CHAPTER 4

Mechanical Properties Of Metals - II

Fracture of Metals – Ductile Fracture

- Fracture results in separation of stressed solid into two or more parts.
- **Ductile fracture**: High plastic deformation & slow crack propagation.
- Three steps:
  - Specimen forms neck and cavities within neck.
  - Cavities form crack and crack propagates towards surface, perpendicular to stress.
  - Direction of crack changes to 45° resulting in cup-cone fracture.

Fracture of Metals – Brittle Fracture

- No significant plastic deformation before fracture.
- Common at high strain rates and low temperatures.
- **Three stages**:
  - Plastic deformation concentrates dislocation along slip planes.
  - Microcracks nucleate due to shear stress where dislocations are blocked.
  - Crack propagates to fracture.
- Example: HCP Zinc single crystal under high stress along {0001} plane undergoes brittle fracture.

Brittle Fractures (cont..)

- Brittle fractures are due to defects like
  - Folds
  - Undesirable grain flow
  - Porosity
  - Tears and Cracks
  - Corrosion damage
  - Embrittlement due to atomic hydrogen
- At low operating temperature, ductile to brittle transition takes place.

Toughness and Impact Testing

- Toughness is a measure of energy absorbed before failure.
- Impact test measures the ability of metal to absorb impact.
- Toughness is measured using impact testing machine.
Impact testing (Cont…)

• Also used to find the temperature range for ductile to brittle transition.

• Sinking of Titanic: Titanic was made up of steel which has ductile-brittle transition temperature 32°C. On the day of sinking, sea temperature was -2°C which made the structure highly brittle and susceptible to more damage.

Fracture Toughness

• Cracks and flaws cause stress concentration.

\[ K_I = Y \sigma \sqrt{a} \]

\( K_I \) = Stress intensity factor.
\( \sigma \) = Applied stress.
\( a \) = edge crack length
\( Y \) = geometric constant.

\[ K_{IC} \] = critical value of stress intensity factor (Fracture toughness)

Example:
AI 2024 T851 \( \rightarrow \) 26.2 MPam\(^{1/2}\)
4340 alloy steel \( \rightarrow \) 60.4 MPam\(^{1/2}\)

Measuring Fracture Toughness

• A notch is machined in a specimen of sufficient thickness B.
• \( B \gg a \) (plain strain condition)
• \( B = 2.5(K_{IC}/\text{Yield strength})^2 \)
• Specimen is tensile tested.
• Higher the \( K_{IC} \) value, more ductile the metal is.
• Used in design to find allowable flaw size.

Fatigue of Metals

• Metals often fail at much lower stress at cyclic loading compared to static loading.
• Crack nucleates at region of stress concentration and propagates due to cyclic loading.
• Failure occurs when cross sectional area of the metal too small to withstand applied load.

Fatigue Testing

• Alternating compression and tension load is applied on metal piece tapered towards center.

• Stress to cause failure \( S \) and number of cycles required \( N \) are plotted to form SN curve.

Cyclic Stresses

• Different types of stress cycles are possible (axial, torsional and flexural).

Mean stress = \( \sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \)

Stress range = \( \sigma_r = \sigma_{max} - \sigma_{min} \)

Stress amplitude = \( \sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \)

Stress range = \( R = \frac{\sigma_{max}}{\sigma_{min}} \)
Structural Changes in Fatigue Process

- Crack initiation first occurs.
- Reversed directions of crack initiation caused surface ridges and groves called slipband extrusion and intrusion.
- This is stage I and is very slow (10^10 m/cycle).
- Crack growth changes direction to be perpendicular to maximum tensile stress (rate microns/sec).
- Sample ruptures by ductile failure when remaining cross-sectional area is small to withstand the stress.

Fatigue Crack Propagation Rate

- Notched specimen used.
- Cyclic fatigue action is generated.
- Crack length is measured by change in potential produced by crack opening.

Fatigue Crack Growth rate

\[ \log \left( \frac{da}{dN} \right) = m \log(\Delta K) + \log(A) \]

Limiting value of \( \Delta K \) below which there is no measurable Crack growth is called stress intensity factor range threshold \( \Delta K_{th} \)

Factors Affecting Fatigue Strength

- Stress concentration: Fatigue strength is reduced by stress concentration.
- Surface roughness: Smoother surface increases the fatigue strength.
- Surface condition: Surface treatments like carburizing and nitriding increases fatigue life.
- Environment: Chemically reactive environment, which might result in corrosion, decreases fatigue life.

Stress & Crack Length – Fatigue Crack Propagation.

\[ \frac{da}{dN} = f(\sigma,a) \]

\[ \Delta K = K_{max} - K_{min} = \text{stress intensity factor range} \]

\[ A, m = \text{Constants depending on material, environment, frequency, temperature and stress ratio.} \]

Fatigue Life Calculation

\[ \frac{da}{dN} = A \Delta K^m \]

But \[ \Delta K = Y \sigma \sqrt{a} \]

Therefore \[ \Delta K^m = Y^m \sigma^m \pi^{m/2} a^{m/2} \]

Therefore \[ \frac{da}{dN} = A(Y^m \sigma^m \pi^{m/2} a^{m/2})^m \]

Integrating from initial crack size \( a_i \) to final crack size \( a_f \) at number of fatigue cycles \( N_i \)

\[ \int a_i \rightarrow a_f \]

Integrating and solving for \( N_i \)

\[ N_i = \frac{1}{A Y^m \sigma^m \pi^{m/2}} \left( a_f^{m/2} - a_i^{m/2} \right) \]

(Assuming \( Y \) is independent of crack length)
Creep in Metals

- Creep is progressive deformation under constant stress.
- Important in high temperature applications.
- **Primary creep**: creep rate decreases with time due to strain hardening.
- **Secondary creep**: Creep rate is constant due to simultaneous strain hardening and recovery process.
- **Tertiary creep**: Creep rate increases with time leading to necking and fracture.

Creep Test

- Creep test determines the effect of temperature and stress on creep rate.
- Metals are tested at constant stress at different temperature & constant temperature with different stress.

Creep Test (Cont..)

- Creep rupture test is same as creep test but aimed at failing the specimen.
- Plotted as log stress versus log rupture time.
- Time for stress rupture decreases with increased stress and temperature.

Larsen Miller Parameter

- **Larsen Miller parameter** is used to represent creep-stress rupture data.
  \[ P(\text{Larsen-Miller}) = T[\log t_r + C] \]
  \[ T = \text{temperature}(K), \ t_r = \text{stress-rupture time h} \]
  \[ C = \text{Constant (order of 20)} \]

  Also, \[ P(\text{Larsen-Miller}) = T^{(0\text{C})} + 273(20+\log t_r) \]
  or \[ P(\text{Larsen-Miller}) = T^{(0\text{F})} + 460(20+\log t_r) \]

- At a given stress level, the log time to stress rupture plus constant multiplied by temperature remains constant for a given material.

L.M. Diagram of several alloys

Example: Calculate time to cause 0.2% creep strain in gamma Titanium aluminide at 40 KSI and 1200°F

From fig, \( p = 38000 \)

\[ 38000 = (1200 + 460)(\log t_{0.2\%} + 20) \]

\[ t_{0.2\%} = 776 \text{ h} \]
Case Study – Analysis of Failed Fan Shaft

• Requirements
  ➢ Function – Fan drive support
  ➢ Material 1045 cold drawn steel
  ➢ Yield strength – 586 Mpa
  ➢ Expected life – 6440 Km (failed at 3600 km)
• Visual examination (avoid additional damage)
  ➢ Failure initiated at two points near fillet
  ➢ Characteristic of reverse bending fracture

Failed Shaft – Further Analysis

• Tensile test proved yield strength to be 369 MPa (lower than specified 586 MPa).
• Metallographic examination revealed grain structure to be equiaxed (cold drawn metal has elongated grains).

• Conclusion: Material is not cold drawn – it is hot rolled !.
  ➢ Lower fatigue strength and stress raiser caused the failure of the shaft.

Recent Advances: Strength + Ductility

• Coarse grained – low strength, high ductility
• Nanocrystalline – High strength, low ductility (because of failure due to shear bands).
• Ductile nanocrystalline copper : Can be produced by
  ➢ Cold rolling at liquid nitrogen temperature
  ➢ Additional cooling after each pass
  ➢ Controlled annealing
• Cold rolling creates dislocations and cooling stops recovery
• 25 % microcrystalline grains in a matrix of nanograins.

Fatigue Behavior of Nanomaterials

• Nanomaterials and Ultrafine Ni are found to have higher endurance limit than microcrystalline Ni.
• Fatigue crack growth is increased in the intermediate regime with decreasing grain size.
• Lower fatigue crack growth threshold $K_{th}$ observed for nanocrystalline metal.