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FRACTURE

Introduction

Fracture is the separation or fragmentation of a solid body into two or more parts under the action of load. During fracture atomic bonds are broken and new surfaces are formed.

TYPES OF FRACTURE

Fractures are broadly classified into

(i) Ductile or Type I fracture

(ii) Brittle or Type II fracture

(iii) Shear or Type III fracture

i) Ductile fracture or Type I fracture

It is characterised by an appreciable amount of plastic deformation. The fracture proceeds relatively slowly and the fracture surface is dull in appearance. Ductile fracture is of two types:

(a) Highly ductile fracture.

(b) Moderately ductile fracture or Cup and Cone Fracture.

(a) Highly ductile fracture : In this the material necks down to a point fracture and yields to 100% reduction in cross sectional area.

Eg : soft metals like pure gold, lead etc.,

Fig. 1.41 : Highly ductile fracture

(B) CUP AND CONE FRACTURE - STAGES

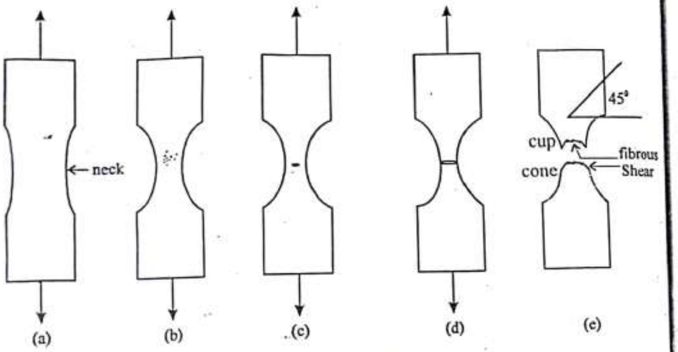

Fig. 1.42 : Stages of Cup and cone fracture

Stage (a) - Initial necking or reduction in cross - sectional area takes place.

(b) - Small cavities or voids form in the interior of the cross section.

(c) - As load is increased these minute cavities join together (co-alesce) to form an elliptical crack which has its long axis perpendicular to the direction of load.

(d) - The crack continues to grow in a direction parallel to its major axis.

(e) - Finally, fracture results due to rapid propagation of the crack.

The fracture surface has two portions. One is the outer perimeter of the neck where fracture takes place by shear deformation at an angle of 45° approximately to the tensile load because this is the angle at which the shear stress is maximum. The other portion is the interior which has an irregular or fibrous appearance while the sheared portion will have a shiny surface.

ii) Brittle fracture or Type II fracture

Like in ductile fracture, here also small cavities join together to form a crack and this crack propagates. But all these stages happen instantly and the material failure takes place suddenly.

Fracture surface is granular and almost normal to the direction of the tensile load. There is successive and repeated breaking of the bonds at the atomic level, along specific crystallographic planes called cleavage planes (for example (0001) basal plane in HCP zinc).

Tendency for brittle fracture is increased with (a) decreasing temperature (b) increasing strain rate or rate of loading (c) tri-axial stress conditions usually produced by a notch.

Intergranular fracture : In this the crack propagates along the grain boundaries and fracture occurs.

Intragranular Fracture : In this the fracture crack passes through the grains and the fractures surface looks granular. This is also known as *Transgranular fracture.*

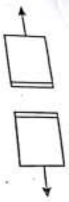

Fig. 1.43 (a) : Brittle fracture

iii) Shear Fracture or Type III fracture

This type of fracture is found in ductile single crystals. This is promoted by shear stresses and occurs as a result of extensive slip on the active slip plane. Fracture surfaces are normally at 45° to the direction of tensile load and appear shiny owing to extensive slip between surfaces before fracture.

Note to students : *To understand the different types of fracture, take chalk pieces and try to break it by (i) pulling it apart (ii) crushing (iii) twisting holding both ends.*

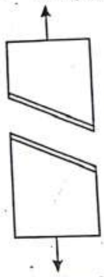

Fig. 1.43 (b) : Shear fracture

Preference of ductile over brittle failure

Ductile fracture is almost always preferred over brittle failure. This is because brittle fracture occurs spontaneously and suddenly without any warning which is due to the rapid crack propagation. In case of ductile fracture which is preceded by considerable plastic deformation, preventive measures can be taken to avoid fractures after identifying plastic deformation.

Study of Fracture Surfaces

It is an important activity in the industry to study the fracture surfaces of materials or components which have failed. Fracture surfaces provide evidence to the mode of failure that would have occured. Fracture surface examination is a great tool in failure analysis.

Note : *Students are advised to observe and interpret the fracture surfaces of different materials subjected to destructive tests in Material Testing Laboratory.*

DUCTILE TO BRITTLE TRANSITION

The different types of fractures that have been discussed so far are not specific to particular materials. In other words, mild steel, a known ductile material will not undergo ductile fracture always nor will cast iron, a known brittle material, will undergo brittle fracture always. In fact, mild steel can undergo brittle fracture while cast iron can undergo ductile fracture, depending upon at what temperature the tensile tests are conducted. In other words, mild steel acts as a ductile material at room temperature but becomes brittle at sub-zero temperature while cast iron can become ductile at higher temperature. Mild steel also fractures in a brittle manner when subjected to sudden loading as is seen in the Impact Test in the MT Lab.

For all materials, there exists two ranges of temperatures during which they act as ductile and brittle. There is also a narrow temperature range through which a material undergoes transition from ductile to brittle and vice-versa.

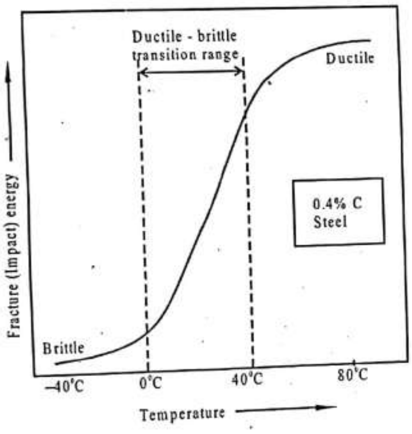

Fig. 1.44 Ductile-Brittle transition curve

The diagram shows ductile-brittle transition for a 0.4% C steel which behaves as a brittle material (low fracture energy) at lower temperature while it remains ductile (high fracture energies) upwards of room temperature.

GRIFFITH'S CRITERION OF BRITTLE FRACTURE

The theoretical cohesive strength of an ideal crystal having no imperfections in it is 100 to 1000 times the strength of real materials normally observed. Griffith originated a theory to explain the discrepancy between the theoretical and observed values of fracture strengths of materials. He assumed that the real material under consideration is not defect free but contains a large number of microscopic cracks which produces stress concentration and lowers the strength of the material. When these microscopic cracks join together the crack formed will propagate and results in brittle fracture. To form any new surface, energy in required and this energy is supplied by the elastic strain energy stored in the metal during loading. This can be stated as,

"*A crack will propagate and result in fracture, when the decrease in elastic strain energy is atleast equal to the energy required to create the new surface*". This is Griffith's criteria for brittle fracture. Griffith's theory can also be stated as "*A crack will propagate and produce brittle fracture where there is no net energy change in the system with any increase in the crack length*".

Derivation of an expression for the fracture strength of a real material based on Griffith's theory :

Consider a plate of unit thickness with a crack of length 2C at the interior. The approximate volume of this crack is πC^2 (thickness is unity)

Elastic strain energy per unit volume released

in order to form the crack $= \dfrac{-\sigma^2}{E}$

(negative sign indicates energy is released)

Total elastic strain energy released for the

spreading of the crack, $U_E = \dfrac{-\sigma^2}{E} \cdot \pi C^2$

Total surface energy gained by the creation of the two crack surfaces, $U_s = 4 C\gamma_s$

$(\because\ \gamma_s \times 2 \times \text{surface area } (2C \times 1))$

$$\text{Net energy, } U = U_E + U_s$$

$$U = \frac{-\sigma^2}{E} \cdot \pi C^2 + 4 C\gamma_s$$

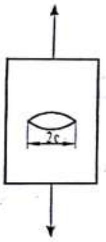

Fig. 1.45 : Plate of unit thickness

According to Griffith, a crack will propagate and produce a brittle fracture when the net energy of the system remains constant even as the crack extends. In other words the crack will propagate into a brittle fracture when change in Net energy with reference to the incremental change in the crack length is zero.

Stress Intensity Factor (K): Defines the magnitude of local stress around the crack tip. It depends on loading, crack size, crack shape & geometric boundaries $K = \beta \cdot \sigma \sqrt{\pi c}$

$\sigma \rightarrow$ stress applied. $c \rightarrow$ crack length

$\beta \rightarrow$ correction factor.

$$\text{i.e. } \frac{dU}{dC} = 0 \Rightarrow \frac{d}{dC}[U_E + U_s] = 0$$

$$\frac{d}{dC}\left[\frac{-\sigma^2}{E}\pi C^2 + 4C\gamma_s\right] = 0$$

$$\frac{\sigma^2}{E}\pi . 2C = 4\gamma_s$$

$$\therefore \quad \sigma_f = \sqrt{\frac{2E\gamma_s}{\pi C}}$$

Where σ_f is the fracture strength of the material in the presence of cracks of known length.

Relation for fracture strength when thickness is also considered :

$$\sigma_f = \sqrt{\frac{2\gamma_s E}{(1-r^2)C\pi}}$$

Where γ_s = Surface energy/unit area

γ = Poisson's ratio.

Concept of Fracture Mechanics

Fracture Mechanics is the engineering analysis of various factors that causes fracture of engineering materials. Fracture mechanics makes it possible to determine whether a crack of given length in a material is dangerous and whether it will propagate to fracture at a given stress level. It also permits the selection of materials for resistance to fracture and the selection of an appropriate design which is resistant to fracture.

Elements of Fracture Mechanics

i) Strain Energy release rate (G)

When metals are stressed, strain energy stored within the metal increases. This stored energy is responsible for increasing the crack length and thereby gets reduced. Therefore *'Strain energy release rate'* is the rate of transfer of strain energy to the process of crack extension.

For a crack length of 2 C, the strain energy release rate is given by, $G = \frac{\pi C \sigma_f^2}{E}$

A comparison of this equation with Griffith's equation $\sigma_f^2 = \frac{2E\gamma_s}{\pi C}$ shows that $G = 2\gamma_s$

Irwin's Theory: $\sigma_{ij} = \frac{k}{\sqrt{2\pi r}} f_{ij}(\theta)$.

Showed that crack propogation occurs when the critical strain energy release rate (G_c) is achieved (a [illegible]

ii) Fracture Toughness

All engineering materials have cracks or flaws present in them. Therefore the fracture resisting capability of a material must be evaluated in the presence of such defects. The fracture resistance of a material in the presence of cracks or discontinuities is known as its **'fracture toughness'**.

Fracture toughness of a material can also be defined as the critical value of the 'strain energy release rate' (G) which makes the crack propagate to fracture.

Another parameter which is more commonly used to describe the fracture toughness of a material is known as the **'Critical stress Intensity factor'** (K_{IC})

$$K_{IC} = \sigma_f Y \sqrt{\pi C}$$

K_{IC} is a property of the material just like 'yield strength' or ultimate tensile strength' and can be determined from fracture tests. Fracture initiates in a material as soon as K_{IC} is reached, either through increasing stress or increasing crack length (C) or both.

List of Formulae

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1. Theoretical cohesive strength, $\sigma_{max} = \sqrt{\frac{E\gamma_s}{a_o}}$ (N/m²)

Where E = Young's Modulus (N/m²)

γ_s = Surface energy/unit area (J/m²)

a_o = Equilibrium distance for stability between two atoms (m)

2. Fracture strength of a material with a crack.

$$\sigma_f = \sqrt{\frac{2E\gamma_s}{\pi C}}$$

Where C = half length of a known crack but with unit thickness (m)

3. Fracture strength when thickness is also considered.

$$\sigma_f = \sqrt{\frac{2\gamma_s E}{(1-\gamma^2)C}}$$

where γ_s = Surface energy/unit area

γ = Poissons ratio

4. Strain energy release rate, $G = \frac{\pi C \sigma_f^2}{E}$

5. Critical stress intensity factor, $K_{IC} = Y \sigma_f \sqrt{\pi C}$
(or Plain Strain Fracture Toughness)

where σ_f = fracture stress
C = half length of crack
Y = Size Factor (constant) (Assume 1 if not given)

SOLVED PROBLEMS

1. Determine the critical crack length for a unit thickness crack in a thick material of K_{IC} 24.2 MPa $\sqrt{m}$, which is under a stress of 350 MPa. Assume size factor, y = 1.
(Jan. 2004, VTU)

Solution :

Given data :

(i) Critical stress Intensity factor, $K_{IC} = 24.2$ MPa $\sqrt{m}$
(ii) Given value of (fracture) stress, $\sigma_f = 350$ Mpa
(iii) Size factor, y = 1
(iv) Critical length of crack, 2 C = ?

We know that, $K_{IC} = Y \sigma_f \sqrt{\pi C}$

$$24.2 = 1 \times 350 \times \sqrt{\pi C}$$

Half length, C = 0.00152 m

∴ Critical crack length, **2 C = 0.00304 m**

2. The critical stress intensity factor (K_{IC}) of a material used for a component is 26 MP $\sqrt{m}$. What is the applied stress that will cause fracture if the component contains a internal crack length 1.72 mm? Assume geometric constant y = 1.

Solution :

Given data :

(i) $K_{IC} = 26$ MPa $\sqrt{m}$
(ii) Crack length, 2 C = 1.72 mm
$C = 0.86$ mm $= 0.86 \times 10^{-3}$ m

(iii) Geometric constant, y = 1
(iv) Fracture strength, σ_f = ?

We know that $K_{IC} = Y \sigma_f \sqrt{\pi C}$

$$26 = 1 \times \sigma_f \sqrt{\pi \times 0.86 \times 10^{-3}}$$

$$\therefore \sigma_f = \mathbf{500.20\ MPa}$$

3. A relatively large plate of a glass is subjected to a tensile stress of 40 MPa. If the specific surface energy and modulus of elasticity for this glass are 0.3 J/m² and 69 GPa, respectively, determine the maximum length of a surface crack that will result in a fracture.

Solution :

Given data :

(i) Tensile stress, $\sigma_f = 40$ MPa
$\sigma_f = 40 \times 10^6$ N/m²
(ii) Specific surface energy, $\gamma_s = 0.3$ J/m²
(iii) Modulus of Elasticity, E = 69 GPa
or $E = 69 \times 10^3$ MPa
or $E = 69 \times 10^9$ N/m²
(iv) Critical crack length, 2C = ?

We know that, from Griffith's theory,

$$\sigma_f = \sqrt{\frac{2E\gamma_s}{\pi C}}$$

Substituting, $$40 \times 10^6 = \sqrt{\frac{2 \times 69 \times 10^9 \times 0.3}{\pi C}}$$

$$\therefore C = 8.2 \times 10^{-6}\ \text{m}$$

or Critical crack length, **2C = 16.4 μm** or **2C = 16.4 × 10⁻⁶ m**

Fracture Toughness :- Is the highest SIF that can be supported by cracked structure.

FATIGUE

Introduction

In several applications, components have to withstand different kinds of load at different times. Materials subjected to these fluctuating or repeated loads tend to show a behaviour which is different from what they show under steady loads. This behaviour is known as fatigue and due to this the strength and service life of several components get reduced. Therefore fatigue is a general term used to describe the behaviour of materials under repeated cycles of stress and strain which causes a deterioration of the material and results in a progressive fracture.

Fatigue occurs at stresses well within the ordinary elastic range as measured in the static tension test. Fracture resulting from fatigue is very difficult to predict and hence a good understanding of fatigue behaviour is very important.

Springs deflecting to various amounts, aircraft wings subjected to repeated gust loads, rubber tyres deforming repeatedly with each revolution of the wheel etc., can all lead to failure by fatigue.

TYPES OF FATIGUE LOADING WITH EXAMPLES

i) Completely reversed cycle of stress :

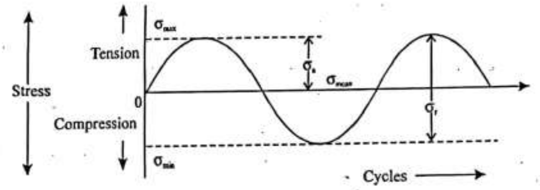


Fig. 1.46 : Alternate tensile and compressive stresses

σ_a = Stress amplitude
σ_{max} = maximum stress
σ_{mean} = 0
σ_r = range of stress
σ_{min} = minimum stress

Fig 1.46 illustrates the type of fatigue loading where a member is subjected to opposite loads alternately with a mean of zero. For example bending of steel wire continuously in either directions leads to alternate tensile and compressive stresses on its surface layers and failure by fatigue.

ii) Repeated stress cycles :

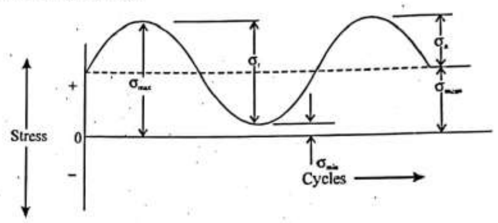


Fig. 1.47 : Various degrees of tension

Fig 1.47 shows the type of fatigue loading where a member is subjected to only tension but to various degrees. A spring subjected to repeated tension as in a toy would lead to fatigue failure.

iii) Irregular or Random stress cycle :

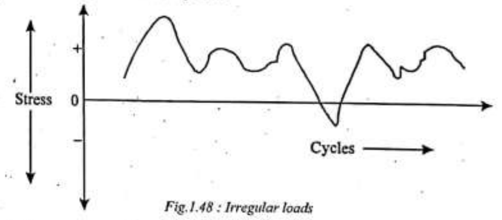


Fig.1.48 : Irregular loads

Fig 1.48 shows a type of fatigue loading where a member could be subjected to irregular loads just as in the case of an aircraft wing subjected to wind loads.

Stages of fatigue failure

Let us consider a ductile material which is subjected to simple alternating tensile and compressive stresses. Failure by fatigue is found to take place in three stages :

(i) Crack nucleation (ii) Crack growth (iii) Fracture

Fig. 1.49 (a) : Crack Nucleation

Fig. 1.49 (b) : Crack growth

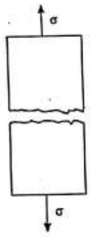


Fig. 1.49 (c) : Fracture

i) **Crack nucleation :**

During the first few cycles of loading, localized changes take place in the structure a various places within the material. These changes lead to the formation of submicroscopi cracks. These cracks are usually formed at the surface of the specimen. There are severa theories like Orowans theory, Cottrell & Hull theory etc., which explain the mechanism o crack nucleation.

ii) **Crack growth :**

The submicroscopic cracks formed grow as the cycles of loading continue and becom microscopic cracks.

iii) **Fracture :**

When critical size is reached, the crack propagates. The area of cross-sectio supporting the load gets reduced thus increasing the stress value and fracture finally occurs.

Non-propagating cracks

Cracks which do not propagate and result in fracture are known as non-propagatin cracks. In any solid, there will always be a number of cracks. Only such cracks whic attain the critical size will grow (propagate). According to Griffith's theory a crack wil propagate and result in brittle fracture only when there is no net energy change in th system with any increase in crack length .

We know that $$\sigma_f = \sqrt{\frac{2E\gamma_s}{\pi C}}$$

or $$C = \frac{(2E\gamma_s/\pi)^2}{\sigma_f}$$

Where C = half of crack length which results in fracture

MECHANISMS OF FATIGUE FAILURE

Some of the theories which explain the mechanism of crank nucleation leading to fatigue fracture are mentioned below.

a) Wood's theory b) Orowan's theory
c) Cottrell and Hull theory d) Mott theory

a) **Wood's theory**

We know that **'slip'** takes place along certain crystallographic planes due to shear stresses acting along those planes. When an alternate load is applied, the direction of the shear stresses also change alternately. This causes back and forth slip movements in opposite directions. Slip bands are produced due to this systematic buildup of fine slip movements in either directions. These slip movements are in the order of 1 nanometer. These slip bands are nothing but intrusions and extrusions formed on the surface of the specimen to form surface irregularities which are initiated as cracks. Once the cracks are nucleated, growth of these cracks takes place continuously due to stress concentration before fracture occurs.

Typically, the crack growth period accounts for 75-90% of the fatigue life in the part.

The stages through which slip band extrusions and intrusions are formed are illustrated in the fig. 1.50.

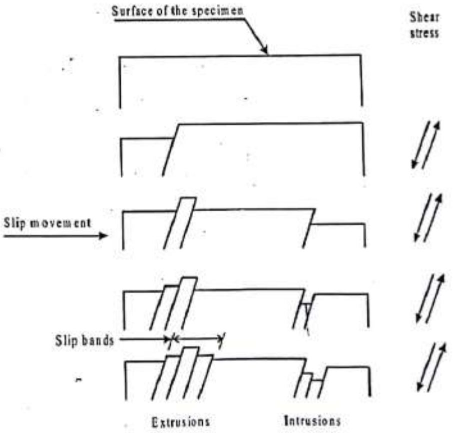
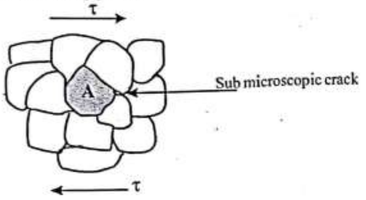


Fig. 1.50 : Wood's mechanism of Fatigue Crack Nucleation

b) Orowans 'Polycrystalline Model' theory

Consider a polycrystalline sample consisting of a number of grains. Let 'A' be one of the grains which is weaker then the surrounding grains.



When load is applied to this sample, grain A being weaker than the rest, yields in the directions of loading. When the load is reversed, grain A tries to yield in the opposite direction. As the loads are continuously alternated, grain A continuously yields in opposite directions and faster than the rest of the grains. This causes a relative movement between grain A and the surrounding grains and leads to the formation of fine submicroscopic cracks at the grain boundary of grain A.

In a polycrystalline sample, there may be a number of such grains which may be weaker than their surrounding grains. Hence a number of submicroscopic cracks may be expected to form at their boundaries. Subsequent cycles of stresses helps in the coalescence of a number of submicroscopic cracks to form a bigger crack which may grow and result in fracture.

In general fatigue cracks begins at the surface of the specimen, probably because the grains adjacent to the surface are less restricted than the surrounding grains. Therefore weak grains like *'grain A'* can be expected to be found next to the surface.

FATIGUE TESTING - BY R R MOORE REVERSED-BENDING MACHINE

Fatigue failures in engineering materials are observed by conducting the fatigue test which involves the plotting of an S-N diagram. One such test is the R R Moore reversed-bending fatigue testing machine.

Specimens subjected to fatigue test are made to undergo fluctuating or opposite stresses. One such test arrangement is shown in the fig. where the specimen is bent with the help of weights as well as rotated. By this, alternate tensile and compressive stresses are imposed on the various layers of the specimen.

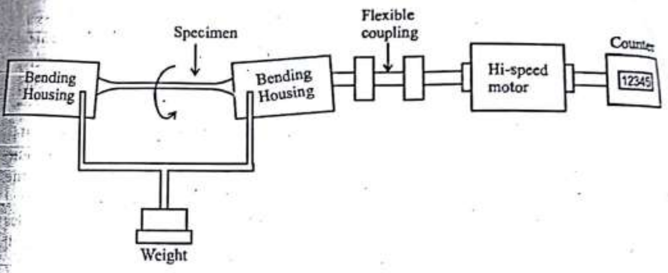


Fig. 1.51 : RR Moore Fatigue Test

A counter coupled to the motor counts the number of cycles to failure. The experiment could be conducted for different loads, and different number of cycles to fractures are noted to draw the S-N diagram.

S-N DIAGRAMS

The S-N curve which gives information on the fatigue behaviour of a material is a plot of stress (S) against the number of cycles to failure (N). The value of stress that is plotted can be σ_a, σ_{max}, σ_{min}. The values of N are usually taken along a log scale.

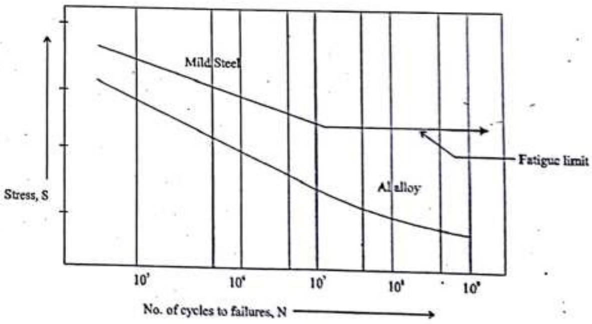


Fig. 1.52 : S-N curves of Mild steel and Alloy

The S-N curve is plotted by applying a cyclic load at any particular value of stress and repeated continuously until the specimen fails. The number of cycles required for failure at that stress in plotted. Specimens would fail for different number of cycles when held at different stresses and hence a number of points are obtained. By joining all these points, a S-N curve typical of that material is obtained.

Fig 1.52 shows the S-N curves for two metals-mild steel and an aluminimu alloy. It is seen from the S-N curves for both metals that the number of cycles which a metal can endure before failure, increases with decreasing stress. But in the case of mild steel, the S-N curve becomes horizontal at a certain limiting stress. Below this limiting stress, called the *fatigue limit* or *endurance limit*, the material can endure an infinite number of cycles without failure. This means that if the stress is below the fatigue limit, the material will never fail for any number of cycles of stresses.

In the case of the **non-ferrous** aluminium alloy, the S-N curve slopes gradually downward with increasing number of cycles. This material does not have a true fatigue limit because the S-N curve never becomes horizontal. In such cases the fatigue limit is arbitrarily taken as the stress at which 10^8 cycles (for example) is required for failure.

FATIGUE PROPERTIES

1) Fatigue Life (N) :

It is the total number of cycles required to bring about final fracture in a specimen at a given stress. Fatigue life for a given condition is a property of the individual specimen and is arrived at after testing a number of specimens at the same stress.

2) Fatigue life for P percent survival (N_P) :

It is the fatigue life for which P percent of the population of samples tested have a longer life than the rest.

For example, N_{90} is the fatigue life for which 90% of the samples would be expected to survive and 10% to fail at a particular stress.

3) Median Fatigue Life :

It is the fatigue life for which 50% of the population of samples fail and the other 50% survive at a particular stress.

4) Fatigue Strength (σ_n) :

It is the stress at which a material can withstand repeatedly 'N' number of cycles before failure. In other words it is the strength of a material for a particular fatigue life.

5) Fatigue Limit or Endurance Limt (σ_E) :

It is the stress below which a material will not fail for any number of cycles. For ferrous materials it is approximately half of the ultimate tensile strength. For non-ferrous metals since there is no fatigue limit, endurance limit is taken to be the stress at which it endures 'N' number of cycles without failure. 'N' is usually taken as 5×10^8 cycles for non-ferrous metals.

FACTORS AFFECTING FATIGUE LIFE

1) Effect of stress concentration on fatigue :

Stress concentrations are actually responsible for the majority of fatigue failures occuring in practice. All machine elements contain stress raisers like fillets, key ways, screw threads, porosity etc., Fatigue cracks are nucleated in the region of such geometrical irregularities.

The actual effectiveness of stress concentration is measured by the *fatigue strength reduction factor* (K_f).

It is defined as the ratio of the fatigue strength of a member without any stress concentration (σ_n) to the fatigue strength of the same member with the specified stress concentration (σ'_n).

$$K_f = \frac{\sigma_n}{\sigma_n'}$$

Fatigue failure by stress concentration can be minimized by reducing the avoidable stress - raisers through careful design and the prevention of stress raisers by careful machining and fabrication.

2) Size Effect :

Experiments have shown that fatigue strength of large members is lower than that of small specimens. This may be due to two reasons :

i) The larger member will have a larger distribution of weak points than the smaller one and on an average, fails at a lower stress.

ii) Larger members have larger surface areas. This is important because the imperfections that cause fatigue failure are usually at the surface.

3) Surface Roughness

Practically almost all fatigue cracks nucleate at the surface of the members. Therefore the conditions of the surface such as surface roughness and surface oxidation or corrosion are very important.

Experiments have shown that different surface finishes of the same material can appreciably affect fatigue performance. Smoothly polished specimens have higher fatigue strengths.

4) Surface Residual Stress :

Residual stresses are nothing but locked up stresses which are present in a part even when it is not subjected to an external force. Residual stresses arise during casting or during cold working when the plastic deformation would not be uniform throughout the cross section of the part. Residual stresses can be either tensile or compressive depending on whether it was plastically deformed earlier by tensile or compressive loads respectively.

Those residual stresses at the surface of the members add themselves to the external cyclic stress that is being applied and help in the nucleation of cracks and their further propagation.

5) Effect of Temperature :

(i) **Low temperature :** Fatigue tests on metals carried out at below room temperature shows that fatigue strength increases with decreasing temperature.

(ii) **High temperature :** In general, fatigue strength of metals decreases with increasing temperature above room temperature.

6) Effect of Environment :

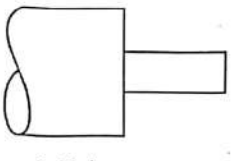
Environment also plays an important role in the fatigue behaviour of materials. If fatigue takes place in a metal which is present in a corrosive environment, the rate at which the fatigue crack propagates is greatly increased due to the chemical attack. The combination of corrosion attack and cyclic stresses on a metal is known as corrosion fatigue.

FATIGUE PROTECTION METHODS

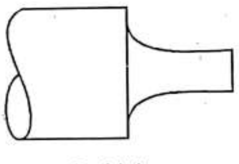
A number of methods are available to improve fatigue performance of materials. Some of them are design based while some others are based on either service condition or surface treatment.

1. Design for fatigue

Fatigue performance can be improved by avoiding sharp corners and instead providing a rounded fillet as shown in fig. This is because fatigue cracks are usually initiated at the intersection of two sections.



Bad design



Good design

2. Surface Treatment

During machining operation small scratches and grooves are invariably introduced into the workpiece surface due to cutting tool action. These surface markings can limit the fatigue life. Therefore in order to overcome these, the surface finish of the workpiece is improved by polishing which enhances the fatigue life significantly.

3. Introduce residual Compressive Stress

Introducing residual compressive stresses within the outer layer of the workpiece can nullify or reduce the effect of external tensile stresses. But if the external stresses acting on the specimen is also compressive, this will not help.

4. Case Hardening

This is a technique by which both surface hardness and fatigue life are enhanced for Steel alloys. This is accomplished by either Carburizing or Nitriding process in which a thin layer (or a case) of the surface of the workpiece is hardened (Refer chapter on Heat Treatment for details)

5. Reduce Corrosion

Corrosion decreases fatigue performance. To overcome this, some of the approaches are:

i) Applying protective surface coatings
ii) Selecting more corrosion - resistant materials
iii) Reducing the corrosivenesss of the environment.

CREEP

Description of the Phenomenon

When materials under several service conditions are required to sustain steady loads fo long periods of time, they undergo a time dependent deformation. This is known as **creep** and can also be defined as '*the slow and progressive deformation of a material with time at constan stress*'. In other words, creep deformation refers to that permanent deformation which occurs in materials that are exposed to lower values of stress (< elastic limit) but for a prolonged length of time.

Creep in most of the materials, however, is found to occur predominantly at highe temperatures than at lower temperatures. Therefore the study of creep is very important for those materials which are used at high temperatures like components of gas turbines, furnaces rockets, missiles etc. But there are exceptions like lead and plastic which undergo creep at room temperature also.

At elevated temperature, the tensile properties of most engineering metals are very sensitiv to both strain rate and time of exposure than at lower temperatures.

Generally temperatures above 0.4 T_m (T_m=Melting temperature) are considered as highe temperatures.

THREE STAGES OF CREEP - THROUGH CREEP CURVE

The creep curve is obtained by applying a constant tensile load below the yield point to specimen maintained at constant temperature. The strain or the elongation of the specimen i then determined as a function of time.

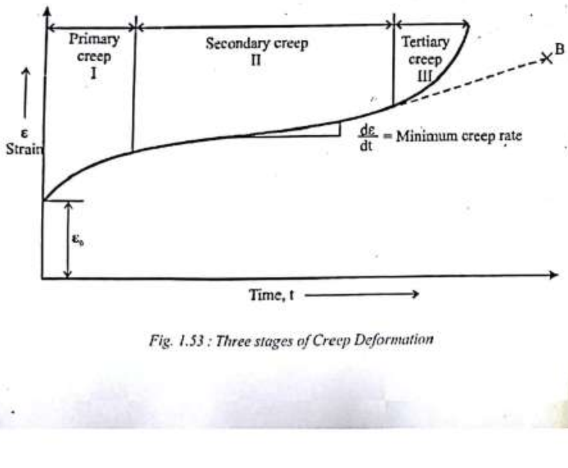


Fig. 1.53 : Three stages of Creep Deformation

As soon as the specimen is loaded, there will be an instantaneous strain which is denoted by ϵ_0 on the creep curve. Further deformation of the metal only after the instantaneous strain is considered as '*creep deformation*'.

Creep deformation of materials upto failure are divided into 3 stages : (i) Primary creep (ii) Secondary creep (iii) Tertiary creep.

(i) Primary Creep :

This is the first stage of the creep which represents a region of decreasing creep rate. In this region the rate at which the material deforms decreases with time until it reaches a constant value. The creep rate goes on reducing because as the metal deforms it undergoes *strain hardening* and offers more and more resistance to further elongation. Primary creep is predominantly a period of transient creep. Primary Creep is important for those materials which undergo creep at room temperature.

(ii) Secondary Creep :

This stage is a period of nearly constant creep rate. The creep rate is constant because '*strain-hardening*' and '*recovery*' effects balance each other. The average value of the creep rate during secondary creep is called the minimum creep rate. This is an important part of the curve because most of the working components will be in this state. Secondary creep is also known as *steady state creep*. Creep in this region takes place by the viscous flow in the materials.

(iii) Tertiary Creep :

This stage is a period of increasing strain rate. Tertiary creep occurs when there is an effective reduction in cross-sectional area due to necking or internal void formation. So the stress at that cross-section increases and consequently the value of strain also increases at a faster rate before the occurrence of fracture.

If the stress is kept constant instead of the load or if true strain is taken into consideration then the resulting fracture due to creep would be at 'B'.

Transient Creep

The principle characteristic of transient creep is the decreasing rate in deformation. Deformation is rapid at first but gradually becomes slower and slower as the rate approaches some fixed value. Transient creep in metals is observed at all temperatures, even near absolute zero. Hence it is sometimes referred to as '**Cold Creep**'.

Initially as soon as the metal is loaded, instantaneous strain (ϵ_0) takes place which is stopped by the strain hardening of the material. As the load is held constant the material undergoes transient creep where small additional amounts of elongation takes place produced by thermal activation. Each increment in strain due to yielding causes a further small increase in the strength due to strain-hardening. Consequently, as time progresses, further elongation becomes more and more difficult and the rate of deformation decreases. Thus transient creep approaches a constant rate on the creep curve and enters the secondary stage.

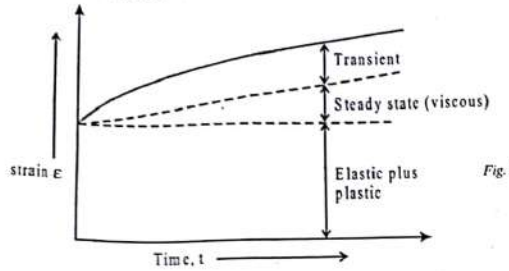


Fig. 1.54 : Transient and Viscous Creep

Viscous Creep

Viscous creep is characterized by the viscous flow of the material which means that there is a constant or a steady increase in deformation at constant stress. This is in the absence of a strengthening mechanism like strain hardening. Although strain hardening is present its effect is just balanced by the *'recovery'* process which has the opposite effect i.e., softening the metal; On one hand the strength of the material is increased for each increment in plastic strain due to strain hardening and on the other hand the strength is decreased by Recovery so that more plastic deformation takes place. This cycle is repeated continuously and keeps the creep rate constant for a long time. Viscous creep is stopped when there is considerable reduction in cross-sectional area and enters the tertiary stage. The rate of deformation increases rapidly in this 3^{rd} stage and fracture occurs at the end of this stage.

Viscous creep is also known as **'Hot creep'** since it is observed only at higher temperatures.

Fig. 1.55 : Components of Creep curve

Effect of low temperature

Temperatures below $T_m/4$ are normally called as lower temperatures. Lower temperatures have an effect of decreasing the creep rate. This is because strain hardening effects will be more and 'recovery' process is negligible. Creep occurring at lower temperatures is known as **'logarithmic creep'** and follows the equation,

$$\epsilon = \alpha \ln t$$

where ϵ - strain, α = constant and t = time.

To move any dislocation, a suitable activation energy in needed which may be provided by a higher load or a higher temperature. Different dislocations need different levels of activation energy to begin their movement. On the application of load at lower temperatures, the dislocations with the lowest activation energy move first to produce the initial creep strain. When these easy-to-move dislocations are exhausted, creep can continue only by the movement of dislocation of higher activation energies. Since lower temperatures cannot provide high activation energies, the creep rate decreases.

Low temperature logarithmic creep obeys a mechanical equation of state i.e., the rate of strain at a given time depends only on the instantaneous values of stress and strain and not on the previous strain history.

Effect of high temperature :

Higher temperature have an effect of increasing the creep rate. The following are the *'structural changes'* that take place during creep at higher temperatures :

(i) Mobility of atoms increases rapidly with temperature and they occupy lower energy positions.

(ii) Mobility of dislocations also increase and they overcome the obstacles by the mechanism of climb.

(iii) The concentration of vacanies increases with temperature and the rate of diffusion increases.

(iv) *Recrystallization* takes place as a result of increased rate of diffusion.

(v) *Additional slip systems* come into effect at elevated temperatures. Example In FCC aluminium apart from (111) plane, slip takes place also on (100) and (211) planes.

(vi) Grains in polycrystalline materials move relative to each other. This 'grain-boundary sliding' is a shear process which occurs in the direction of the grain boundary and leads to intergranular cracks. Creep at higher temperatures is strongly dependent on previous strain history and hence does not follow a mechanical equation of state.

Effects of (i) Temperature and (ii) Stress on creep curve

As we observe from the above diagram failure due to creep takes place faster when either stress or temperature is increased. In other words, higher the operating temperature or stress, steady state creep duration is lower.

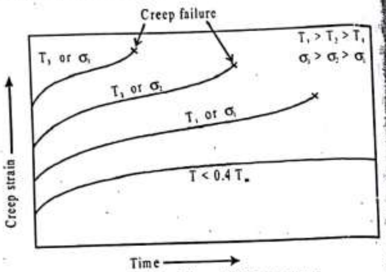


Fig. 1.56 : Temp. & Stress Vs Creep curve

MECHANISMS OF CREEP

Among the many theories of Creep mechanisms, the following important ones are discussed

(i) Dislocation glide

This involves the movement of dislocations along slip planes and the barriers are overcom by thermal activations. This mechanism occurs at higher values of stress.

(ii) Dislocation climb

Under certain conditions an edge dislocation can move out of a slip plane onto an another parallel plane directly above or below the slip plane. This is the process of dislocation climb. Dislocation climb occurs by the diffusion of vacancies to the dislocation sites and the dislocations in turn climb up to fill the vacancy. Dislocation climb is controlled by diffusion and hence occurs most readily at elevated temperature.

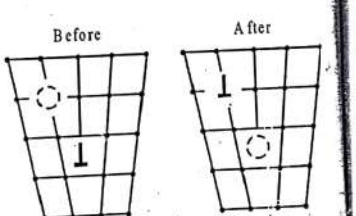


Fig. 1.57 : Dislocation climb

When dislocations come across obstacles they use vacancies or interstitial atoms to climb and go around them for slip and hence plastic deformation to continue.

(iii) Grain boundary sliding

At elevated temperatures, the grains in polycrystalline materials are able to move relative to each other. This is called *grain boundary sliding* and is a shear process which occurs in the direction of the grain boundary. A large number of grains sliding with each other eventually results in plastic deformation due to creep. Grain boundary sliding is further promoted by increasing the temperature and / or decreasing the strain rate.

Since grain boundary sliding and hence creep deformation is pronounced at finer grain sizes, it is better to use a coarse grained material for better creep properties. In fact, Ni-based super alloy single crystals with no grain boundaries are used to make turbine blades which eliminates the possibility of creep at higher temperatures by pre-empting grain boundary sliding.

(iv) Diffusion Creep

Consider specimen A subjected to a tensile load P at a higher temperature. The effect of the tensile load would be to increase the length and decrease the lateral dimension. The effect of the higher temperature would be to increase vacancy movement. As the workpiece is stretched in one direction, atoms from the sides move towards the top of the specimen while vacancies migrate from the top to the sides. This diffusion of atoms and vacancies in opposite directions over a period of time contributes to more elongation, and is known as diffusion creep.

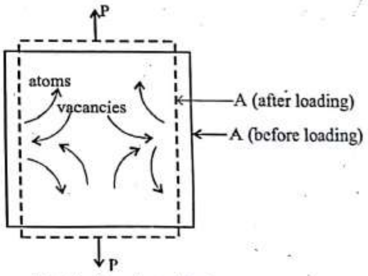


Fig. 1.58 : Creep due to diffusion

CREEP RESISTANT MATERIALS

Following are a few factors which affect the creep behaviour of materials:

i) **Melting temperature:** Higher the melting temperature, better is the creep resistance

ii) **Elastic Modulus:** Higher the value better is the creep resistance.

iii) **Grain size:** Finer the grain size lower is the creep resistance and vice - versa.

iv) Cast structure: Single crystals produce the best creep resistance followed by columnar grains and then by equi-axed grains.

v) Crystal defects: Greater the population of crystal defects like vacancies, lower will be the creep resistance.

Materials which have one or more favorable properties mentioned above makes good alloys for high - temperature use. Some of them are:

a) Nickel-based super alloys such as Waspaloy, Astroloy, IN 100 etc. which contain Chromium, Molybdenum, Cobalt, Titanium etc.

b) Stainless steels both austenitic as well as martensitic.

c) Refractory alloys based on Cobalt, Molybdenum and Tungsten.

CREEP PROPERTIES

(i) Creep Strength :

It is defined as, *"the highest stress that a material can withstand without excessive deformation for a specified length of time"*. It is also known as *'Creep limit'*

ex. Creep strength for a steam turbine blade may be that stress which will produce just 0.2% creep for 10,000 hours of working at 800°C.

(ii) Creep Rupture strength :

It is defined as, *"the highest stress that a material can withstand without rupture for a specified length of time"*.

ex. For the same turbine blade the rupture strength is that stress which produces a fracture in 10,000 hours at 800°C.

Creep rupture strength is also known as **"Stress - rupture strength"** or simply **"rupture strength"**

Experiments to determine :

(i) Creep strength

To determine 'Creep strength', the test is carried out at relatively low stresses so as to avoid tertiary creep. Precise Measurement of strain is very important since the minimum creep rate has to be determined. Tests are frequently conducted for periods from 2000 hrs - 10,000 hrs and the total strain is often less than 0.5%

(ii) Creep rupture strength

Higher loads are used to determine 'rupture strength' so that the creep rate may be higher. The loads may be such that the tests may be terminated in 1000 hrs and the total strain may be around 50%.

Simpler strain measuring devices such as dial gauges can be used. Rupture strength equipments are simpler to build to maintain and to operate than 'Creep strength' testing equipments.

STRESS RELAXATION

Stress relaxation is the time dependent decrease in stress acting on a body which is constrained to a certain fixed deformation. In other words it is the reduction in the value of the stress in those components which are not allowed to elongate. Stress relaxation takes place in bolts and other members which are required to hold rigid bodies in tight contact. Stress in such a member will reduce after long periods of time.

Expression for stress relaxation

Consider a tensile specimen which is subjected to a constant initial load σ_i at elevated temperatures.

The total strain ϵ of the specimen is given by,

$$\epsilon = \epsilon_e + \epsilon_p \quad \text{where} \qquad \epsilon_e = \text{elastic strain}$$

$$\epsilon = \frac{\sigma}{E} + \epsilon_p \quad \text{---- (1)} \qquad \epsilon_p = \text{plastic (creep) strain}$$

Due to creep, the specimen tries to increase in length. But if its is constrained at it's two ends, the total strain remains constant at any point of time. However whatever strain the specimen has undergone will become plastic while the elastic strain goes on decreasing. In other words all the elastic deformation is converted to plastic deformation with the passage of time.

Since the total strain does not change with respect to time, differentiate ϵ with respect to t and equate it to zero.

$$\frac{d(\epsilon)}{dt} = \frac{d}{dt}(\epsilon_e + \epsilon_p) = 0$$

$$\frac{d\epsilon_e}{dt} = \frac{-d\epsilon_p}{dt} \quad \text{---- (2)}$$

But $$\epsilon_e = \frac{\sigma}{E} \text{ and } \frac{d\epsilon_p}{dt} = B\sigma^n$$

where

σ = stress

E = Young's modulus

B, n = constants (n > 1)

Substituting these values in (2)

$$\frac{d}{dt}\left(\frac{\sigma}{E}\right) = -B\sigma^n$$

$$\frac{1}{E}\frac{d\sigma}{dt} = -B\sigma^n$$

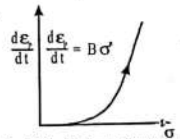


Fig.1.59 : Minimum Creep rate

Integrating both sides,

$$\frac{1}{E}\int\frac{d\sigma}{dt} = -\int B\sigma^n$$

$$\int\frac{d\sigma}{\sigma^n} = -BE\int dt$$

$$\frac{-1}{(n-1)\sigma^{(n-1)}} = -BEt + C \qquad \text{---- (3)}$$

To find the value of C

At $t = 0$, $\sigma = \sigma_i$ where σ_i = initial stress

$$\frac{-1}{(n-1)\sigma_i^{(n-1)}} = -BE \times 0 + C$$

$$\therefore\ C = \frac{-1}{(n-1)\sigma_i^{(n-1)}} \qquad \text{---- (4)}$$

Substituting (4) in (3)

$$\frac{-1}{(n-1)\sigma^{(n-1)}} = -BEt - \frac{1}{(n-1)\sigma_i^{(n-1)}}$$

$$\therefore\ \boxed{\frac{1}{\sigma^{(n-1)}} = \frac{1}{\sigma_i^{(n-1)}} + BE\,(n-1)t}$$

The above equation is the expression for stress - relaxation. This equation gives the value of stress σ at any point of time 't' with the initial stress being σ_i. It is seen from the relation that σ is inversely proportional to 't' i.e., stress goes on decreasing with time with the other quantities being constant.

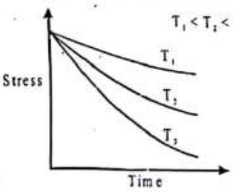


Fig.1.60 : Stress Vs time

List of Formulae

1. Low temperature creep strain, $\epsilon = \propto ln(t)$

Where

$\propto$ = constant

t = time

2. Stress relaxation expression

$$\frac{1}{\sigma^{(n-1)}} = \frac{1}{\sigma_i^{(n-1)}} + BE\,(n-1)\,t$$

where

σ_i = Applied constant stress

E = Young's Modulus

B, n = Constants (n > 1)

t = time (hrs)

σ = Relaxed stress after time duration 't'

3. Minimum creep rate, $\frac{d\epsilon_p}{dt} = B\sigma^n$

where

σ = applied stress

B, n = constants (n > 1)

SOLVED PROBLEM

1. A steel bolt, clamping two rigid plates together, is held at 600° C with initial tightening stress 75 MPa. The minimum creep rate is 2.8×10^{-8} m/m /hour at a stress of 30 MPa. Determine the stress remaining after one year in the steel bolt. Take $E = 2 \times 10^5$ MPa and constant $n = 3$.

Solution :

Given data :

(i) Initial stress, $\sigma_i = 75$ MPa

(ii) Minimum creep rate, $\frac{d\epsilon_p}{dt} = B\,\sigma^n = 2.8 \times 10^{-8}$ m/m/hour

where $\sigma = 30$ MPa

(iii) Young's Modulus, $E = 2 \times 10^5$ MPa

(iv) Constant $n = 3$

(v) $t = 1$ year $= 365 \times 24 = 8760$ hours

(vi) $b = ?$, Relaxed stress, $\sigma = ?$

To find b

We know that,

$$\frac{d\epsilon_p}{dt} = B\,\sigma^n$$

Taking log on both sides,

$$\log\left(\frac{d\epsilon_p}{dt}\right) = \log B + n \log \sigma$$

$$\log(2.8 \times 10^{-8}) = \log B + 3 \log 30$$

$$-7.55 = \log B + 4.431$$

$$\log B = -11.98 \approx -12$$

$$B = 10^{-12}$$

Relaxed stress,

$$\frac{1}{\sigma^{n-1}} = \frac{1}{\sigma_i^{(n-1)}} + BE\,(n-1)\,t$$

Substituting the values

$$\frac{1}{\sigma^{3-1}} = \frac{1}{75^{(3-1)}} + 10^{-12} \times 2 \times 10^5\,(3-1)\,8760$$

$$\frac{1}{\sigma^2} = 35040.000177 \times 10^{-7}$$

$$\sigma^2 = \frac{1}{35040 \times 10^{-7}}$$

$$\sigma = 16.89 \text{ MPa}$$

This means that the initial tightening stress of 75 MPa has eased (relaxed) to 16.89 MPa after a passage of one year.