Module 5

FRACTURE
FATIGUE

Fracture

- When stressed beyond elastic limit, a material can fail in 2 ways:

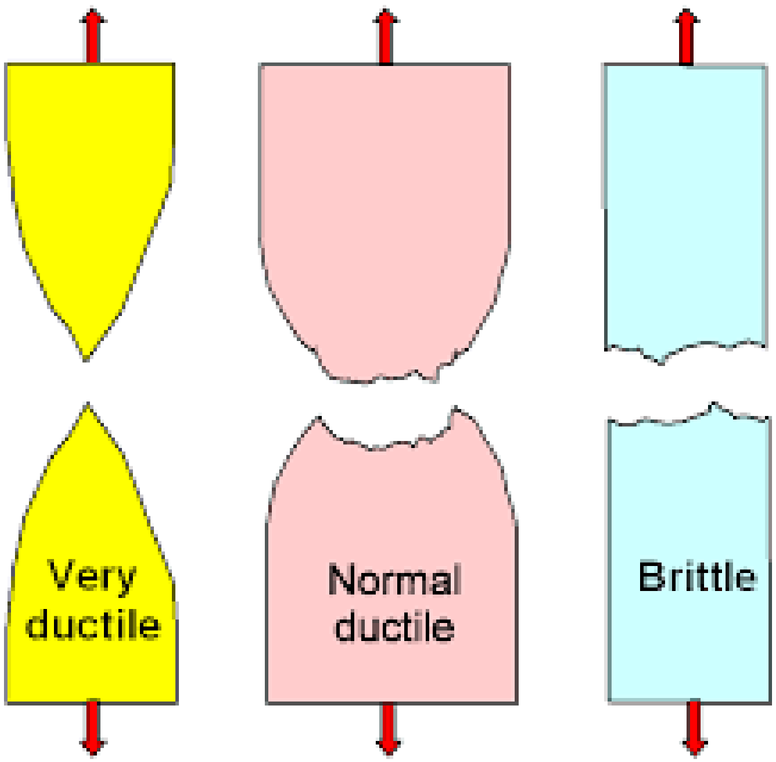
  (a) it yields to almost 100% reduction in c/s area and complete rupture

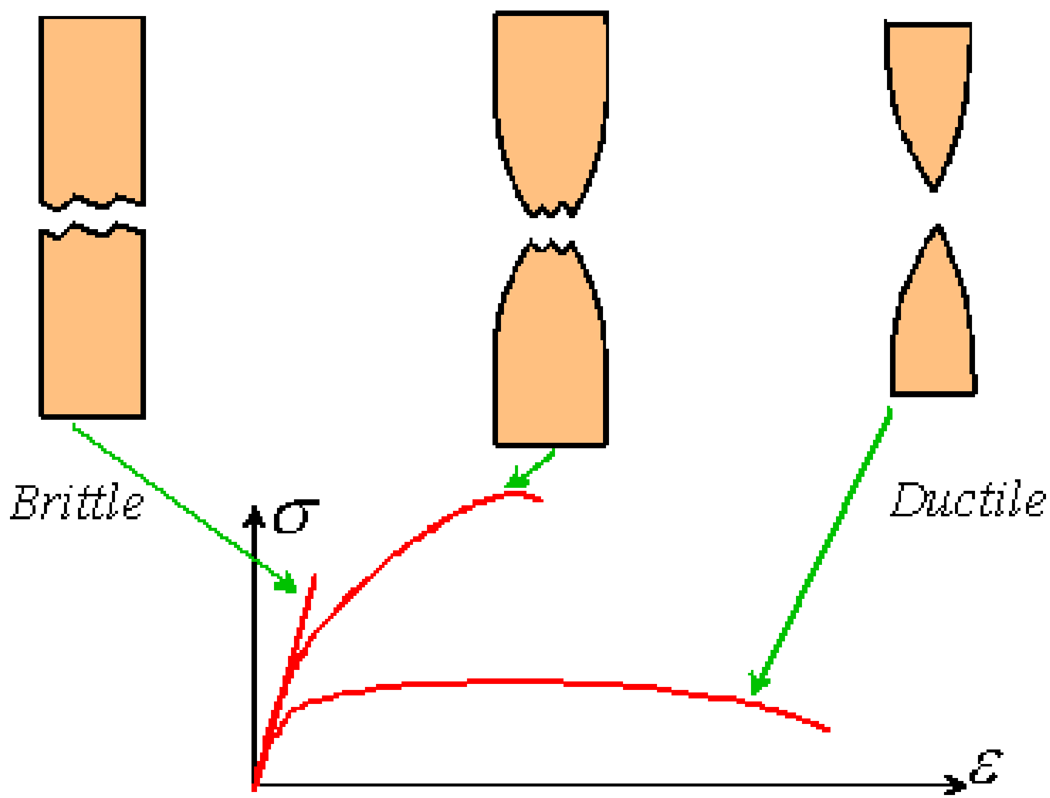
  (b) it fails without any plastic deformation

- Fracture: ultimate failure of a material by breaking in to 2 or more pieces under the influence of an external load

- Tensile, compressive, shear loads
- During failure, to separate atoms completely, a load>F_{max} should be applied
- Fracture is initiated by a microscopic crack
- When loaded stress concentration at crack increases and when it exceeds F_{max} atomic bond breaks and crack propagates till fracture

- Brittle fracture – even when the stress is within the elastic range
- Ductile fracture – after some amount of plastic deformation
- Fracture process involves crack formation and propagation
- Fracture mode depends on propagation
- Slow propagation-stable crack-ductile fracture
- Rapid propagation-unstable crack-brittle fracture


Very ductile
Normal ductile
Brittle


Brittle
σ
Ductile
ε

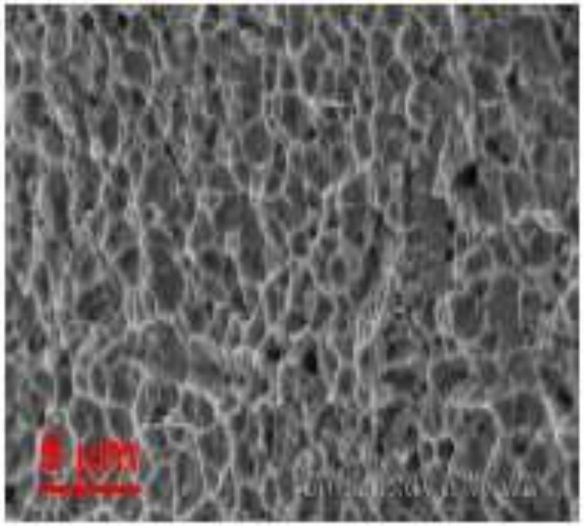
Ductile vs. Brittle Failure

cup-and-cone fracture

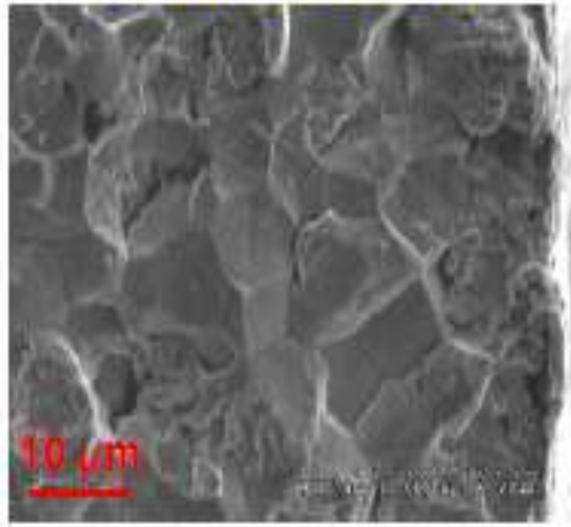
brittle fracture

Adapted from Fig. 8.3, *Callister 7e.*

Ductile fracture

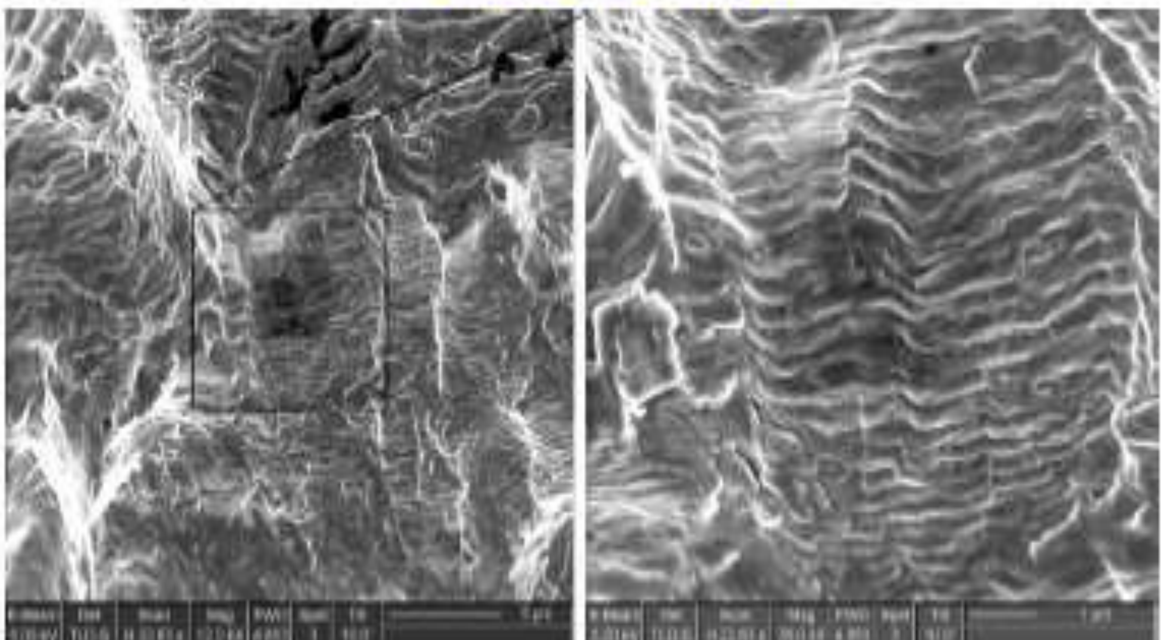


Brittle fracture



Creep fracture

Fatigue fracture



- Preferred one – ductile fracture
- Brittle fracture occurs suddenly without any warning
- Ductile fracture, deformation gives indication

Characteristics of Ductile fracture

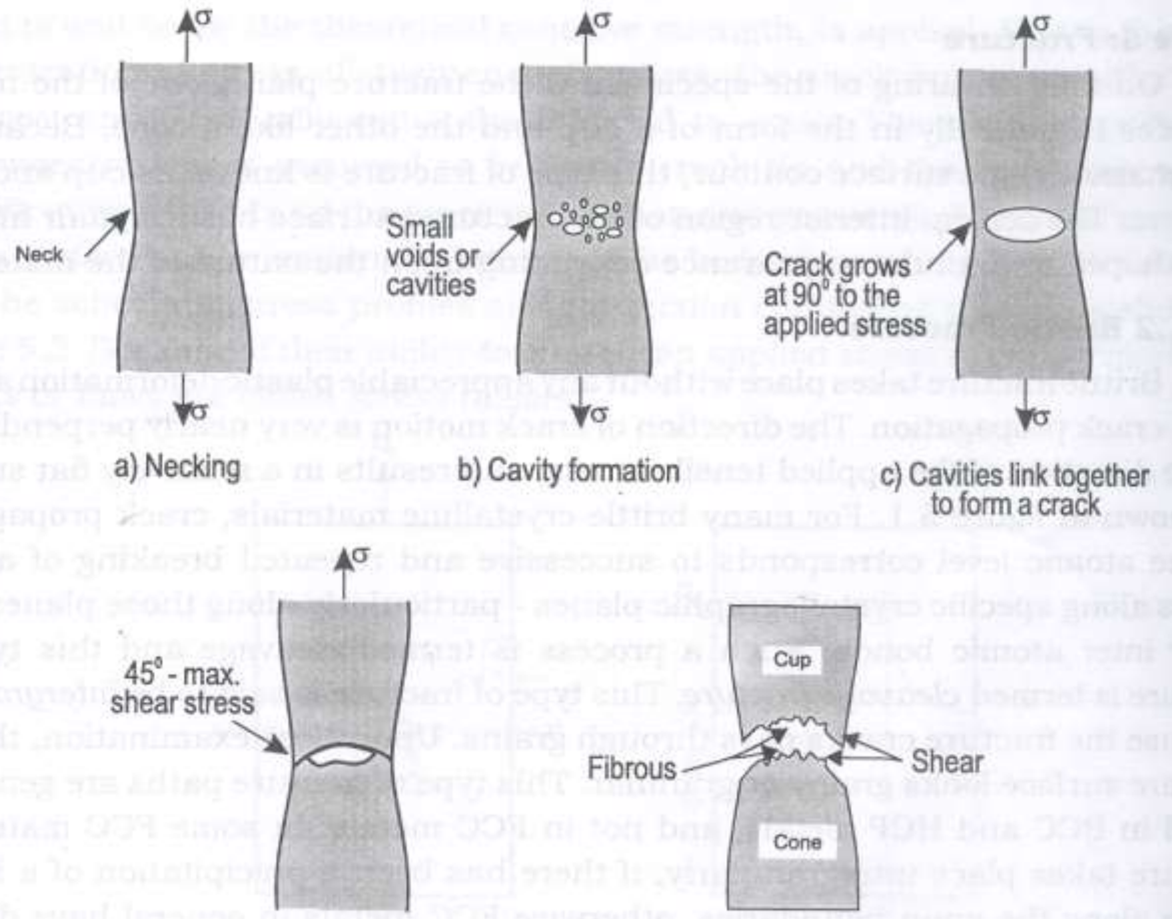
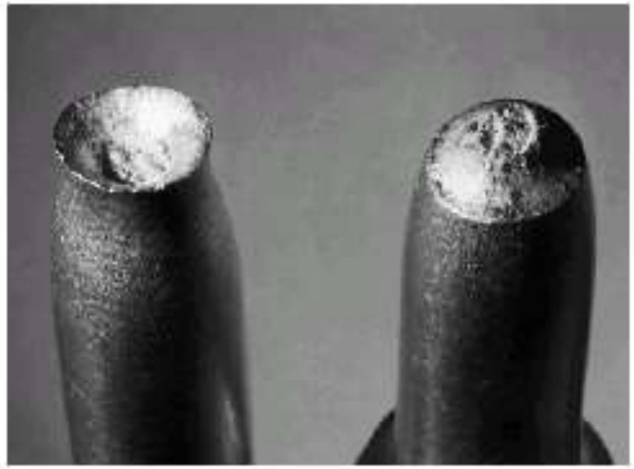


Figure 5.2 *Stages of ductile fracture*

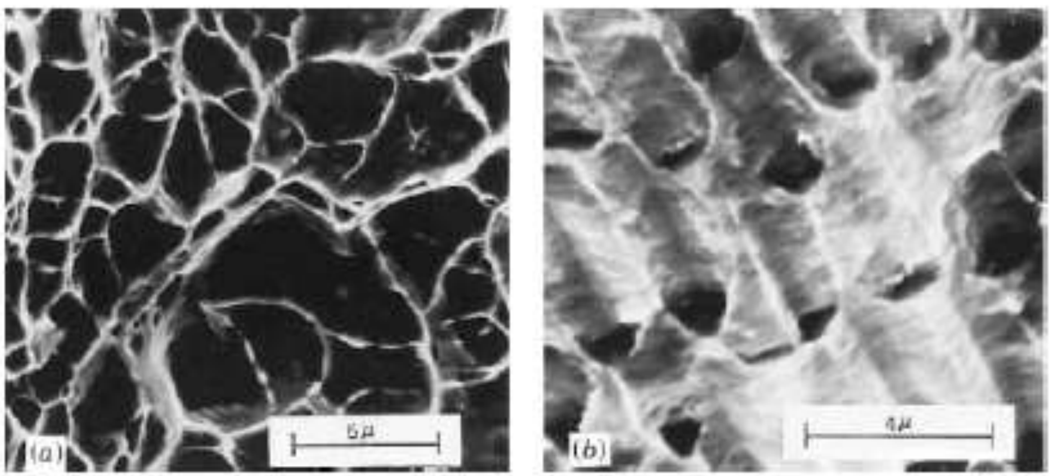
Stages in ductile fracture

1. Necking
2. Cavity formation (micro cracks)
3. Crack formation
4. Crack propagation
5. Fracture

Ductile Fracture



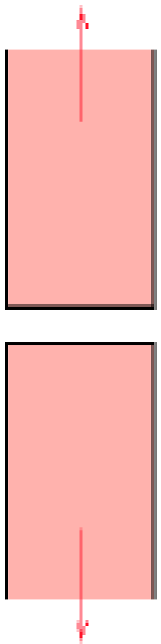
(Cap-and-cone fracture in Al



Scanning Electron Microscopy: *Fractographic* studies at high resolution. Spherical “dimples” correspond to micro-cavities that initiate crack formation.

Brittle fracture

- Takes place without any appreciable plastic deformation and by rapid crack propagation
- Direction of crack motion is nearly perpendicular to the direction of applied tensile stress
- flat surface

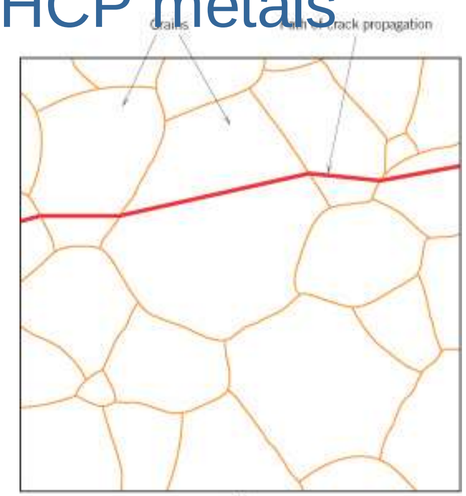


Brittle fracture in a mild steel

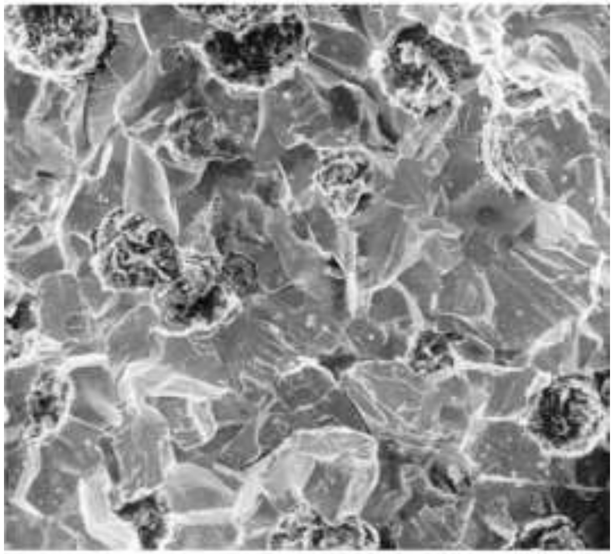
- No appreciable plastic deformation
- Crack propagation is very fast
- Crack propagates nearly perpendicular to the direction of the applied stress
- Crack often propagates by cleavage - breaking of atomic bonds along specific crystallographic planes (cleavage planes).

Transgranular Fracture

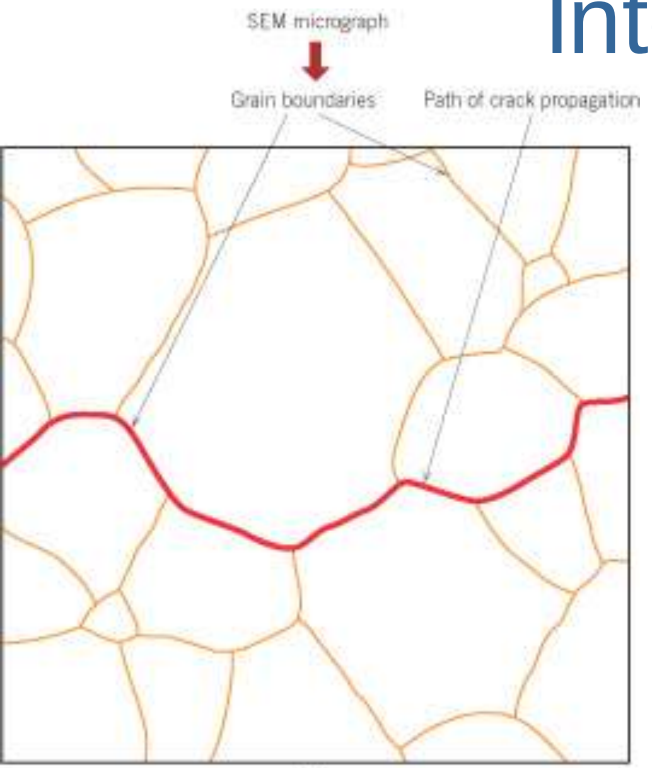
- Also called intragranular fracture because fracture crack passes through the grains
- Cleavage - in most brittle crystalline materials, crack propagation that results from the successive & repeated breaking of atomic bonds along specific planes – particularly along those planes with fewer inter atomic bonds.
- Such a process is termed as cleavage and known as cleavage fracture
- Flat surface look grainy or granular
- BCC and HCP metals



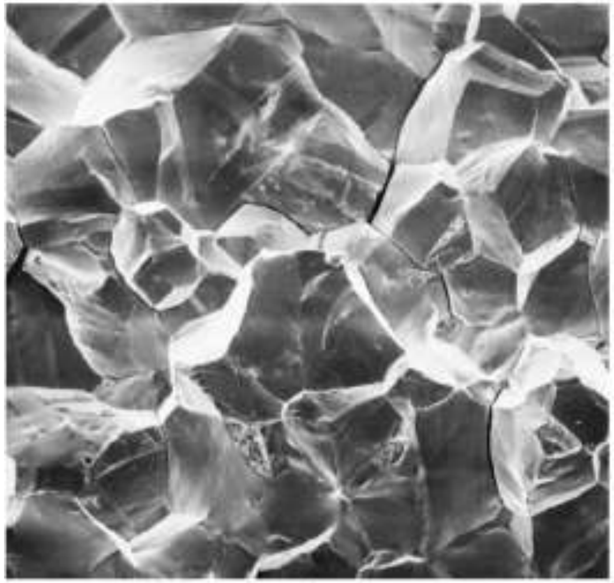
(a)


(b)

Intergranular Fracture



(a)



(b)

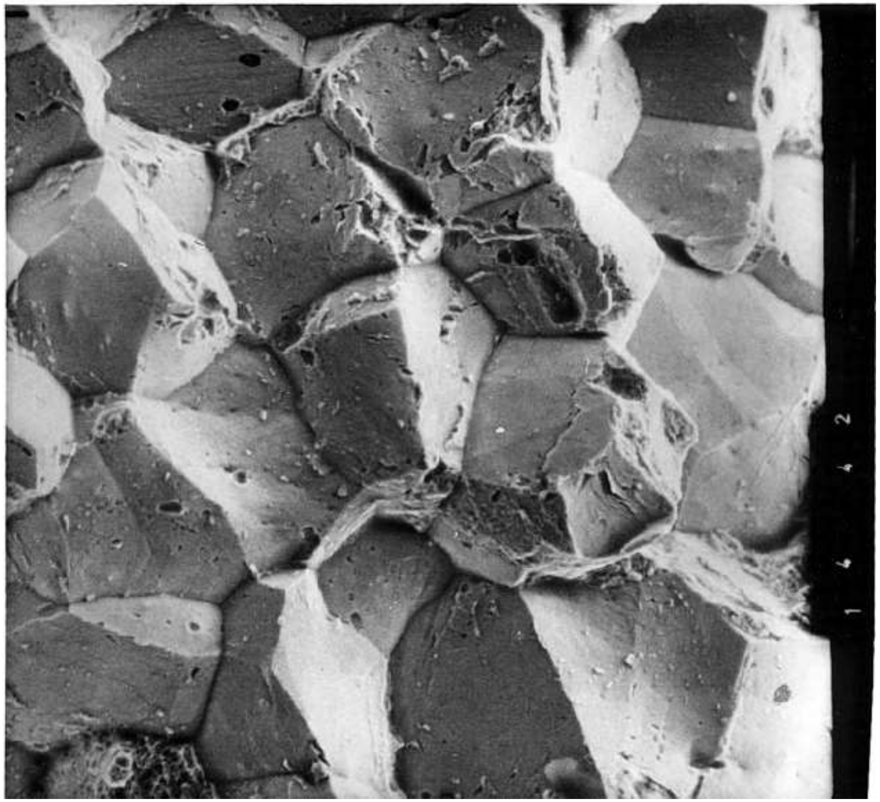
- Intergranular failure is typically due to elemental depletion (chromium) at the grain boundaries or some type of weakening of the grain boundary due to chemical attack, oxidation, embrittlement or due to the precipitation of brittle phase along grain boundarties
- Some FCC metals otherwise FCC metals are ductile in nature.

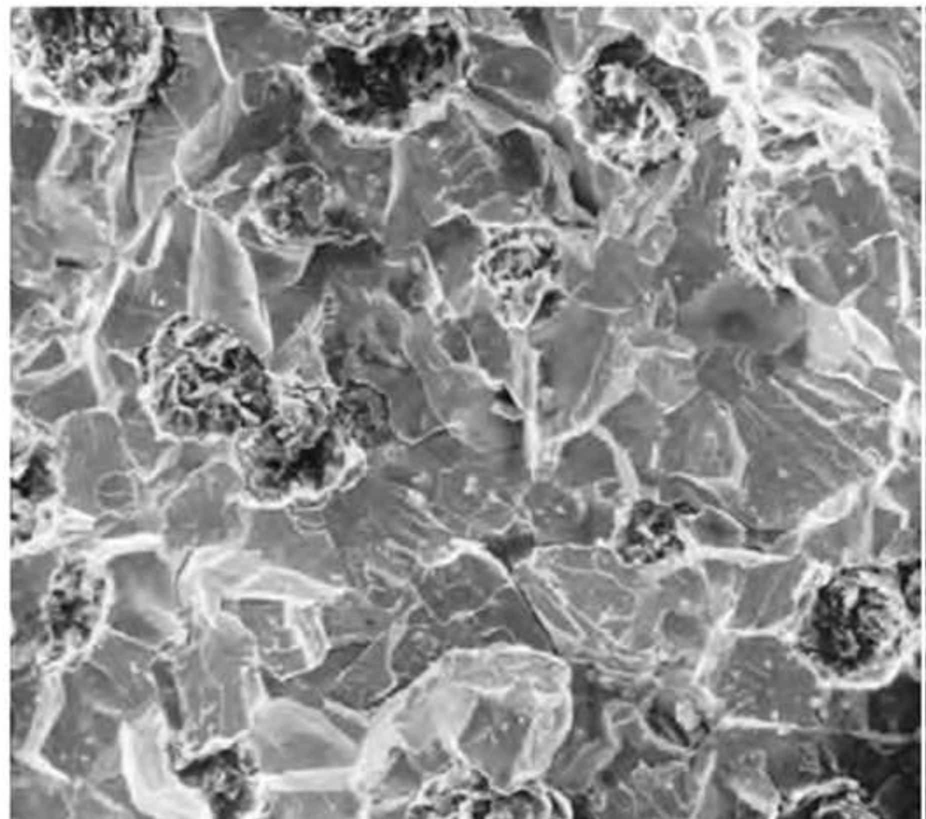
- Tendency for brittle fracture increases with

  a) increasing strain rate

  b) decreasing temperature

  c) stress concentration conditions





Ductile fracture	Brittle fracture
• Material fractures after plastic deformation and slow propagation of crack	• Material fractures with very little or no plastic deformation.
• Surface obtained at the fracture is dull or fibrous in appearance	• Surface obtained at the fracture is shining and crystalling appearance
• It occurs when the material is in plastic condition.	• It occurs when the material is in elastic condition.
• It is characterized by the formation of cup and cone	• It is characterized by separation of normal to tensile stress.
• The tendency of ductile fracture is increased by dislocations and other defects in metals.	• The tendency brittle fracture is increased by decreasing temperature, and increasing strain rate.
• There is reduction in cross – sectional area of the specimen	• There is no change in the cross – sectional area.

Griffith’s theory of fracture

- The measured fracture strengths of most brittle materials are lower than theoretical values
- <u>Griffith Theory:</u>
- Brittle materials contain microscopic cracks which produce stress concentration when a normal stress is applied
- this leads to reach the theoretical cohesive strength near the cracks
- Hence crack propagates and cause the material to fracture

- The stress amplification is at the crack tip, and depends on crack orientation and geometry
- Cracks are able to amplify an applied stress – stress raisers

- Crack is assumed to be elliptical in shape, and with major axis $\perp$ to the applied stress
- Maximum stress at the crack tip is given by

$$\sigma_m = 2\sigma_0\sqrt{\frac{c}{\rho}}$$

- For a long micro crack with small ρ, the factor $\sqrt{(c/\rho)}$ will be large – higher value of σ_m

- Stress concentration factor – σ_m / σ_0

Energy Balance approach

- When a material is stressed in tension elastic strain energy is stored as it elongates
- At higher stress crack becomes larger and material fails
- As crack propagates surface area increases for which an increase in surface energy is required
- The source of this increased surface energy which is released as the crack spreads

- "*A crack will propagate when the decrease in elastic strain energy is at least equal to the energy required to create the new crack surface*"
- Elastic strain energy,

Elastic strain energy = ½ x Stress x Strain x Volume

$$U_E = (\sigma^2/2E) \text{ x Area x thickness}$$

$$U_E = (\sigma^2/2E) 2\pi c^2 \text{x} 1 = \sigma^2 \pi c^2/E$$

- If surface energy per unit area is γ_s then surface energy for a crack of length 2c and unit width will be

$$U_s = (2c\gamma_s) \text{ x } 2,$$ since two surfaces for crack

$$U_s = 4\gamma_s c.$$

- Change in surface energy must be equal to change in elastic strain energy

$$\frac{dU_E}{dc} = \frac{dU_S}{dc}$$

which can be written as $$\frac{d}{dc}\left(\frac{\sigma^2 \pi c^2}{E}\right) = \frac{d}{dc}(4\gamma_s c)$$

this reduces to $$\frac{2\sigma^2 \pi c}{E} = 4\gamma_s$$

$$\sigma^2 = \frac{4E\gamma_s}{2\pi c},$$

$$\sigma = \sqrt{\frac{4E\gamma_s}{2\pi c}}$$

$$\sigma = \sqrt{\frac{4E\gamma_s}{2\pi c}}$$

- It gives the stress required to propagate a crack in a brittle material as a function of the micro crack
- When the critical stress is applied to a brittle material, the pre existing crack propagates spontaneously with a decrease in energy, leading to fracture…

Classification of fracture

- Ductile and Brittle depending on the amount of strain before fracture
- Shear and cleavage depending on the crystallographic mode
- Fibrous and granular depending on appearance

Stress concentration and stress raisers

- Geometrical discontinuity – hole, notch, change in c/s

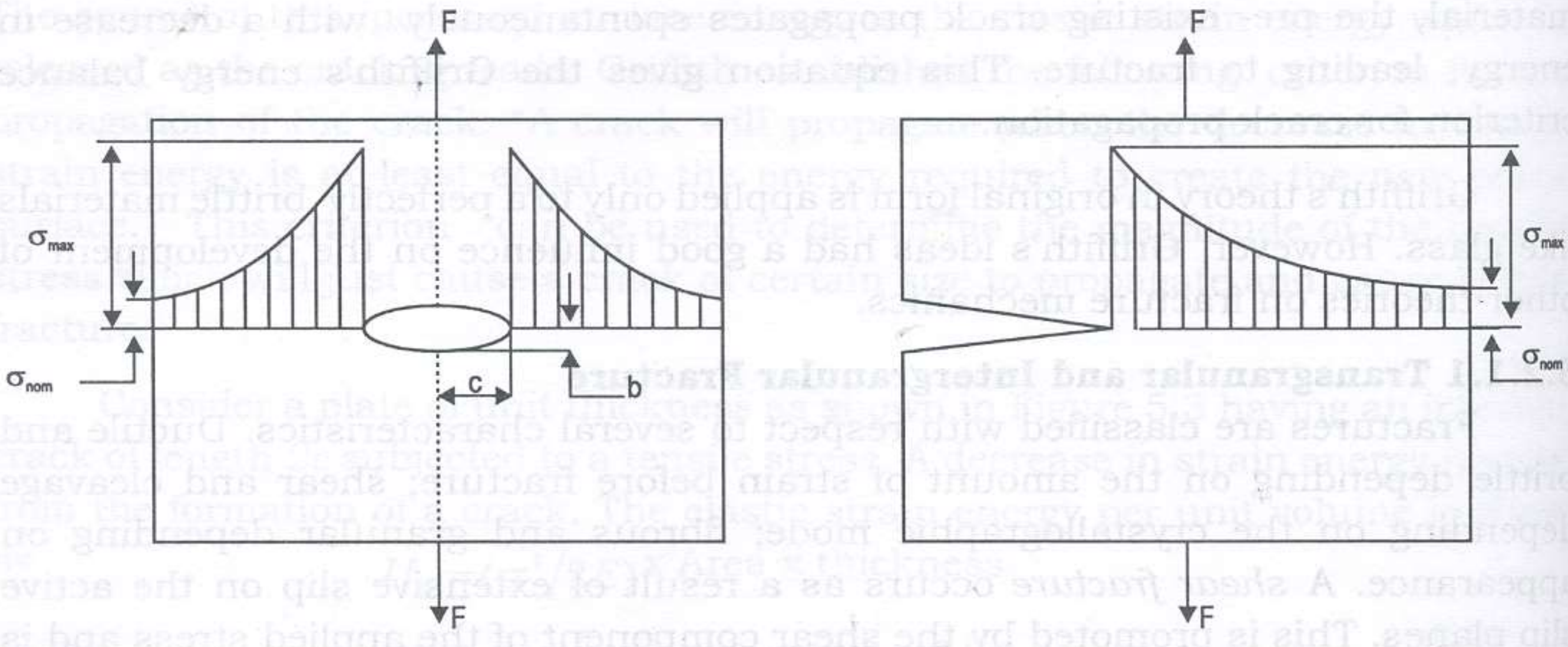


Figure 5.4 *Stress distribution due to hole/notch*

- If no discontinuity, uniformly distributed stress
- σ_{nom} equal to load divided by area
- When hole/notch present σ_{max} at tip of hole drops off with distance away from tip
- Applied stress is amplified, hence discontinuities are known as stress raisers
- Magnitude of stress amplification dependent on geometry and orientation
- Microcracks, inclusions, porosity, tears, folds, poor surface finish-inherent/during manufacturing
- Sharp corners, fillets, key way recess

- Stress concentration is expressed as the ratio of max stress to nominal stress
- Ratio, $K_t = \sigma_{max} / \sigma_{nom}$ - stress concentration factor
- The effect of stress raiser is more pronounced in a brittle material than in a ductile material

Impact loading

- When load is applied suddenly stress inside the material may reach to ultimate tensile strength, σ_u
- Critically stressed point may not get enough time to reduce the effect of stress concentration
- When σ_u is reached a brittle fracture occurs
- Thus if there is impact loading, on ductile material, stress concentration effect must be considered

Ductile-Brittle transition

- Sometimes ductile materials fracture suddenly with very little plastic deformation
- This transition occurs in some metals when

  a) temperature is lowered

  b) rate of straining is increased

  c) notch or stress raiser is introduced

- In steel and other BCC materials, transition when temperature lowered
- It is an important engg: phenomenon
- Reason for transition at lower temperatures –
  at high temp- easy slip

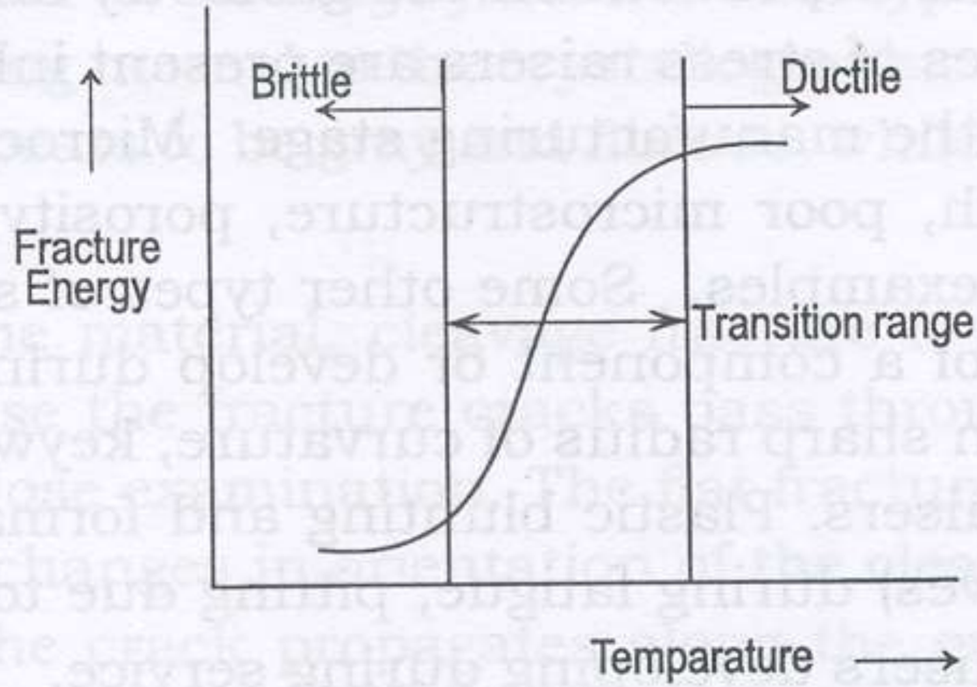


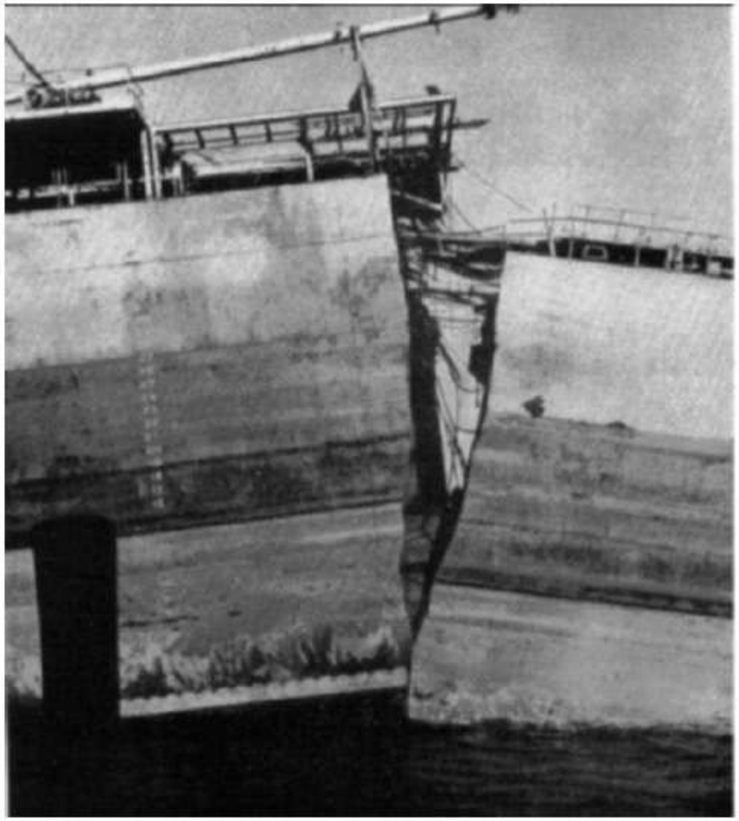
Figure 5.5 *Ductile - brittle transition*

Ductile-Brittle transition temperature

- At DBTT $\sigma_f = \sigma_Y$
- ie. Stress to propagate a crack is equal to stress to move dislocations (yield stress)
- When $\sigma_Y < \sigma_f$, material first yields plastically and then fractures. ie, at higher temperatures than DBTT material is ductile
- At temperatures less than DBTT – Brittle
- That is at all temperatures below DBTT, $\sigma_Y = \sigma_f$ and fracture occurs before yielding
- Commonly observed in BCC and HCP structures
- For ceramics this transition occurs at temperatures in excess of 1000°C

Ductile to Brittle Transition

- ➢Failure of Liberty ships in WW II - Low-carbon steels were ductile at Room Temperature tensile tests, they became brittle when exposed to lower-temperature ocean environmets
- ➢.The ships were built and used in the Pacific Ocean but when they were employed in the Atlantic Ocean, which is colder, the ship's material underwent a ductile to brittle transition.



Methods of protection against fracture

- Cracks and their propagation are the main reasons for fracture
- For protection – make cracks ineffective
- ***Methods***
- introduce compressive stresses on the surface to counteract the tensile stress that cause crack to propagate
- Polishing the surface
- Avoid sharp corners and notches
- Improve purity
- Avoid precipitation along grain boundaries
- Grain refinement in polycrystalline materials
- In composites, use ductile material in a matrix of brittle material

Fracture strength

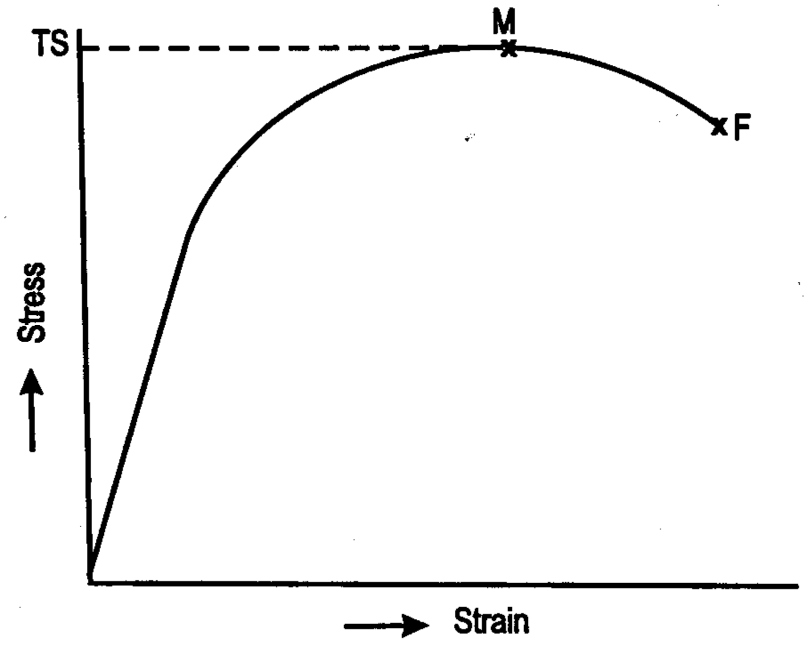


Figure 5.6 *Stress – strain curve of a ductile material*

Fracture mechanics

- A branch of mechanics dealing with behavior of materials containing cracks or other small flaws
- Fracture toughness: measures the ability of the material containing a flaw to withstand an applied load
- Fracture toughness test – tensile load is applied to a specimen prepared with a flaw of known size

- Stress intensity factor, $K = f\sigma\sqrt{(\pi c)}$
- f = geometry factor
- σ = applied stress
- c = flaw size
- The critical value of stress intensity factor which causes the flaw to grow and lead to failure can be used to represent fracture toughness, K_C
- K_C depends on thickness of specimen
- When specimen thickness is much more than crack size, K_C becomes a constant K_{IC} (PLANE STRAIN FRACTURE TOUGHNESS)
- K_{IC} is considered as a property of material which depends on many factors like temp, strain rate microstructure with unusual units of $MPa\sqrt{m}$

Significance of fracture mechanics

- The approach can be used to to design and select materials considering the presence of flaws
- K_{IC}, σ and c are the variables to be considered here
- If the max: flaw size, c and applied stress σ are known, a material having a fracture toughness K_{IC} that is large enough to prevent the flaw to grow can be selected
- When flaw size c and fracture toughness K_{IC} are known the max: stress σ that the component can withstand can be calculated

Modes of fracture

Mode I fracture – Opening mode (a tensile stress normal to the plane of the crack),
Mode II fracture – Sliding mode (a shear stress acting parallel to the plane of the crack and perpendicular to the crack front), and
Mode III fracture – Tearing mode (a shear stress acting parallel to the plane of the crack and parallel to the crack front).

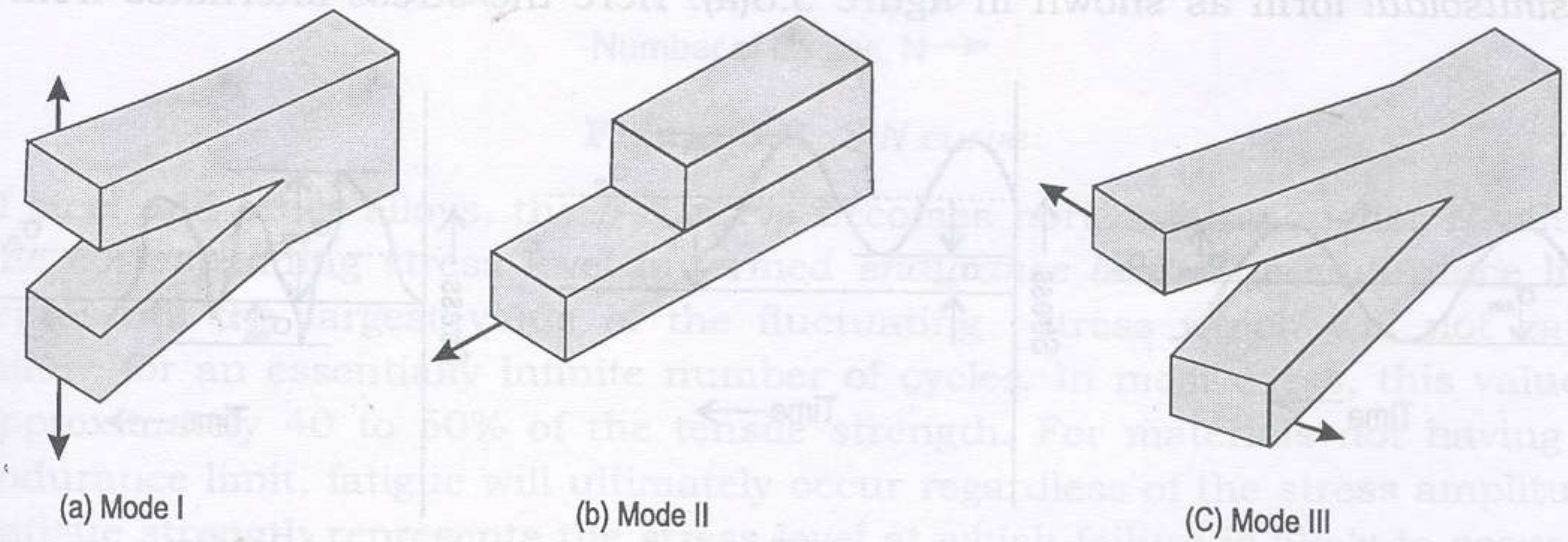
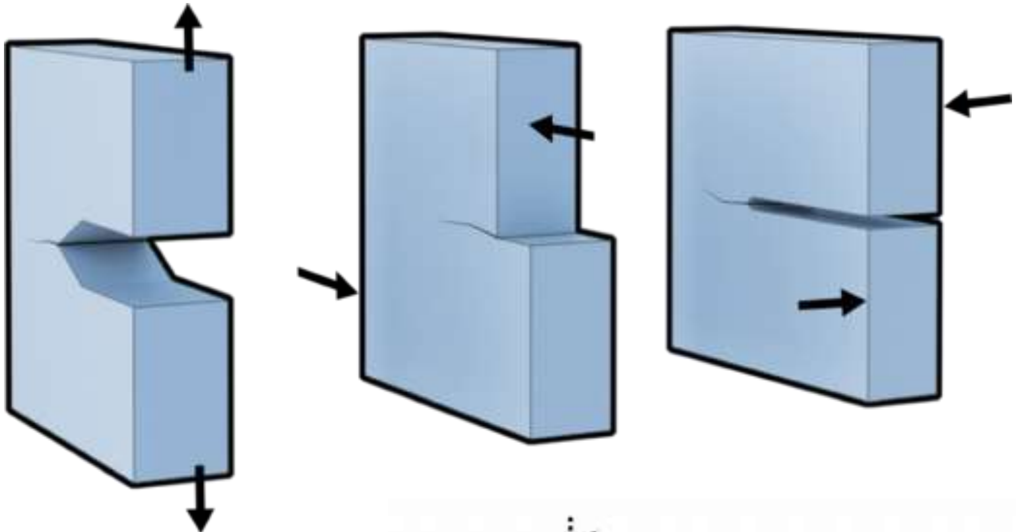
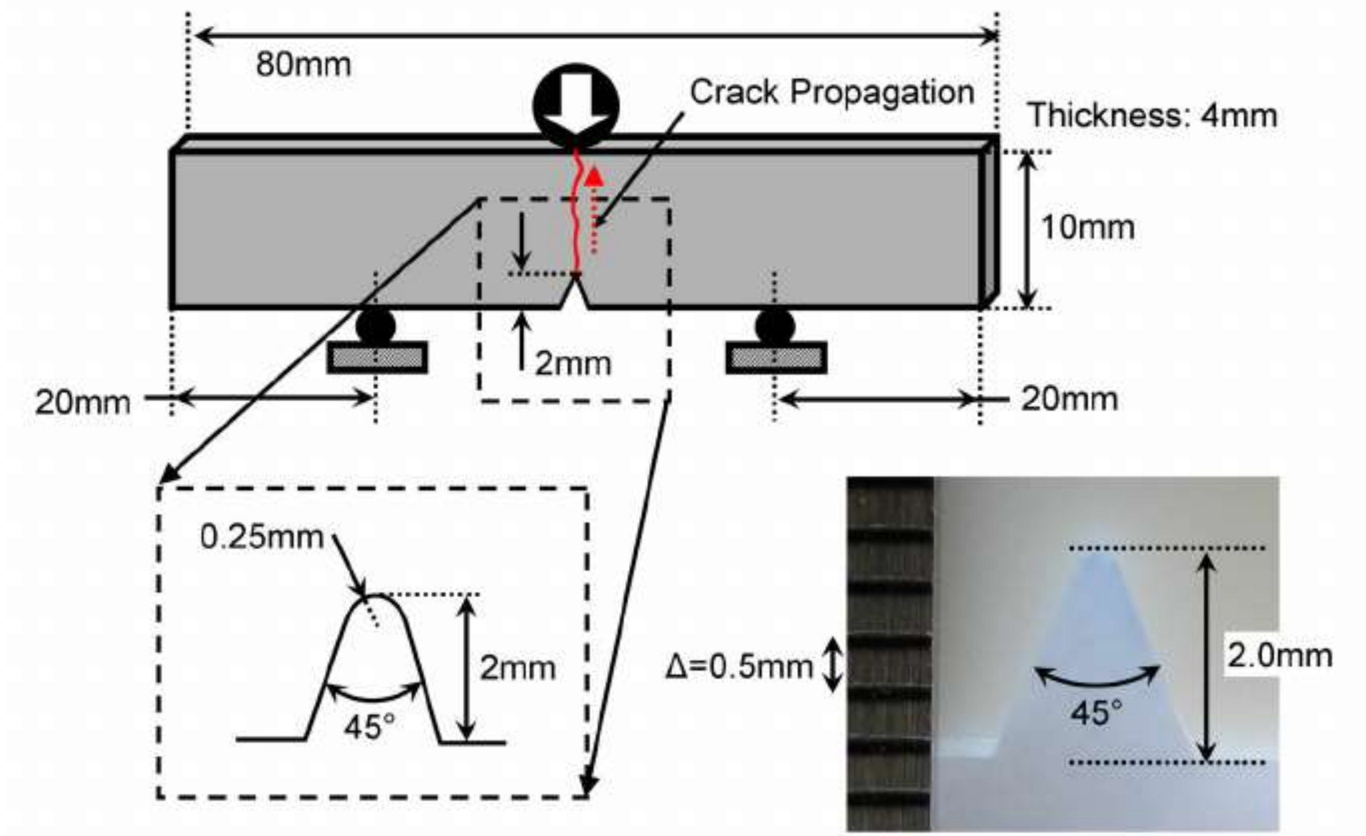
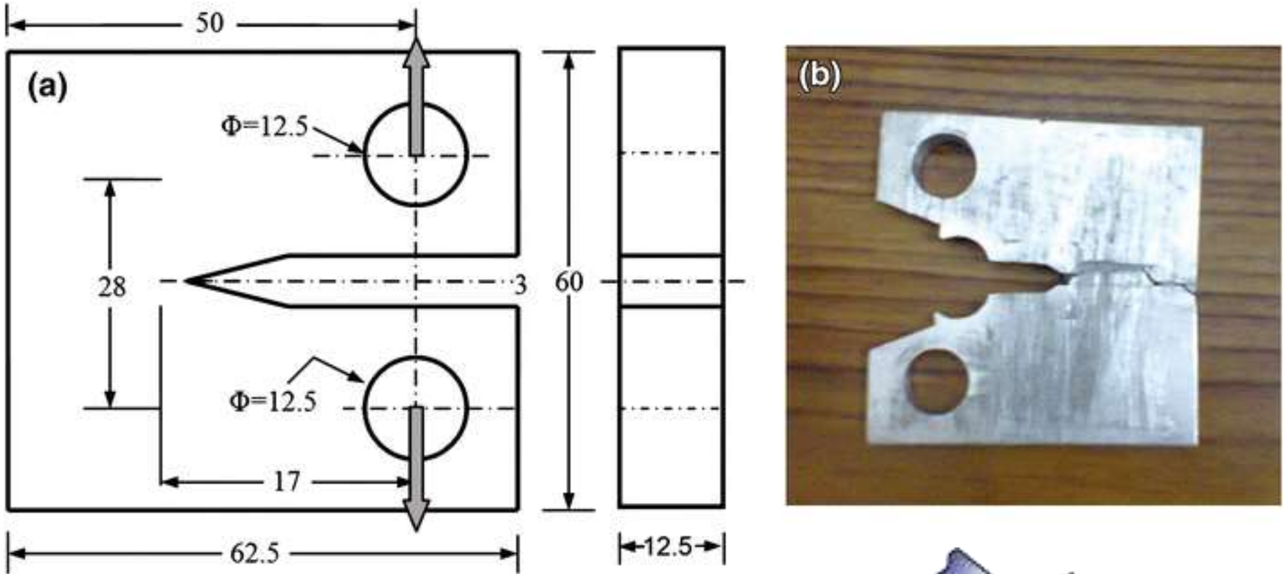


Figure 5.7 *Modes of Fracture*

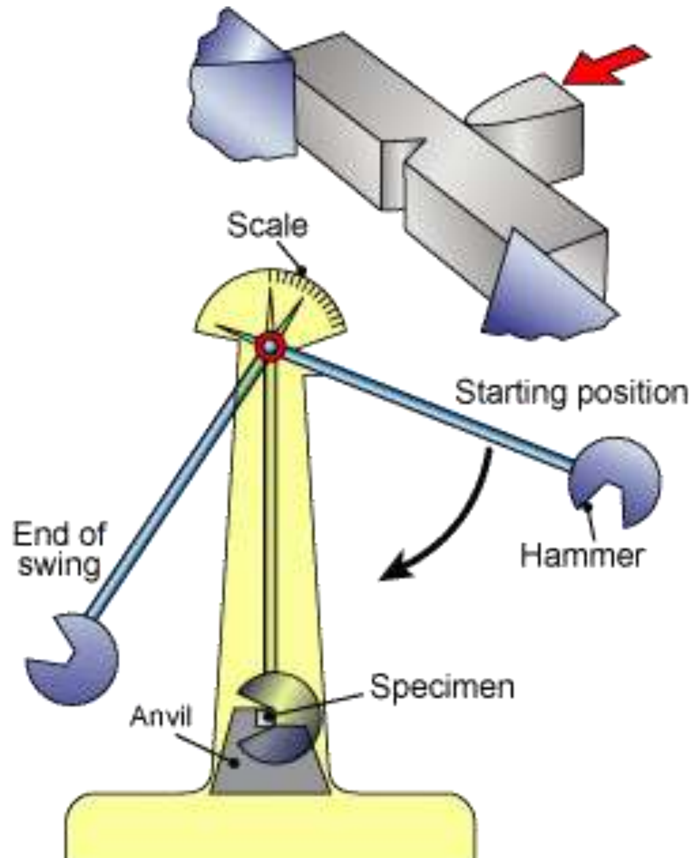




80mm
Crack Propagation
Thickness: 4mm
10mm
2mm
20mm
20mm
0.25mm
2mm
45°
Δ=0.5mm
2.0mm
45°



All dimensions are in mm



Fatigue

- Failure of materials much below the stress required to cause fracture, when subjected to repetitive or fluctuating stresses – Fatigue
- Rotating shafts, bridges, machine components, automobile parts etc.
- Single largest cause of failure in metals(80-90%)
- Without any warning or signs of failure
- Brittle in nature

Stress cycles

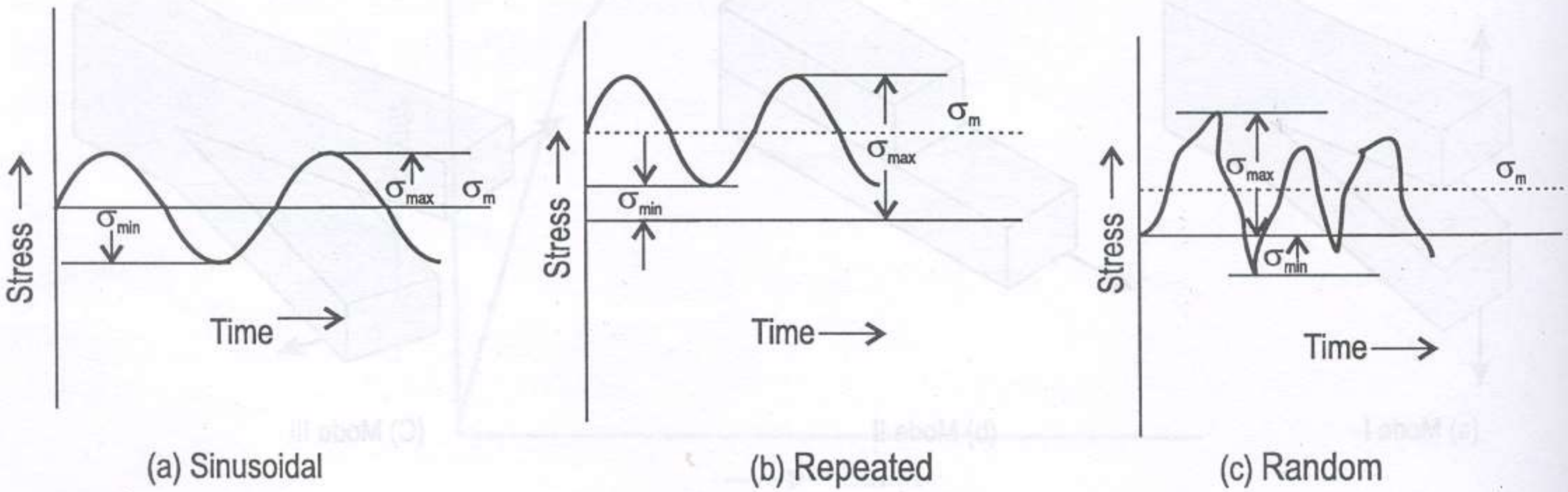


Figure 5.8 *Stress Cycles*

S-N curve

- Fatigue test and S-N curve

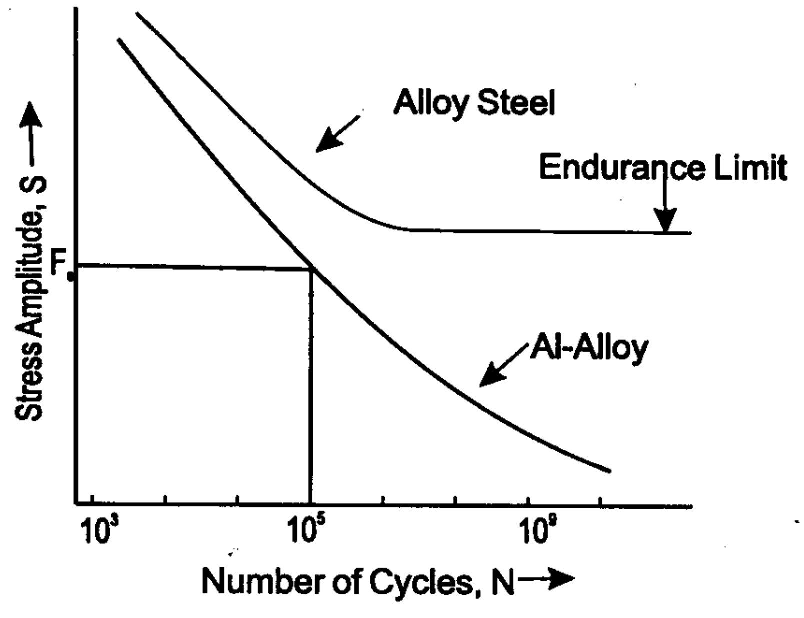


Figure 5.8 *S-N curve*

- Endurance limit – largest value of fluctuating stress which will not cause failure for infinite no: of cycles
- Fatigue strength – stress level at which failure is likely to occur for some given no: of cycles
- Fatigue life – no: of cycles to cause failure at a specified stress level

Mechanism of fatigue

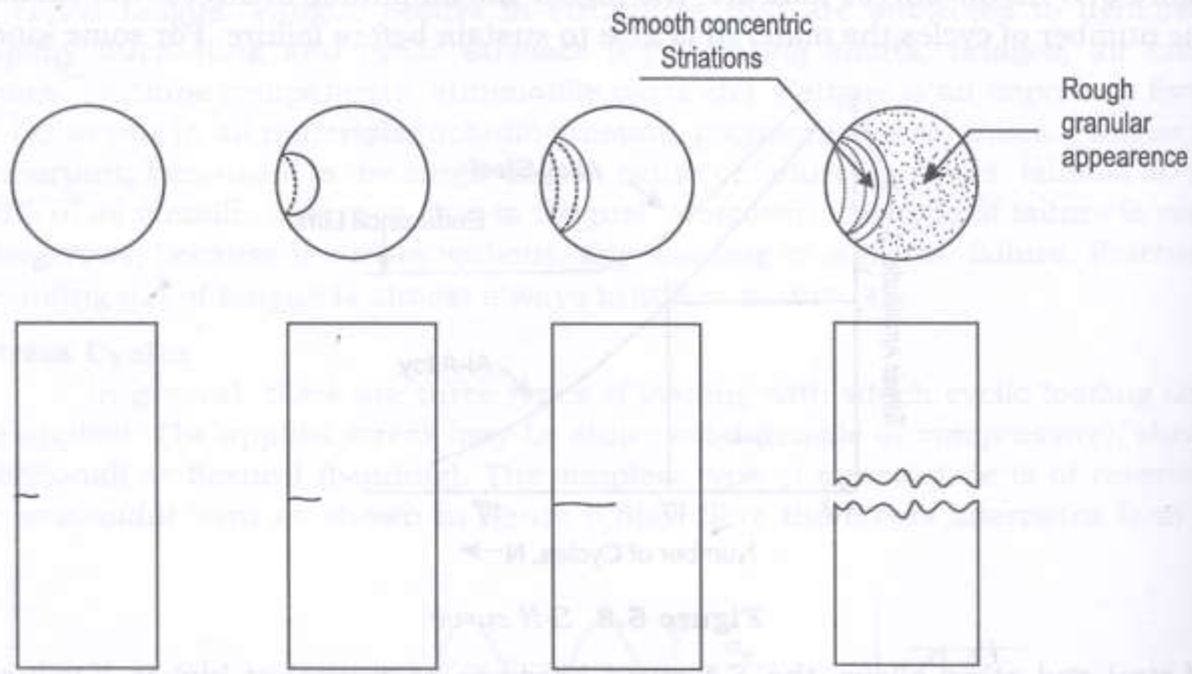
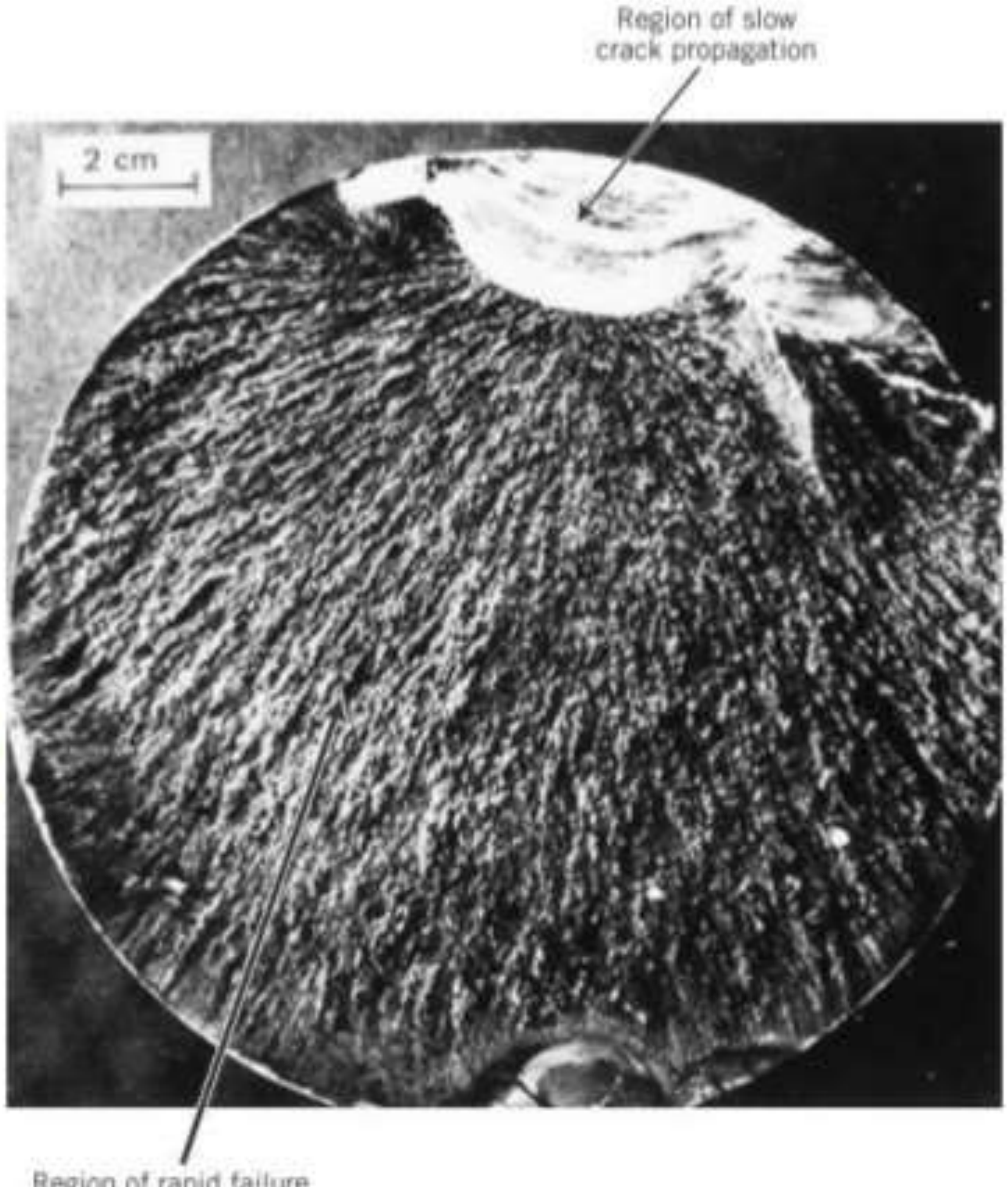


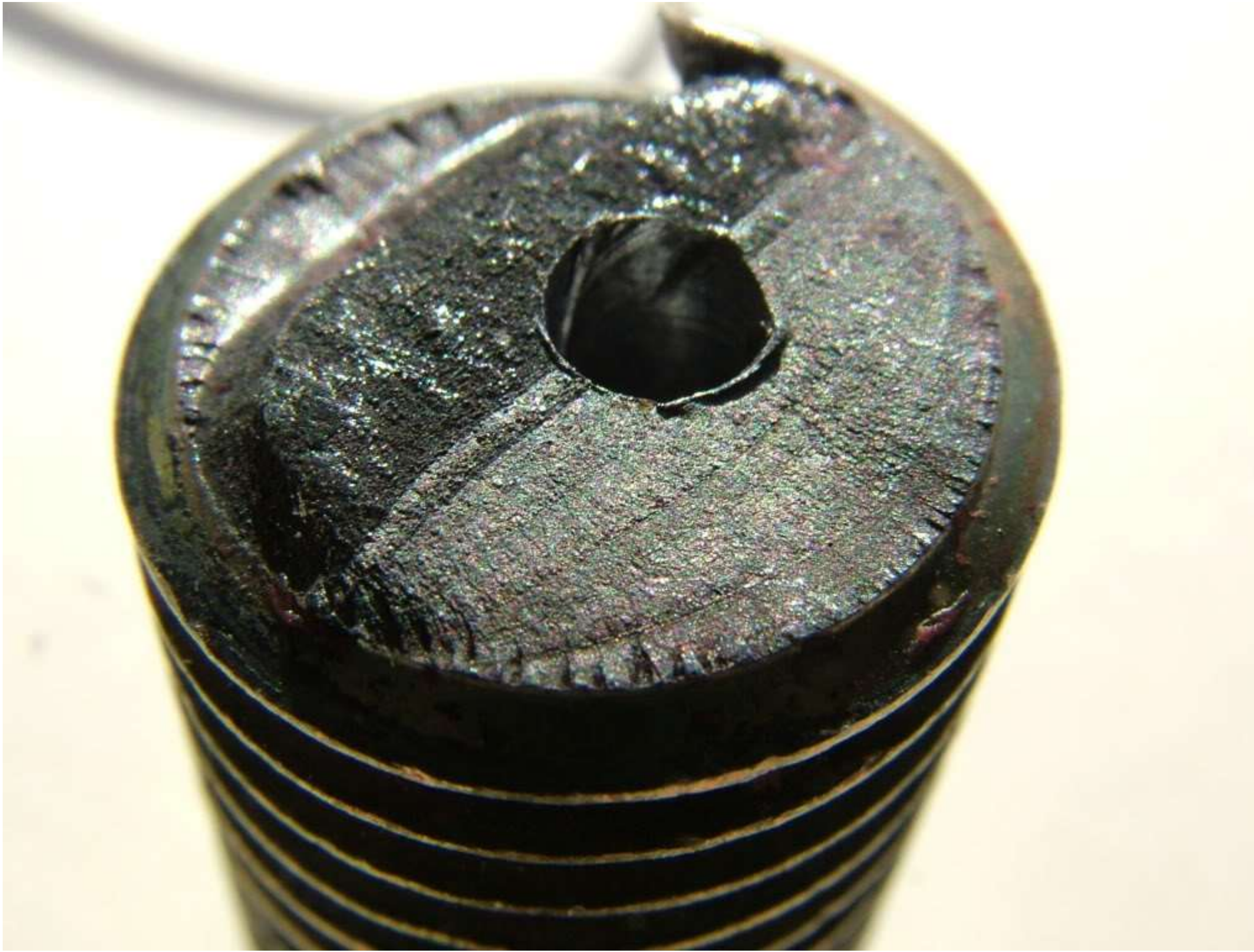
Figure 5.10 *Stages of fatigue failure*

Fatigue

- Fracture surface with crack initiation at top. Surface shows predominantly dull fibrous texture where rapid failure occurred after crack achieved critical size.

- Fatigue failure
  1. Crack initiation
  2. Crack propagation
  3. Final failure





Factors affecting Fatigue

- Surface irregularities like scratches, machining marks
- Presence of stress concentration points – notches, keyways, screw threads etc.
- Rate of cycling
- Environment in which component is functioning
- Temperature
- Stress gradient
- Size of the component

Protection against fatigue

- By preventing or delaying the initiation of cracks at the surface
- Methods
- Surface treatments

  a) shot peening

  b) surface rolling

  Carburising followed by hardening and nitriding

  Polishing the surface

  Preventing decarburisation while heat treatment
- Grain refinement
- Proper design

Thermal fatigue

- Thermal stress result when the change in dimensions of a member as a result of temperature change is prevented by some constraint
- Value of thermal stress, $\sigma = \alpha E \Delta T$
- Failure due to single application of thermal stress – thermal shock
- Failure after repeated application of thermal stress – thermal fatigue

Effect on metal cutting Tool life

- In machining operations in which there is interrupted cutting, heat is generated at each cut
- Thus tool is subjected to heating and cooling cycle
- If thermal conductivity is low and α high, tool failure can take place
- Careful selection of tool material to avoid tool failure due to thermal fatigue

Fatigue test

- Rotating beam test machine

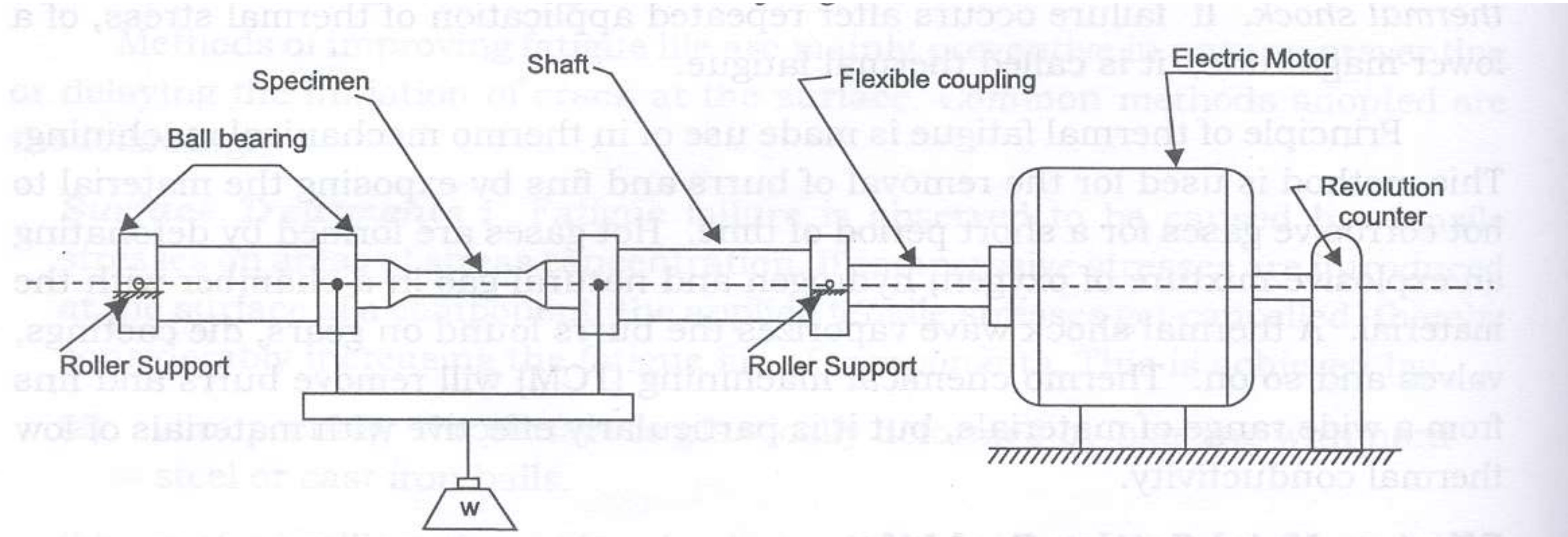


Figure 5.12 *Fatigue testing machine*