

## **Unit 5**

Introduction of creep , Creep Curve, Structural Changes during Creep, Creep mechanisms, Temperature dependence of creep, Deformation maps, Extrapolation of creep data, Alloys for high temp. use, Fatigue introduction, Nomenclature, Effect of Mean Stress, Miner's Rule, S-N curve, Factors affecting fatigue, LCF, HCF, Structural changes in fatigue, Crack Propagation

### Reference Books

1. Mechanical Metallurgy, Dieter G. E., Mc Graw Hill, 1988.
2. Mechanical Behaviour of Materials, William F. Hosford, Cambridge University Press, 2010.
3. Materials Science & Engineering: An Introduction, William D. Callister, Jr., John Wiley & Sons, Inc., 2007.

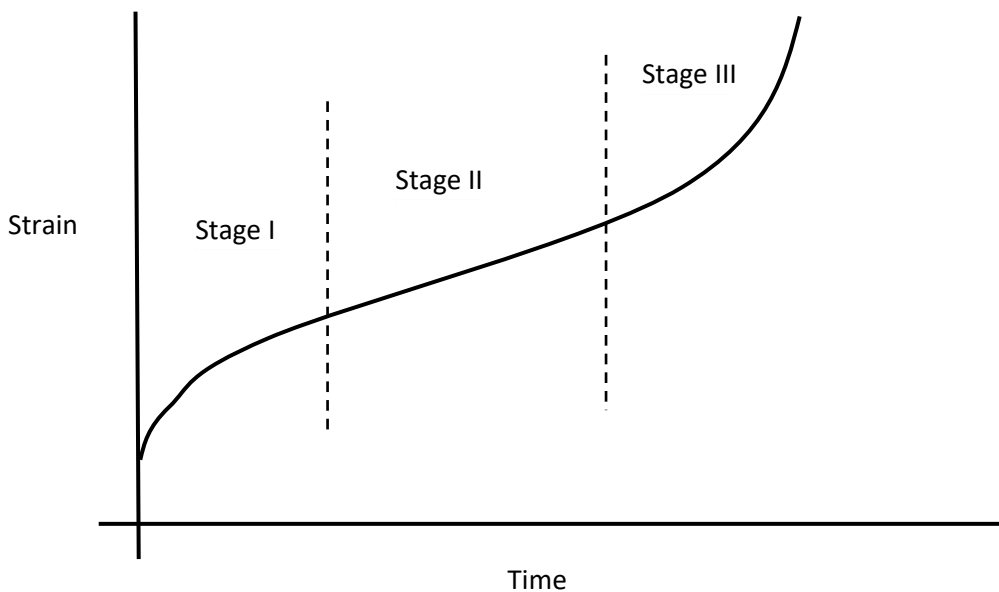
## Unit 5

### 1. Introduction of creep

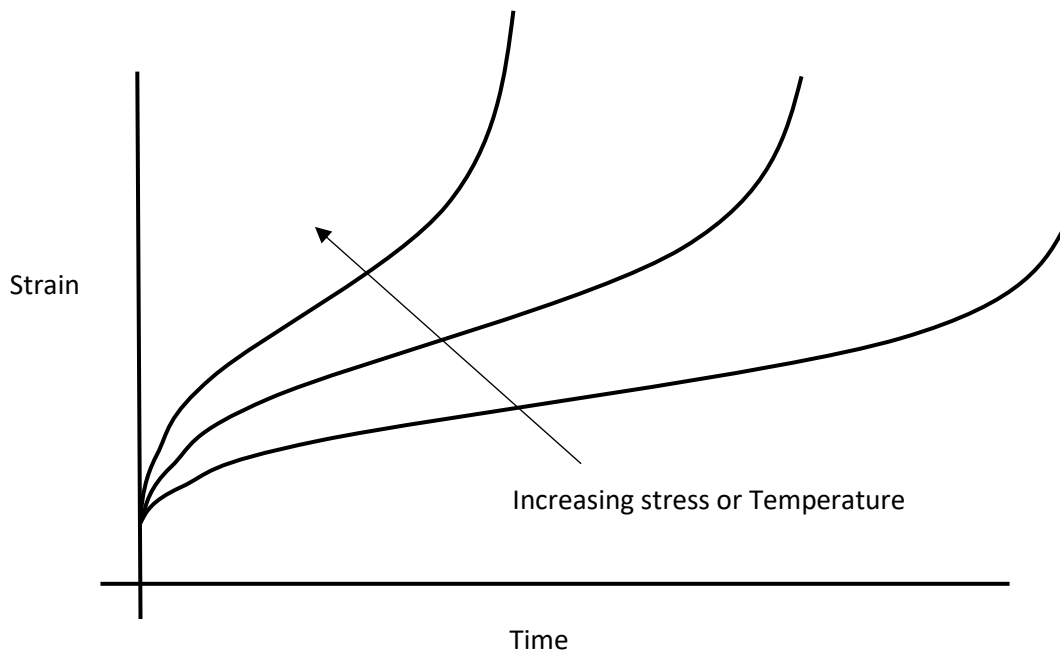
Creep is a time-dependent plastic deformation that occurs in a material at high temperature and high load/stress.

### 2. Creep Curve

As soon as the load is applied, there is an instantaneous elastic response, followed by period of Stage I or transient creep where the rate is high. The strain rate then becomes steady in Stage II or steady-state creep and finally in Stage III creep, the strain rate increases again and accelerates till failure. The acceleration in Stage III is due to the increase in true stress as the cross-sectional area continuously decreases due to load and porosity.



Decreasing temperature and stress leads to slower creep rates but failure occurs at lower strains.



### 3. Creep mechanisms

#### Viscous flow

It is the dominant mechanism in amorphous materials. In polycrystalline materials, grain boundary sliding is viscous in nature where the sliding velocity is directly proportional to stress and inversely proportional to the viscosity. The rate of extension due to the sliding is dependent on the grain boundary area. It means, more the area (smaller grain size 'd'), more is the elongation.

$$\text{Thus, } \dot{\epsilon} = C \left( \frac{\sigma}{\eta} \right) / d$$

The flow is also thermally activated, so  $\eta = \eta_0 \exp \left( \frac{Q_v}{RT} \right)$

The strain rate thus attributable to grain boundary sliding can be written as

$$\dot{\epsilon}_v = A_v \left( \frac{\sigma}{d} \right) \exp \left( \frac{Q_v}{RT} \right)$$

If grain boundary sliding were the only active mechanism, there would be accumulation of material from one end and a deficit at the other. Thus the other deformation mechanisms are required

#### Diffusion Controlled creep

When load is applied, a driving force for the diffusion of atoms from the grain boundaries parallel to the loading direction (bonds break) to the grain boundaries perpendicular to the loading direction. This diffusion produces a plastic elongation.

If the creep occurs by diffusion through the lattice, it is called Nabarro-Herring creep. Diffusion flux,  $J$ , between the parallel and perpendicular to stress axis is proportional to stress and the lattice diffusivity,  $D_L$ , and is inversely proportional to the diffusion distance,  $d/2$ , between the diffusion source and sink.

$$J = CD_L \sigma / (d/2)$$

C is a constant. The velocity,  $v$ , with which the diffusion source and sink move apart is proportional to the diffusional flux,  $J$ . So

$$v = CD_L \sigma / (d/2)$$

$$\dot{\epsilon}_{N-H} = v / d/2 = A_L \left( \frac{\sigma}{d^2} \right) D_L$$

$A_L$  is a constant.

If creep occurs by diffusion along grain boundaries, it is called Coble Creep. The total number of grain boundary diffusion paths is inversely proportional to grain size. The creep rate is thus given by

$$\dot{\epsilon}_c = A_G \left( \frac{\sigma}{d^3} \right) D_{gb}$$

$D_{gb}$  is the diffusivity along grain boundaries and  $A_G$  is a constant.

Coble creep is important at low temperatures and Nabarro-Herring creep at higher temperatures as the activation energy is always lower for grain boundary diffusion.

#### Dislocation motion:

Slip is another mechanism of creep. The creep rate is thus controlled by the ability of dislocations to overcome hinderances in their path. At higher temperatures, the way is climb, where the creep rate is not dependent on grain size but on the stress. Thus,

$$\dot{\epsilon} = A_s (\sigma^m)$$

The value of  $m$  is approximately 5. The constant  $A_s$  for climb depends on diffusion, so it has temperature dependence.

For the Stage II of creep, the applicable equations are

$$\dot{\epsilon}_v = A_v \left( \frac{\sigma}{d} \right) \exp \left( \frac{Q_v}{RT} \right)$$

$$\dot{\epsilon} = A_s (\sigma^m)$$

#### Multiple mechanisms

More than one creep mechanism can operate, either independently or cooperatively. If they operate independently, the overall creep rate is given by the sum of rates of individual mechanisms and if they operate simultaneously, they must operate at same rate.

### **4. Temperature dependence of creep**

Creep depends on thermal activation. Thus the following equations are applicable

$$\dot{\epsilon} = f(\sigma) \exp \left( \frac{-Q}{RT} \right)$$

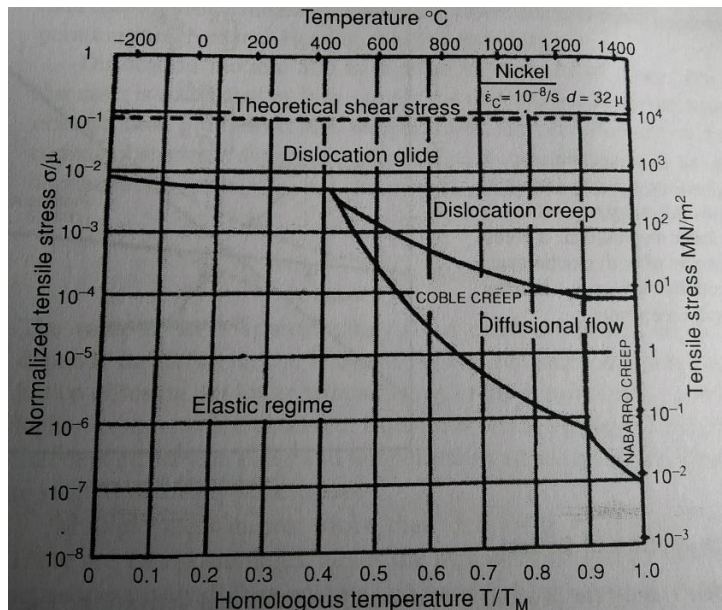
$$Q = R \ln \left( \frac{\dot{\epsilon}_2}{\dot{\epsilon}_1} \right) \left( \frac{1}{T_1} - \frac{1}{T_2} \right)$$

Or  $\dot{\epsilon} = \left( \frac{A}{T} \right) \exp \left( \frac{-Q}{RT} \right) f(\sigma, d)$

### **5. Deformation maps**

The controlling mechanisms of deformation changes with temperature and stress is given by deformation maps. At higher stress. Slip by dislocation motion predominates. At lower stresses, diffusion controlled creep exists where the nature is dependent on grain size.

An example of deformation mechanism map is given below:



## 6. Extrapolation of creep data

### Sherby-Dorn:

The creep strain is plotted as a function of temperature compensated time,  $\theta$ ,

$$\theta = t \exp\left(\frac{-Q}{RT}\right)$$

$\log_{10} \theta$  is referred as Sherby Dorn parameter,  $P_{SD}$ .

Creep strain plotted against  $\theta$  for a given stress or the stress to rupture is plotted against the value of  $P_{SD}$ .

### Larson-Miller Parameter:

$$P_{LM} = T(\log_{10} t_r + C)$$

For most high temperature alloys,  $C=20$ .  $t_r$  is rupture time (hours) and  $T$  is temperature in Kelvin

## 7. Alloys for high temp. use

W and Mo because of their high resistance to creep and high melting point. But they oxidise and hence can only be used when protected.

Superalloys (Ni or Co based alloys) have good oxidation and good creep resistance at high temperatures and have Cr for oxidation prevention

Large grain size materials are preferred

Directional solidification is preferred

## 8. Fatigue introduction

The failure that occurs under cyclic or alternating stress of an amplitude is called fatigue failure. The stages of fatigue include crack nucleation, crack propagation and finally sudden fracture.

The fractured surface will have beach marks or clamshells that indicate the position of crack front at some stage of its fatigue life.

When the crack has progressed far enough, the remaining part of the material will fail either in ductile or brittle manner.

On a much finer scale, markings called striations are visible. The distance between striations is the distance moved by the crack front in one cycle.

External surface will be roughened where actually extrusions and intrusions are formed. They are formed as a result of slip on different sets during tension and compression

Persistent slip bands beneath the surface are associated with intrusions and extrusions. Fatigue cracks originate at intrusions and grow inwards along persistent slip bands.

## 9. Nomenclature

The stress cycles subjected on a material can be

### Reversed

Maximum and minimum stress are equal in magnitude

Stress cycle is tension compression

### Repeated

Maximum and minimum stress are not equal in magnitude

The stress cycles can be tension compression, tension tension, compression compression, zero tension or zero compression

### Complicated

Experienced by aircrafts where periodic unpredictable overloads are common

Terms associated with fatigue:

$$\text{Mean stress, } \sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$$

$$\text{Amplitude, } \sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}$$

$$\text{Range, } \Delta\sigma = \sigma_{max} - \sigma_{min} = 2 \sigma_a$$

$$R = \frac{\sigma_{min}}{\sigma_{max}}$$

## 10. Effect of Mean Stress

Mean stress is usually not zero in service conditions.

According to Goodman,

$$\sigma_a = \sigma_e [1 - \sigma_m / UTS]$$

Where  $\sigma_a$  is a stress amplitude corresponding to a certain life,  $\sigma_m$  is the mean stress and  $\sigma_e$  is the stress amplitude that would give the same life if  $\sigma_m$  were zero. UTS is the ultimate tensile strength.

According to Soderberg,

$$\sigma_a = \sigma_e [1 - \sigma_m / YS]$$

Where YS is Yield Strength

According to Gerber

$$\sigma_a = [1 - (\sigma_m / UTS)^2]$$

### 11. Miner's Rule

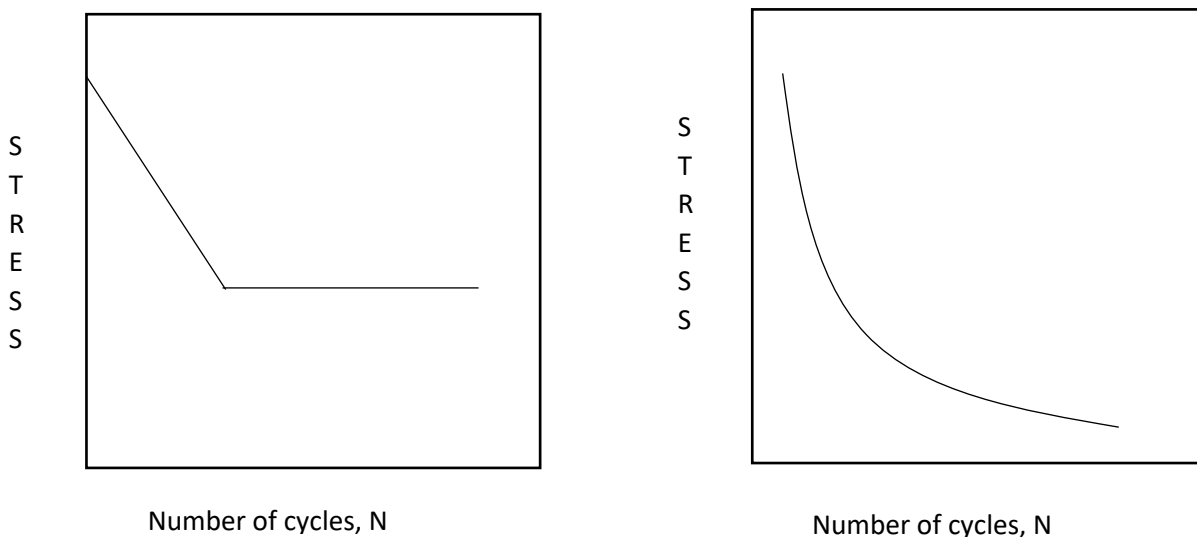
In service conditions, the cyclic amplitude varies during the working life of the part. There may be periods of high stress amplitude followed by low stress amplitude and vice-versa.

Miner suggested that the failure will occur when  $\sum(n_i / N_i) = 1$  where  $n_i$  is the number of cycles applied at an amplitude  $\sigma_{ai}$  and  $N_i$  is the number of cycles that would cause failure at that amplitude.

When  $\sum(n_i / N_i) = 1$ , the entire life is consumed

### 12. S-N curve

Fatigue is represented by S-N curve which are plots of the cyclic stress amplitudes (S) vs the number of cycles to failure (N), with N in log scale.



The first curve is for ferrous materials. It shows the presence of endurance or fatigue limit, that is the stress below which failure will never occur. Non-ferrous materials do not have a fatigue limit. The stress for failure continues to decrease even at a very large number of cycles as

shown in second figure. In this case, fatigue strength is defined as the stress at which failure will occur at  $10^7$  cycles

### 13. Factors affecting fatigue

#### Surfaces

Fatigue cracks usually start at the surfaces and thus the nature of surface strongly affects the fatigue behaviour.

Increased surface hardness increases fatigue limits. Carburising, Nitriding, etc can be used to harden the surfaces

Rough surfaces act as stress concentrators so fatigue strength decreases with surface hardness. Grinding, Polishing increases the smoothness of the surface.

Residual stresses add up to the nominal stresses and affect the fatigue life of the material. Residual tension at the surface lowers the resistance to fatigue while as residual compression raises the failure strength.

#### Metallurgical variables

Increasing the yield strength and hardness increases the endurance limit

Non-metallic inclusions lower fatigue behaviour by acting as internal notches

Ce addition reduce the directionality of fatigue behaviour

#### Size effect

Fatigue strength of a large member is less than a smaller one as the larger specimen has more surface area exposed

#### Design parameters

Endurance limit can be estimated by

$$\sigma_e = \sigma_{eb} C_s C_d (1 - \sigma_m / UTS) / K_f$$

Where

$\sigma_{eb}$  is the base endurance limit (polished unnotched sample)

$C_s$  is the correction factor for surface condition

$C_d$  is the correction factor for specimen size

$1 - \sigma_m / UTS$  accounts for the effect of mean stress

Total strain amplitude  $\frac{\Delta \epsilon}{2}$  can be written as the sum of elastic and plastic strain amplitudes as

$$\frac{\Delta \epsilon}{2} = \frac{\Delta \epsilon_e}{2} + \frac{\Delta \epsilon_p}{2}$$



#### 14. LCF (Low Cycle fatigue)

The total number of cycles is less than  $10^3$

Plastic strain is more than Elastic strain

Crack initiation is rapid and crack propagation accounts for most of the fatigue life

#### 15. HCF (High Cycle fatigue)

The total number of cycles is greater than  $10^4$

Elastic strain is more than plastic strain

Most of the life is spent on crack initiation

#### 16. Crack Initiation and Propagation

The total fatigue life of a material,  $N_f$  can be divided into the cycles required for crack initiation,  $N_i$  and cycles required for crack propagation,  $N_p$

$$N_f = N_i + N_p$$

Crack growth rate depends on range of stress intensity factor,  $\Delta K$ .

$$\Delta K = K_{max} - K_{min} = f \Delta \sigma \sqrt{\pi a}$$
$$\Delta \sigma = \sigma_{max} - \sigma_{min}$$

Below a threshold stress intensity factor, cracks do not grow.

$\frac{da}{dN} = C(\Delta K_I)^m$  is called the Paris law.  $m$  is a material dependent constant and is usually in the range of 2 to 7

Crack Length at any stage can be found by substituting  $\Delta K = f \Delta \sigma \sqrt{\pi a}$  and integrating

$$N = \left[ a^{(1-m/2)} - a_0^{(1-m/2)} \right] / \left[ (1 - m/2) C (f \Delta \sigma \sqrt{\pi})^m \right]$$