes measurable when test temperature is greater than 0.5 times the melting point of the metal in degree Kelvin.

7. Melting point of lead is low (~327°C). Tm = 600°K. Room temperature (~300°K) = $0.5T_m$. Therefore it would creep and the size of indentation will increase with time. A more precise control of time is required to get reproducible result.

8. Engineering strain in stage I = $e_1 = \frac{l_1 - l_0}{l_0}$ and that in stage II = $e_2 = \frac{l_2 - l_1}{l_1}$ whereas total strain = $e_t = \frac{l_2 - l_0}{l_0}$ However true strain in stage I = $\varepsilon_1 = ln\left(\frac{l_1}{l_0}\right)$ and that in stage II = $\varepsilon_2 = ln\left(\frac{l_2}{l_1}\right)$ and total strain = $\varepsilon_t = ln\left(\frac{l_2}{l_0}\right)$ It is easily noted that in case of true strain $\varepsilon_t = \varepsilon_1 + \varepsilon_2 = ln\left(\frac{l_1}{l_0}\right) + ln\left(\frac{l_2}{l_1}\right) = ln\left(\frac{l_2}{l_0}\right)$. This is not true for engineering strain.