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Applied Physics

Lecture-11 & 12

Unit II-Mechanical Properties of solids

Topics to be discussed in this lecture:

Failure in the material:

- Fracture
- Fatigue
- Creep

❖ Fracture

Fractures which are the result of a static overload are described as either ductile or brittle. A characteristic feature of a ductile fracture is plastic deformation prior to failure. In the case of a brittle fracture, there is little, if any, plastic deformation prior to fracture.

A. A. Griffith postulated that brittle materials fracture at stresses well below the theoretical failure stress because of the presence of micro cracks within the material. These cracks have a stress intensification effect and the material fails when the strain energy is sufficient to provide the surface energy for the new surfaces created by fracture. The Griffith fracture stress, σ_f is given by the relationship $\sigma_f = (2\gamma E/\pi a)^{1/2}$ where γ is the surface energy, E is the modulus of elasticity and a is one-half of the crack length.

Fast fracture

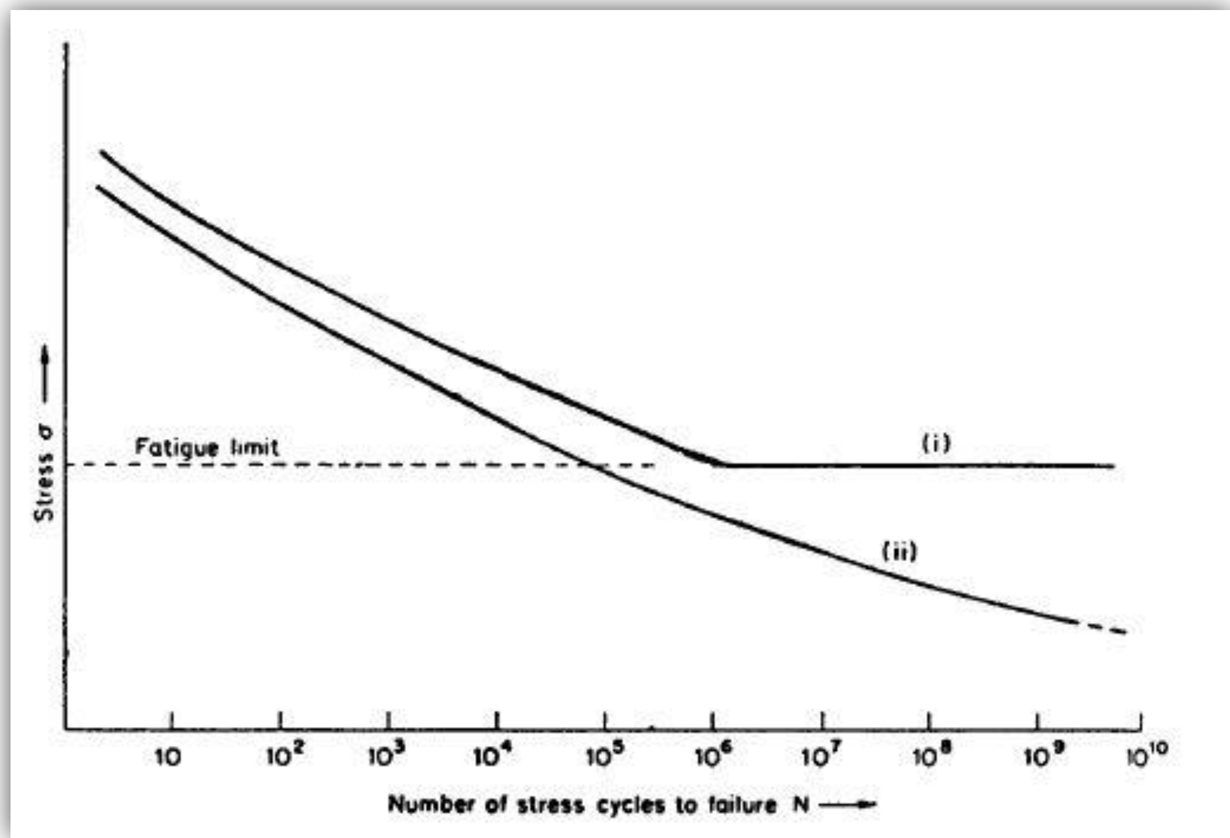
Fast fracture, a catastrophic failure, can occur in metals containing small cracks or flaws, which in other circumstances would be expected to plastically deform prior to failure. The fracture toughness of a metal, K_c (units Pa $m^{1/2}$), is an important property of the material. The stress for fast fracture, σ_f is given by the expression: $\sigma_f = K_c/\sqrt{\pi a}$ where a is one half of the crack length. When a is small σ_f will be greater than σ_y, the yield strength of the metal, but when the crack reaches a critical size the value of σ_f will be equal to σ_y and fast fracture will occur with no plastic deformation.

❖ Fatigue

Fatigue is the response of a material to dynamic loading conditions. A material subjected to repeated cyclical stressing may fail after a number of cycles even though the maximum stress in any one cycle is considerably less than the fracture stress of the material, as determined in short term static tests. Fatigue testing generally involves subjecting a test-piece to alternating stress cycles with a mean stress of zero, the results being plotted in the form of an *S*-*N* curve. *S*-*N* curves for two materials are shown in the figure below.

Most steels give a curve of type (i) with a definite fatigue limit which is usually about one-half of the tensile strength.

Many non-ferrous metals show curves of type (ii) with no definite fatigue limit.



S–N *curves: (i) metal with fatigue limit; (ii) metal with no fatigue limit*

Fatigue parameters

¬ Material fails under fatigue mode at higher number of stress cycles if stress applied is lower.

¬ After a limiting stress, ferrous materials won't fail for any number of stress cycles. This limiting stress is called – **fatigue limit / endurance limit**.

¬ For non-ferrous materials, there is no particular limiting stress i.e. as stress reduces, number of cycles to failure keep increasing. Hence stress corresponding to 10^7 cycles is considered as characteristic of material, and known as **fatigue strength**. Number of cycles is called **fatigue life**.

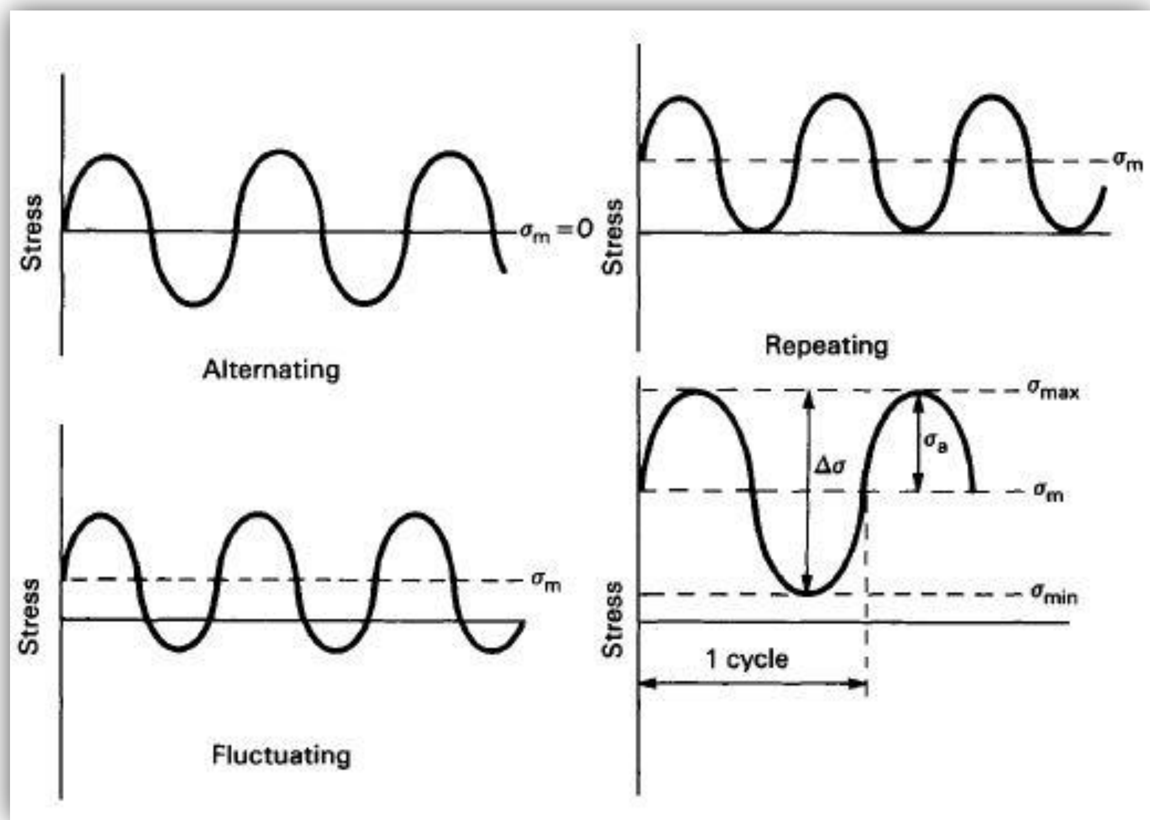
¬ **Endurance ratio** – ratio of fatigue stress to tensile stress of a material. For most materials it is in the range of 0.4-0.5.

1) *Types of Stress Cycle*

Stress cycles are described as *alternating*, when the mean stress, $\boldsymbol{\sigma_m}$, is zero, *repeating*, when the minimum stress, $\boldsymbol{\sigma_{min}}$ is zero, *and.fluctuating*, when the mean stress, $\boldsymbol{\sigma_m}$, has some value other than zero. These cycle types are shown in the figure below.

The stress range of a cycle, $\Delta\sigma$, is ($\boldsymbol{\sigma_{max}}$- $\boldsymbol{\sigma_{min}}$), the cyclic stress amplitude,

$\boldsymbol{\sigma_a} = \frac{1}{2}(\boldsymbol{\sigma_{max}} - \boldsymbol{\sigma_{min}})$, and the mean cycle stress, $\boldsymbol{\sigma_m} = \frac{1}{2}(\boldsymbol{\sigma_{max}} + \boldsymbol{\sigma_{min}})$.



Types of stress cycle

2) *Empirical Relationships*

There are several laws of an empirical nature which have been proposed to give the relationships between stress ranges, mean stresses and fatigue life. These are:

1. **The modified Goodman equation:**

$$\frac{\sigma_a}{\sigma_{FL}} + \frac{\sigma_m}{\sigma_{TS}} = 1$$

2. **The Gerber parabolic equation:**

$$\frac{\sigma_a}{\sigma_{FL}} + \left(\frac{\sigma_m}{\sigma_{TS}}\right)^2 = 1$$

3. **The Soderberg equation:**

$$\frac{\sigma_a}{\sigma_{FL}} + \frac{\sigma_m}{\sigma_Y} = 1$$

In the above equations, $\boldsymbol{\sigma_{FL}}$ is the fatigue strength as determined in tests with a mean stress of zero, $\boldsymbol{\sigma_{TS}}$ is the tensile strength, and $\boldsymbol{\sigma_y}$ is the yield strength of the material.

4. **Miner's law of cumulative fatigue.**

   Miner's cumulative fatigue law is an empirical rule used to estimate the fatigue life of a component when subjected to a series of different loading cycles. For example, if stressed for n1 cycles in a regime which would cause failure in a total of N1 cycles and for n2 cycles in a regime where failure would occur after N2 cycles, then n1/N1 of the fatigue life of the component would be used up in the first case and the fraction n2/ N2 of the fatigue life used in the second instance. Miner's rule can be expressed by stating that failure will occur when $\sum(\frac{n}{N}) = 1$.

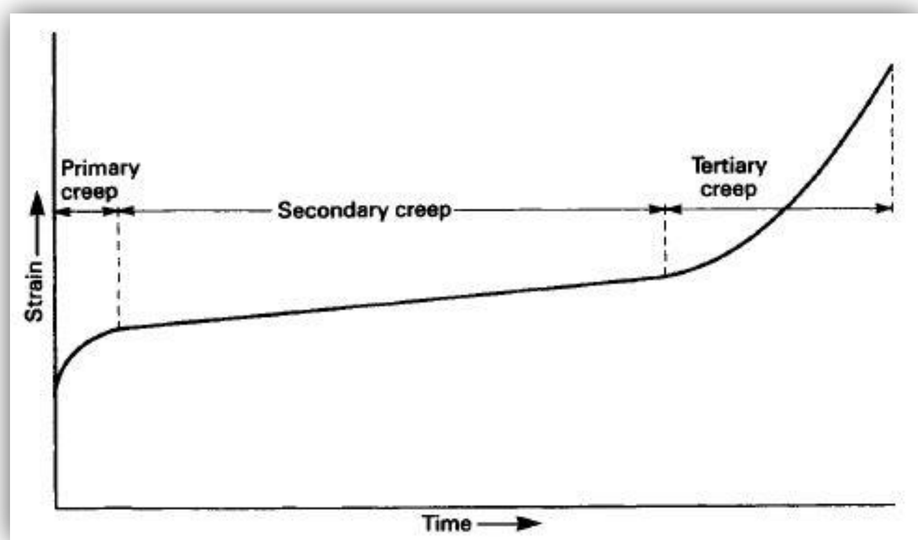
3. Surface Defects

Surface defects will act as points of stress concentration and points for the initiation of fatigue cracks. The two factors are interdependent and both contribute to the stress intensity factor, ΔK, the relationship being: $\Delta K = C\Delta\sigma\sqrt{\pi d}$, where $\Delta\sigma$ is the cyclic stress range, *d* is is the depth of a surface flaw (or depth of a trough in a machined surface profile) and C is a material constant. Catastrophic failure will occur when ΔK reaches a critical value, this value being a function of the material.

❖ Creep

Creep is the continued slow straining of a material under constant load. This is of consequence with many thermoplastics at ordinary temperatures but does not become significant for ceramics, glasses and the majority of metallic materials until the temperature is raised. A typical creep curve showing the development of strain with time at a constant stress and temperature is shown in the figure. The rate of steady state creep is affected by variations of stress and temperature.

Creep curve



(i) Stress

An increase in stress, $\boldsymbol{\sigma}$, will increase the rate of creep strain, $d\varepsilon/dt$, following the relationship: $d\varepsilon/dt = C\boldsymbol{\sigma}^{n}$, C and n being constants for the material.

(ii) Temperature

The creep strain rate increases exponentially with temperature according to an Arrhenius-type relationship: $d\varepsilon/dt = A \exp(- B/T)$, where A and B are material constants and T is temperature (K).