Unit 4

Fracture Theory- Types and modes, Fracture Mechanics - Griffith's theory and its modification, Ductile to Brittle Transition

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 4

1. **Fracture**
   - Fracture is the separation of a body into two or more pieces in response to a static load which is applied at a temperature lower than the melting point of the material.
   - Fracture involves crack initiation and crack propagation.
   - Ductility of a material describes the amount of deformation that precedes fracture.
   - The material can fail by necking down to a minute cross-section, or the surface can be completely perpendicular to the load applied or by shear.

2. **Classification**
   Types of fracture

   Ductile and Brittle

   Ductile
   - Excessive Plastic deformation near the crack and high energy absorption before fracture.
   - Crack propagation is slow.
   - More strain energy is required to induce ductile cracks.
   - More generally, in a tensile test failure occurs after necking. It is usually started by nucleation of voids in the centre of neck. These voids grow with the deformation and coalesce together. The crack grows till the outer rim cannot support the load and fails by sudden shear. This overall failure is called a cup and cone fracture.
   - Voids form at inclusions as the inclusions are weak and/or the matrix inclusion cohesion is not strong.
   - Dimples can be seen on the fractured surface. Each dimple is one half of a microvoid that formed and then separated at fracture.
   - Ductility is quantified in terms of percent elongation or reduction in area.
   - Ductility is a function of temperature, strain rate and stress state.
   - Stable crack propagation.

   Brittle
   - Crack Propagation speed is high with negligible or no plastic deformation and thereby little energy absorption.
   - Occurs suddenly without any warning.
   - Fracture may occur by cleavage (fracture on certain crystallographic planes by bond breaking). Fracture surface may show V shaped chevron markings or lines/ridges generating from the crack. For hard materials, the surface can be more or less smooth.
   - Grain boundary fracture also called intergranular fracture.
   - Toughness depends on grain size. Decrease in grain size increases toughness and ductility.
   - Unstable crack propagation.

- Fracture can be transgranular (through the grains) or intergranular (along the grain boundary).

Modes of fracture

There are three modes of fracture, Mode I, Mode II and Mode III

Mode I: Mode II: Mode III:
Opening   In-plane shear   Out-of-plane shear
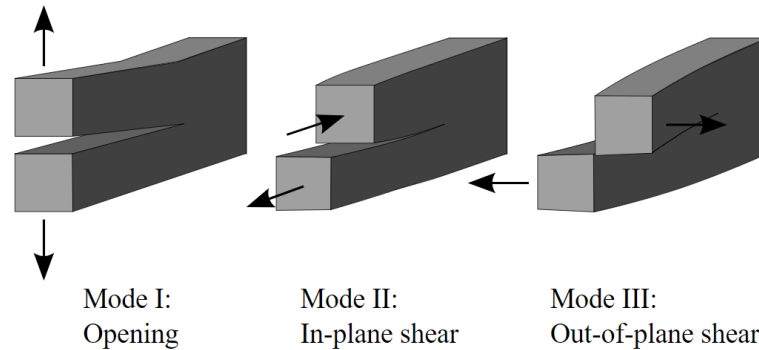
- In mode I, the fracture plane is perpendicular to the normal force.
- In Mode II, fracture occurs under the action of shear stress and propagates in the direction of shear.
- In Mode III, again fracture occurs by shear mode but it propagates in a direction perpendicular to the direction of shear.
- Fracture toughness is given by, K_c

$$K_c = f\sigma(\pi a)^{1/2}$$

- The plane strain fracture toughness (independent of thickness), K_{Ic} is given by
$$K_{Ic} = f\sigma(\pi a)^{1/2}$$
where σ is the applied stress. f depends on specimen geometry and is usually equal to 1.
- If f is equal to 1,

$$K_I = f\sigma(\pi a)^{1/2} = \sqrt{EG_c}$$

3. **Fracture Mechanics**
   - Fracture Mechanics quantifies the relationship between material properties, stress level, crack length and crack propagating mechanisms.

   - Theoretical Fracture Strength, $\sigma_t \approx \dfrac{E}{\pi}$ where E is the modulus which is vastly different from the experimentally observed ones. This discrepancy is explained by the presence of minute cracks or voids inherent of the material. The flaws may be detriment to the fracture strength of the material mainly because the crack tips serve as stress concentrators/ stress raisers.

- If it is assumed that the crack is like an elliptical hole and is aligned perpendicular to the direction of load application, then the maximum stress, σ_m at the crack tip may be approximated as:

$$\sigma_m = 2\sigma_0 \left(\frac{a}{\rho_t}\right)^{1/2}$$

- Where σ_0 is the magnitude of stress applied, ρ_t is the radius of curvature of crack tip and a is half crack length of internal crack or crack length of surface crack.

- The stress concentration factor, $K_t = \frac{\sigma_m}{\sigma_0} = 2\left(\frac{a}{\rho_t}\right)^{1/2}$, is the degree to which the stress is amplified due to the presence of a crack.

4. Griffith's theory and its modification

- According to Griffith, materials always have pre-existing cracks. He mainly considered glass for his work. He considered a large plate with a central crack under a remote stress and calculated the change in energy with crack size.
- The surface energy associated with the crack (2 crack surfaces are created), ΔU_{surf}

$$\Delta U_{surf} = 4at\gamma$$

Where t is plate thickness and 2a is length of an internal crack.

- The surface energy is provided for by the decrease in stored elastic energy which is given by ΔU_{elast}

$$\Delta U_{elast} = {-\pi a^2 t \sigma^2}/{E}$$

Where σ is the stress applied

- Combining the two equations

$$\Delta U_{total} = 4at\gamma - {\pi a^2 t \sigma^2}/{E}$$

- The energy of the system thus first increases with crack length and then decreases. Under a fixed stress there is a critical crack size above which crack growth lowers the energy. This crack size can be found by differentiating the above equation wrt a and setting it to zero

$$\frac{d\Delta U_{total}}{da} = 4t\gamma - 2at\left(\frac{\sigma^2}{E}\right) = 0$$

$$\sigma = \sqrt{\frac{2E\gamma}{\pi a}}$$

- This is Griffiths criterion. It means that a pre-existing crack of size greater than 2a will grow spontaneously till the above equation is satisfied.

- However, in this case plane stress conditions are followed (plate is thin). If plate is thick, the equation is modified to

$$\sigma = \sqrt{\frac{2E\gamma}{(1-v^2)\pi a}}$$

- Orowan's modification

For metals Orowan proposed that the energy used for producing new surface by fracture is not the surface energy γ, but the plastic deformation is also to be taken in account. The Griffith's equation is thus modified to

$$\sigma = \sqrt{\frac{EG_c}{\pi a}}$$

Where G_c includes the plastic work in generating fracture surface.

5. Ductile to Brittle Transition

- The energy absorbed by a material decreases with decrease in temperature and hence the impact tests can be used as a means of determining the ductile to brittle transition temperature. In other words the fracture mode changes from ductile to brittle as the temperature is decreased.
- Transition temperature is not specifically defined but there are many criterions that are used to define this temperature. Some of the definitions are as follows:
- The temperature at which the fracture surface is 50% fibrous.
- The energy absorbed by the Charpy specimen is 15 ft-lb.
- Ductility transition temperature is a temperature below which completely brittle cleavage fracture occurs (5-20 ft-lb energy).
- Fracture-appearance Transition Temperature is a temperature above which the fracture propagates by shear mode (50% fibrous) and hence not catastrophically. This temperature is generally higher than ductility transition temperature.

Metallurgical Factors affecting DBTT

- The transition temperature is increased by 25F with increase in 0.1% of carbon and is lowered by 10F with increase in 0.1% Mn. For satisfactory notch toughness, the Mn:C ratio should be atleast 3:1 (practical limitation 7:1). For every increase of 0.01% P, the transition temperature increases by about 13F.
- An increase in 1 ASTM grain size number in the ferrite grain size (decrease in grain diameter) can result in a 30F decrease in transition temperature of mild steel. Same effect is observed with decreasing the grain size of austenite.
- Cold working, strain aging, quench aging increases the transition temperature.
- FCC and most HCP materials do not exhibit DBTT.