Module 5

Fatigue: - Stress cycles – Primary and secondary stress raisers - Characteristics of fatigue failure, fatigue tests, S-N curve. Factors affecting fatigue strength: stress concentration, size effect, surface roughness, change in surface properties, surface residual stress. Ways to improve fatigue life – effect of temperature on fatigue, thermal fatigue and its applications in metal cutting. Fracture: – Brittle and ductile fracture – Griffith theory of brittle fracture – Stress concentration, stress raiser – Effect of plastic deformation on crack propagation. transgranular, intergranular fracture - Effect of impact loading on ductile material and its application in forging, applications - Mechanism of fatigue failure. Structural features of fatigue: - crack initiation, growth, propagation - Fracture toughness (definition only) – Ductile to brittle transition temperature (DBTT) in steels and structural changes during DBTT, applications.

Fracture

- If the material is stressed beyond elastic limit, two things can happen;
  1. Material yield (deforming plastically to continued plastic deformation to 100% reduction in area then to complete rupture).
  2. Material ruptures without any visible sign of plastic deformation

The ultimate rupture or failure of material by breaking into two or more pieces, under the influence of an external load is called fracture.

- The applied stress can be compressive, tensile or shear
- Fracture is prominent over tension and

Fracture

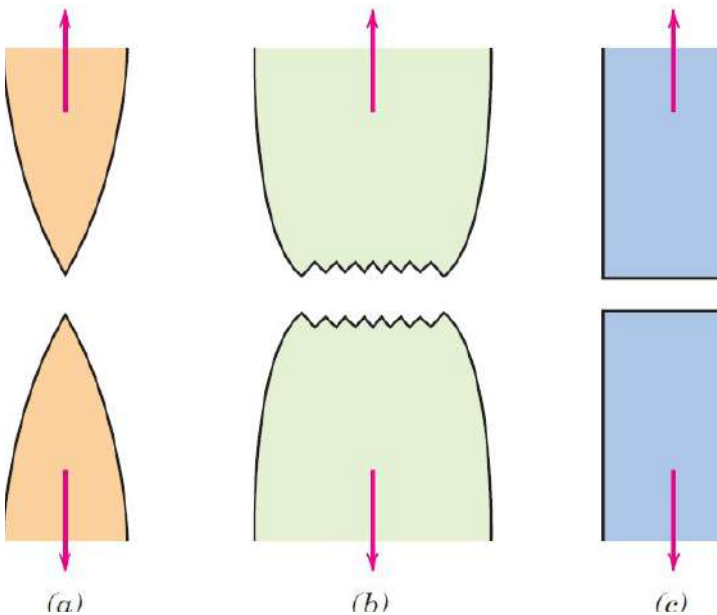
- Fracture is initiated by some kind of imperfection within the material, generally a microscopic crack.
- When the material is stressed, the crack acts like a notch and raises the stress at that point to a higher value.
- For engineering materials, two fracture modes are possible: ***ductile*** and ***brittle***.
- Classification is based on the ability of a material to experience plastic deformation.
- Ductile materials typically exhibit substantial plastic deformation with high energy absorption before fracture.
- On the other hand, there is normally little or no plastic deformation with low energy absorption accompanying a brittle fracture.
- Ductility may be quantified in terms of percent elongation and percent reduction in area.

Ductile and Brittle fracture

- Any fracture or failure involves two steps—**crack formation and propagation**—in response to an applied stress.
- The mode of fracture is highly dependent on the mechanism of crack propagation.
- Ductile fracture is characterized by extensive plastic deformation in the vicinity of an advancing crack, the process proceeds relatively slowly as the crack length is extended.
- Such a crack is often said to be stable (it resists any further extension unless there is an increase in the applied stress).
- For brittle fracture, cracks may spread extremely rapidly, with very little accompanying plastic deformation.
- Such cracks may be said to be unstable, and crack propagation, once started, will continue spontaneously without an increase in magnitude of the applied stress.

Ductile and Brittle fracture

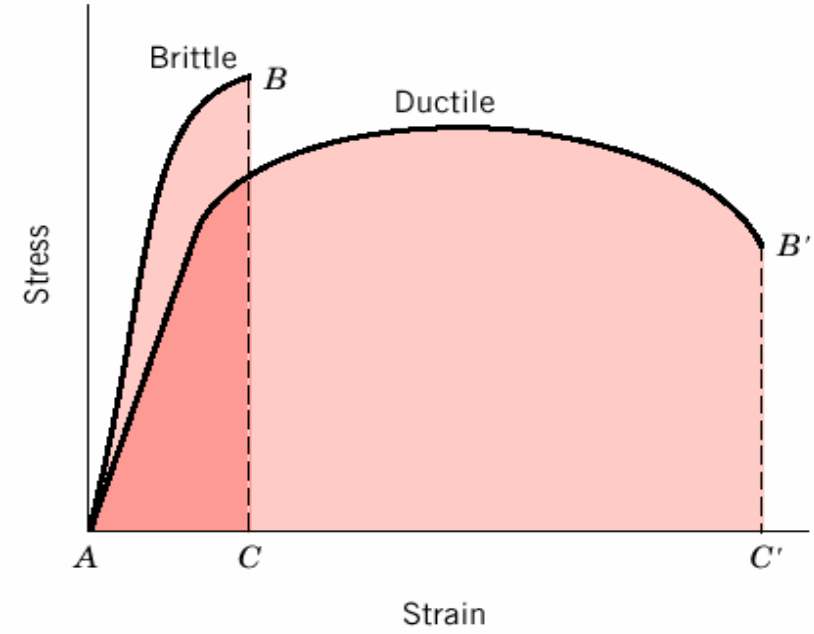
- Ductile fracture is almost always preferred for two reasons.
  - First, brittle fracture occurs suddenly and catastrophically without any warning; this is a consequence of the spontaneous and rapid crack propagation.
  - For ductile fracture, the presence of plastic deformation gives warning that fracture is forthcoming, allowing preventive measures to be taken.
  - Second, more strain energy is required to induce ductile fracture inasmuch as ductile materials are generally tougher.
- Under the action of an applied tensile stress, most metal alloys are ductile, whereas ceramics are notably brittle, and polymers may exhibit both types of fracture.



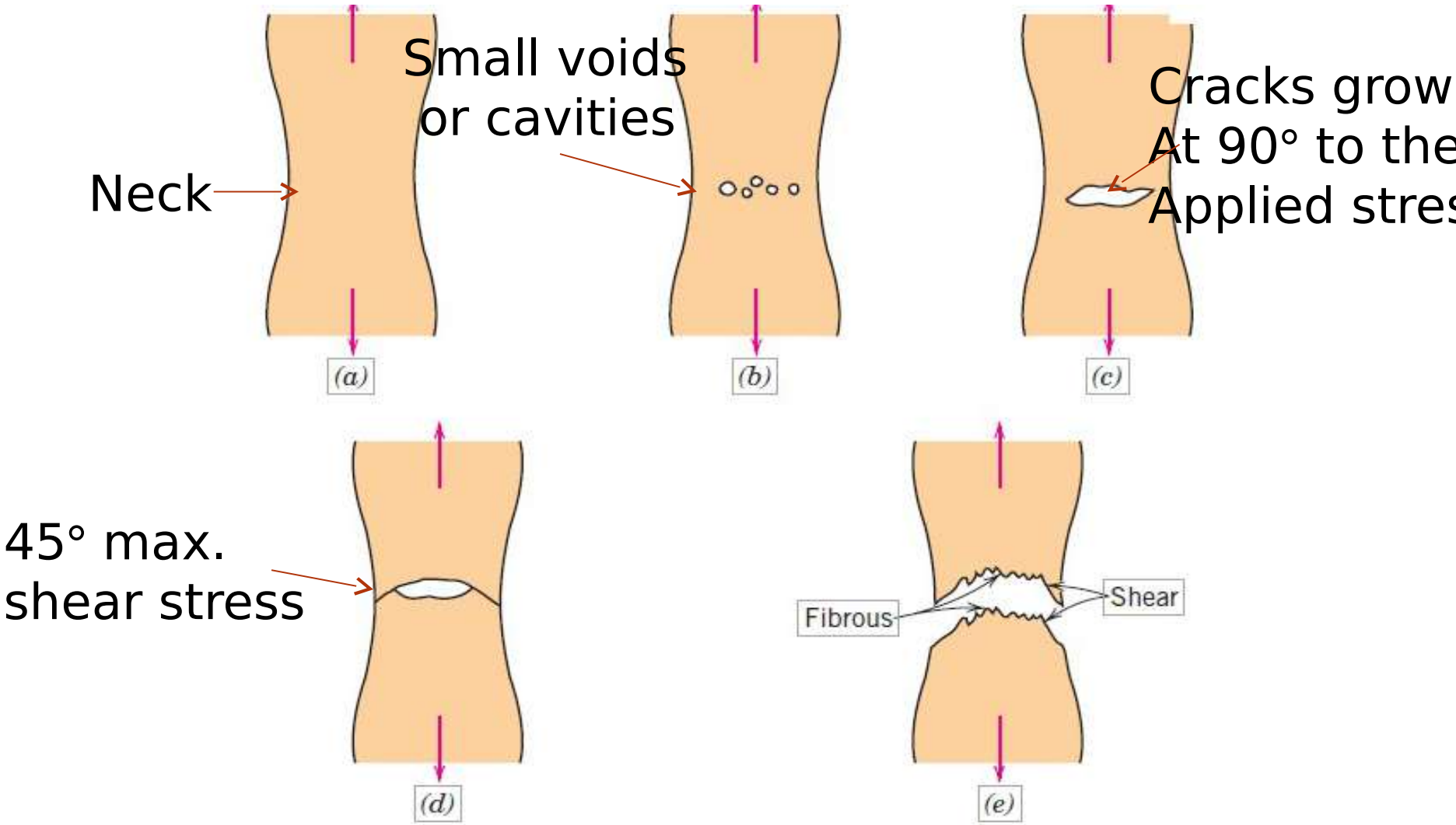
(a)Highly ductile fracture in which the specimen necks down to a point.
(b)Moderately ductile fracture after some necking.
(c)Brittle fracture without

Characteristics of ductile and brittle fracture

- In ductile fracture, some plastic deformation occurs before failure.
- Ductile fracture is evidenced by necking, during which a reduction in area take place.
- Highly ductile materials necks down to a point fracture.
- Ductile fractures occurs a



Stages in ductile fracture



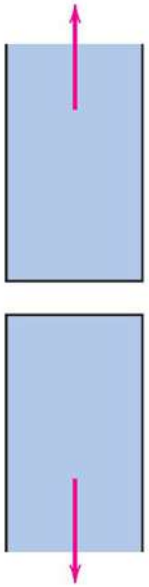
Stages in the cup-and-cone fracture. (a) Initial necking. (b) Small cavity formation. (c) Coalescence of cavities to

Stages in ductile fracture

- ***Stage 1: Necking***
  - In a ductile material, under a tensile stress, elastic deformation occurs up to a certain limiting stress.
  - As the stress is increased further plastic deformation occurs and a rapid reduction in cross sectional area occur and necked region appears.
- ***Stage 2: Cavity formation***
  - With in the neck region small cavities or voids are formed; as the impurities or other discontinuities in the materials gets separated by the application of stress.
- ***Stage 3: Crack formation***
  - On continued loading the microcracks enlarge and joins together to form a single crack. Mostly elliptical with major axis perpendicular to the load.
- ***Stage 4: Crack propagation***
  - Crack grow in the direction of the major axis of the elliptical crack; and finally, propagate to the surface by shearing at an angle of 45° to the direction of loading
- ***Stage 5: Fracture***
  - Once the failure occurs, one of the broken surface will be in the form of a cup and other like a cone. This type of fracture is called as cup and

Brittle fracture

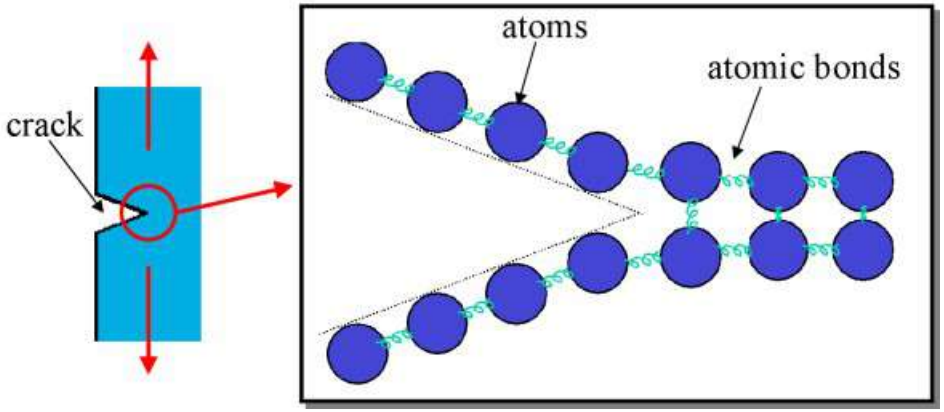
- Brittle fracture takes place without any appreciable deformation, and by rapid crack propagation.
- The direction of crack motion is very nearly perpendicular to the direction of the applied tensile stress and yields a relatively flat fracture surface.
- For most brittle crystalline materials, crack propagation corresponds to the successive and repeated breaking of atomic bonds along specific crystallographic planes with least atomic bonds; such a process is termed ***cleavage***.
- This type of fracture is said to be transgranular (or transcrystalline) or intragranular because the fracture cracks p through the grains.
- Macroscopically, the fracture surface may have a grainy or faceted texture as a result of changes in orientation of the cleavage planes from grain to grain.
- This type fracture found in BCC and HCP crystals.



Brittle fracture

Ductile and brittle fracture

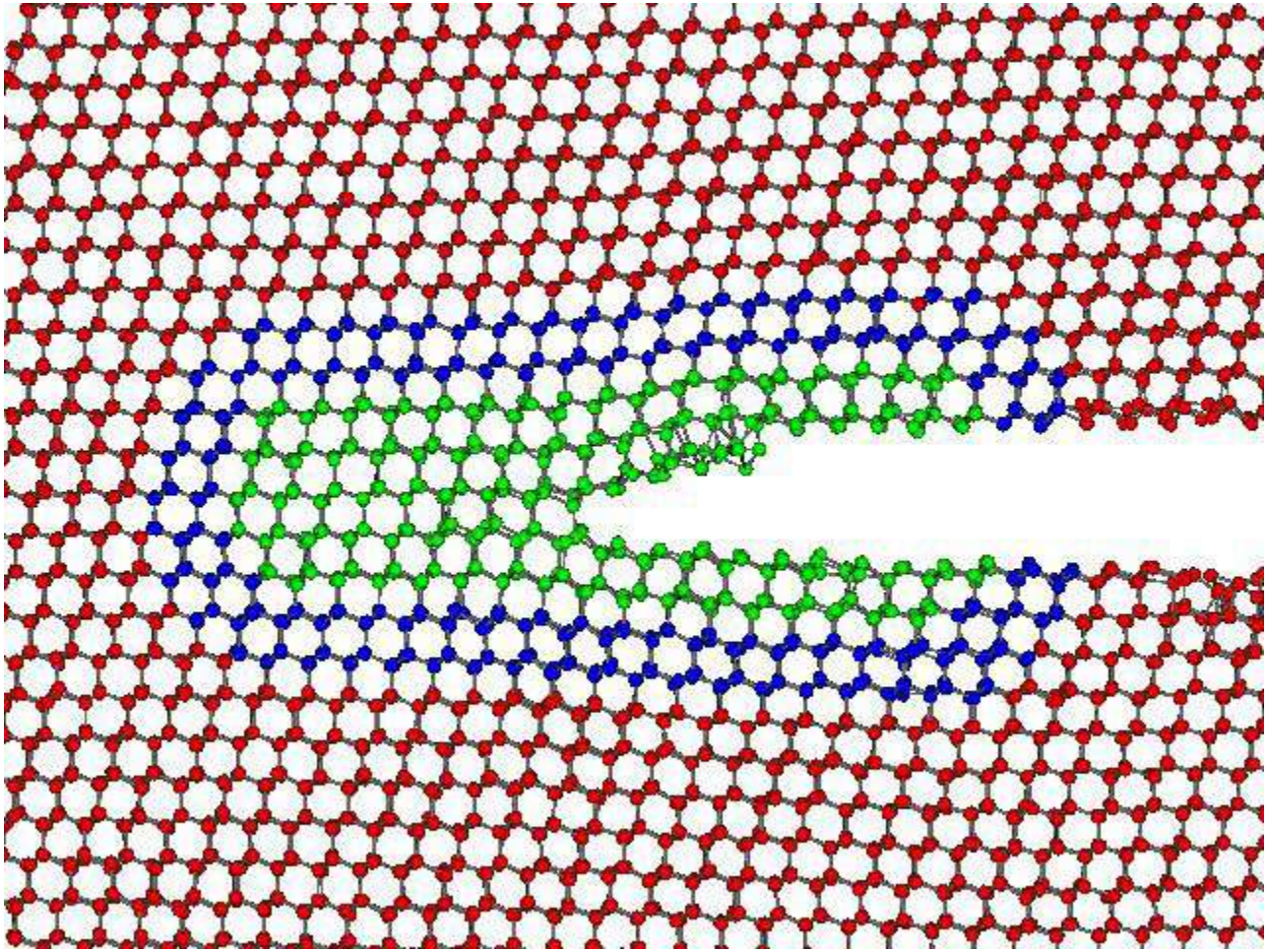
- Brittle fracture is a type of cleavage fracture resulting from the separation of two parallel atomic layers, until the cohesion force (which attracts atoms to one another) falls to zero.
- In a brittle fracture, we "tear" two atomic layers apart.
- This fracture occurs at the end of the elastic range of the stress-strain curve. It occurs suddenly, without any warning, so that failure is immediate.
- Naturally enough, this type of failure is particularly dangerous from the engineering perspective.
- Danger is of course maximal when engineers assume they've used a ductile material, but this material becomes surprisingly brittle under certain conditions.
- Ductile fracture is characterized by considerable plastic strain as the crack propagates. A material about to fracture this way "delivers prior notice".
- An ideal ductile fracture is created by sliding two atomic layers one over the other (shear stress), until both layers are fully separated.
- In the stress-strain curve, the ductile fracture will appear only after the maximal tensile stress, with necking observed in the process.



(a) Cup-and-cone fracture in aluminum. (b) Brittle fracture in a mild steel.

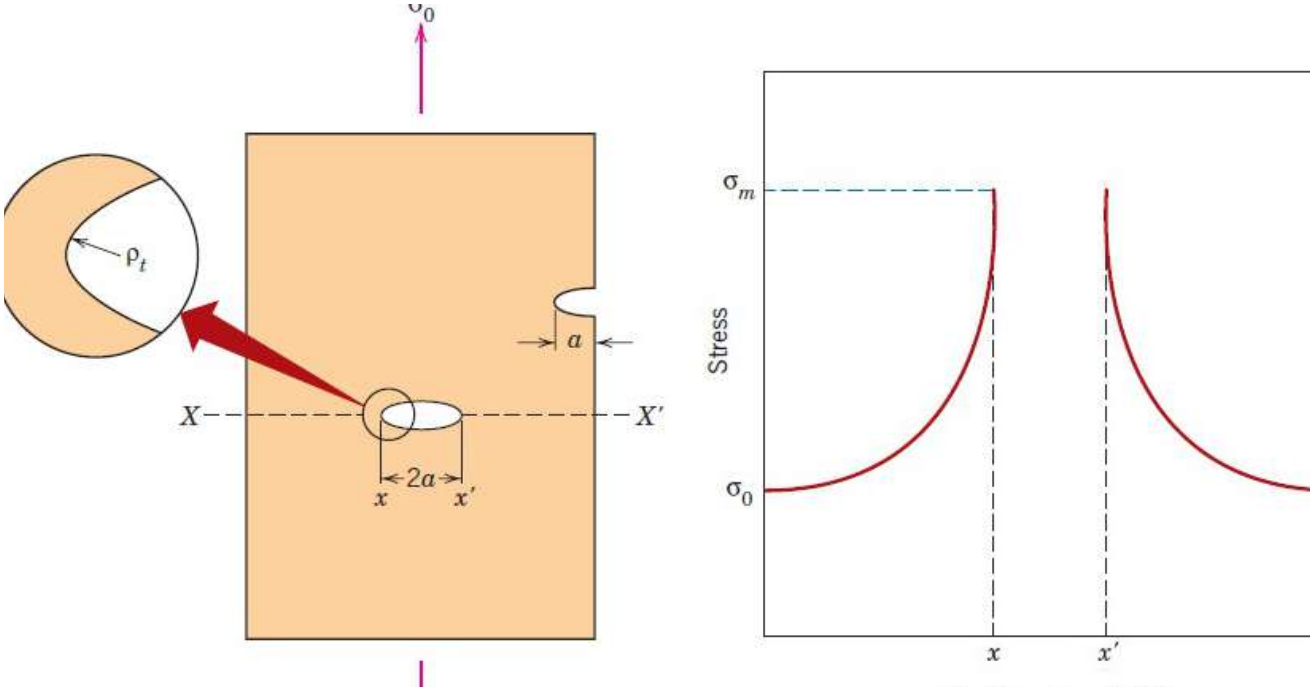
Griffith's theory of fracture

- The fracture strength of many brittle materials are lower than their theoretical values based on atomic bonding energies.
- The failure occurs at a fraction of theoretical strength of the material, this discrepancy is explained by Griffith.
- According to Griffith, the discrepancy in the actual and theoretical strength is due to the presence of very small, microscopic flaws or cracks that always exist under normal conditions at the surface and within the interior of a body of material.
- These flaws can deteriorate the fracture strength because the applied stress may be amplified or concentrated at the tip, the magnitude of this amplification depending on crack orientation and geometry, which is called **stress concentration**.



Griffith's theory of fracture

- In a stress profile across a cross section containing an internal crack, applied stress may be amplified or concentrated at the tip and the magnitude of this localized stress diminishes with distance away from the crack tip.
- This much lower fracture strength is explained by the effect of stress concentration at microscopic flaws. The applied stress is amplified at the tips of micro-cracks, voids, notches, surface scratches, corners, etc. that are called stress raisers.
- Due to their ability to amplify an applied stress in their locale, these flaws are sometimes called **stress raisers.**



Griffith's theory of fracture

- If it is assumed that a crack is similar to an elliptical hole through a plate, and its major axis is perpendicular to the applied stress, the maximum stress, σ_m, occurs at the crack tip and may be approximated by

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

  - σ_0-magnitude of applied stress
  - a- length of an external crack or half the length of an internal crack
  - ρ_t- radius of curvature at the crack tip
- For a relatively long microcrack, that has a small tip radius of curvature, the factor $\left(\frac{a}{\rho_t}\right)^{1/2}$ will be very large; σ_m will be many times than σ_0.
- The ratio σ_m / σ_0 is defined as the ***stress concentration factor***.

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

- ***Stress concentration factor*** is a measure of the degree to which an external stress is amplified at the tip of a crack.
- The effect of a stress raiser is more significant in brittle than

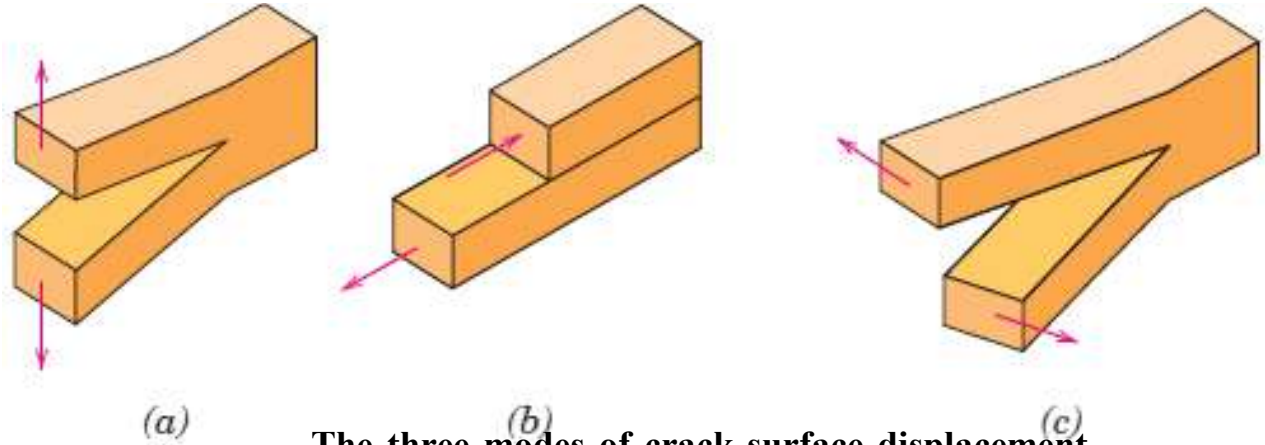
Crack propagation

- A crack will propagate when the decrease in elastic strain energy is at least equal to the energy required to create a new crack surface.
- Using principles of fracture mechanics, it is possible to show that the critical stress σ_c required for crack propagation in a brittle material is described by the expression;

$$\sigma_c = \left(\frac{2E\gamma_s}{\pi a}\right)^{1/2}$$

- The stress required to propagate crack in a brittle material is a function of microcrack.
- When critical stress is applied to a brittle material; the pre-existing crack propagate spontaneously with a decrease in energy, leading to failure.

propagation

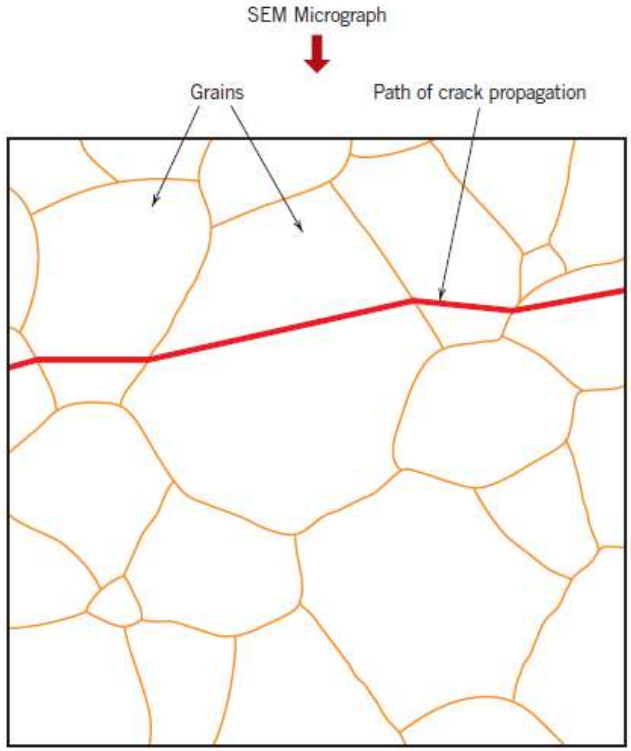


The three modes of crack surface displacement (a) Mode I, opening or tensile mode; (b) mode II, sliding mode; and (c) mode III, tearing mode

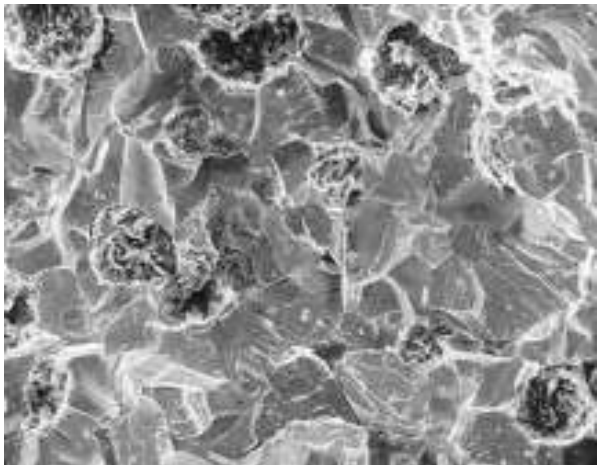
- There are three ways of applying a force to enable a crack to propagate:
  - **Mode I** fracture – Opening mode (a tensile stress normal to the plane of the crack),
  - **Mode II** fracture – Sliding mode (a shear stress acting parallel to the plane of the crack and perpendicular to the crack front), and
  - **Mode III** fracture – Tearing mode (a shear stress acting parallel to the plane of the crack and parallel to the crack

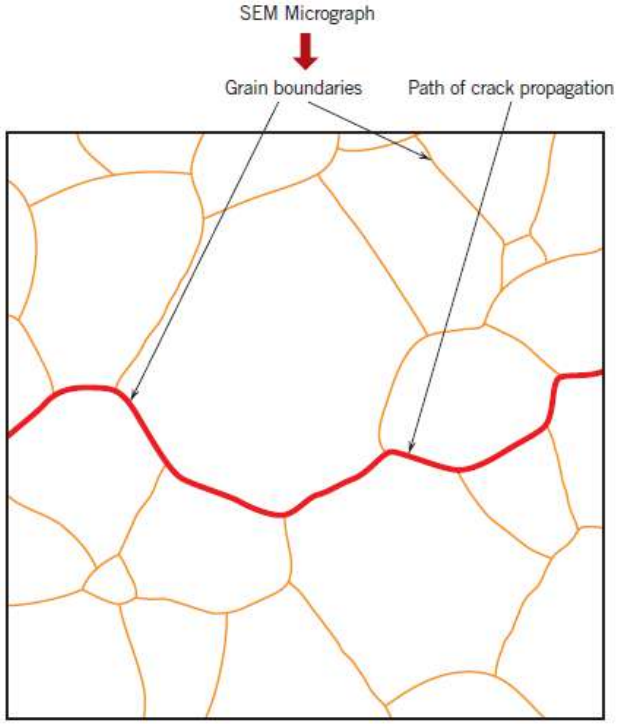
Transgranular and intergranular fracture

- For most brittle crystalline materials, crack propagation corresponds to the successive and repeated breaking of atomic bonds along specific crystallographic planes; such a process is termed **cleavage**.
- This type of fracture is said to be *transgranular* or *intragranular* (or transcrystalline), because the fracture cracks pass through the grains.
- Macroscopically, the fracture surface may have a grainy or faceted texture, as a result of changes in orientation of the cleavage planes from grain to grain.
- In some alloys, crack propagation is along grain boundaries; this fracture is termed intergranular.

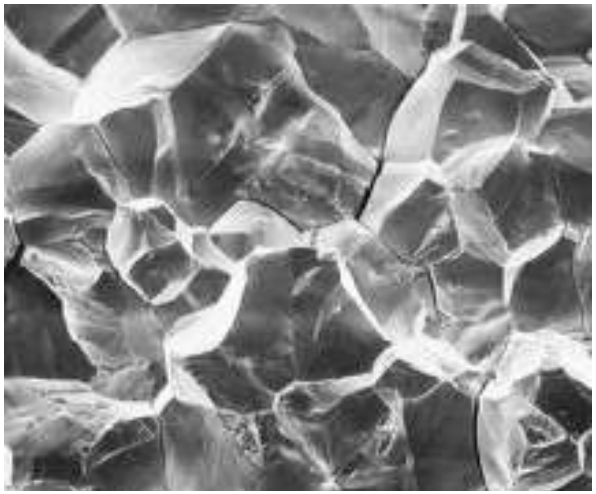


Transgranular fracture





Intergranular fracture



Fracture Toughness

- Using fracture mechanical principles, an expression has been developed that relates this critical stress for crack propagation (σ_c) and crack length (a) as;

$$K_c = Y\sigma_c\sqrt{\pi a}$$

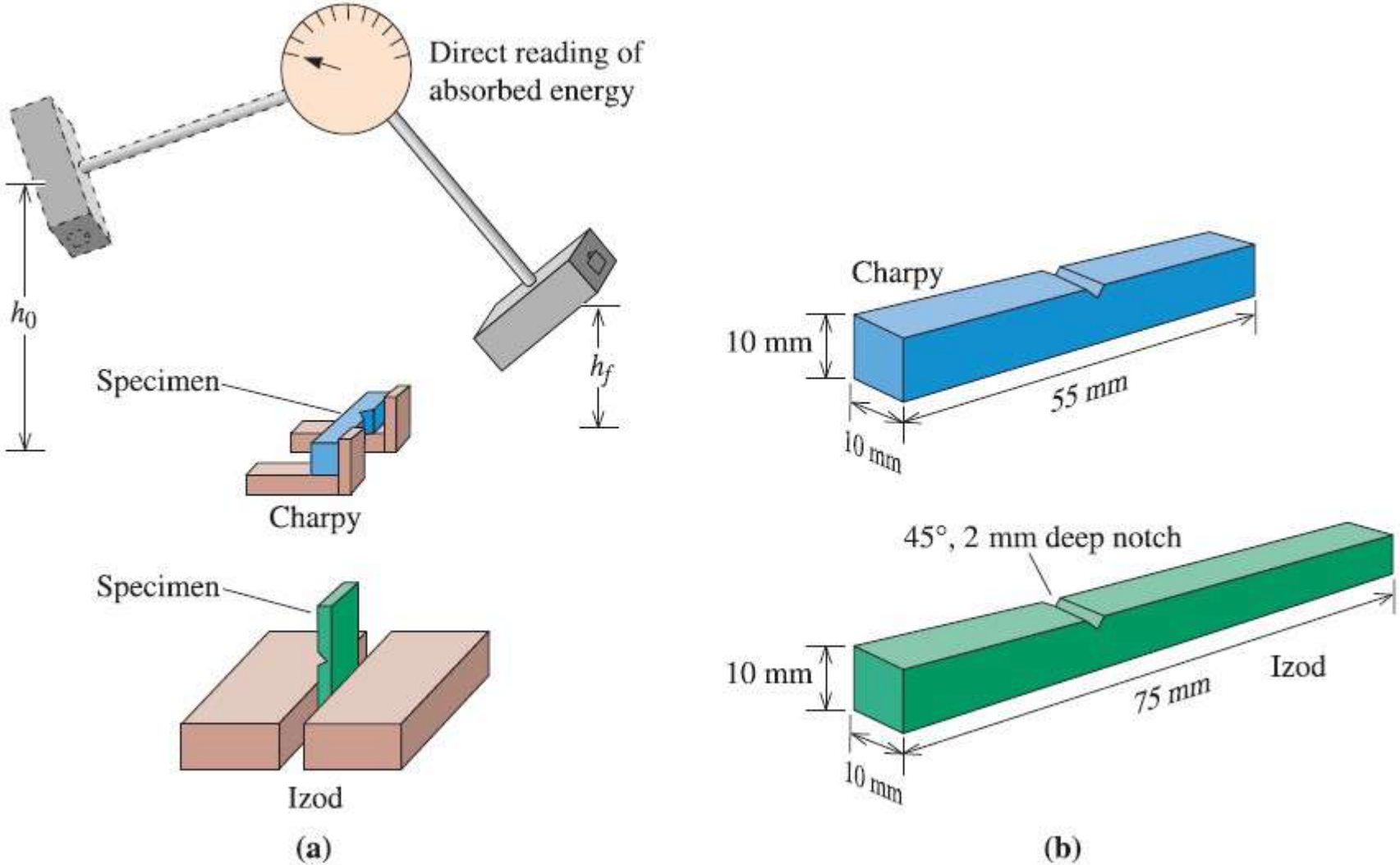
- K_c is the **fracture toughness**, a property that is a measure of a material's resistance to brittle fracture when a crack is present.
- Worth noting is that K_c has the units of MPa√m or psi√in.
- Y is a dimensionless parameter or function that depends on both crack and specimen sizes and geometries, as well as the manner of load application.

Ductile to brittle transition

- Under some circumstances, ductile material fracture abruptly with very little plastic deformation.
- This transformation occurs when the crack propagation precedes over the plastic deformation.
- Ductile to brittle transition can occur in three circumstances;
  - The temperature is lowered.
  - The rate of straining is increased
  - A notch or stress raiser is introduced to

Impact loads

- An impact load is a dynamic load; where load is suddenly applied.
- **When a material is subjected to a sudden, intense blow, in which the strain rate is extremely rapid, it may behave in much more brittle a manner than is observed in the tensile test.**
- Its effect is much grater than a steady load of same magnitude.
- Impact test is used to measure the toughness of the material, *a measure on the capacity of a material to store strain energy before it fails*.
- High toughness is exhibited by materials with high strength and ductility.
- During impact loads, the ductile materials with voids and cracks will behave like brittle materials, and it is not indicated in tensile tests.
- A brittle material requires less energy to break and hence lacks toughness than pure ductile materials.
- Impact test are particularly useful for finding the ductile to brittle transition characteristics of materials.
- The main objective of impact tests is to select materials with high



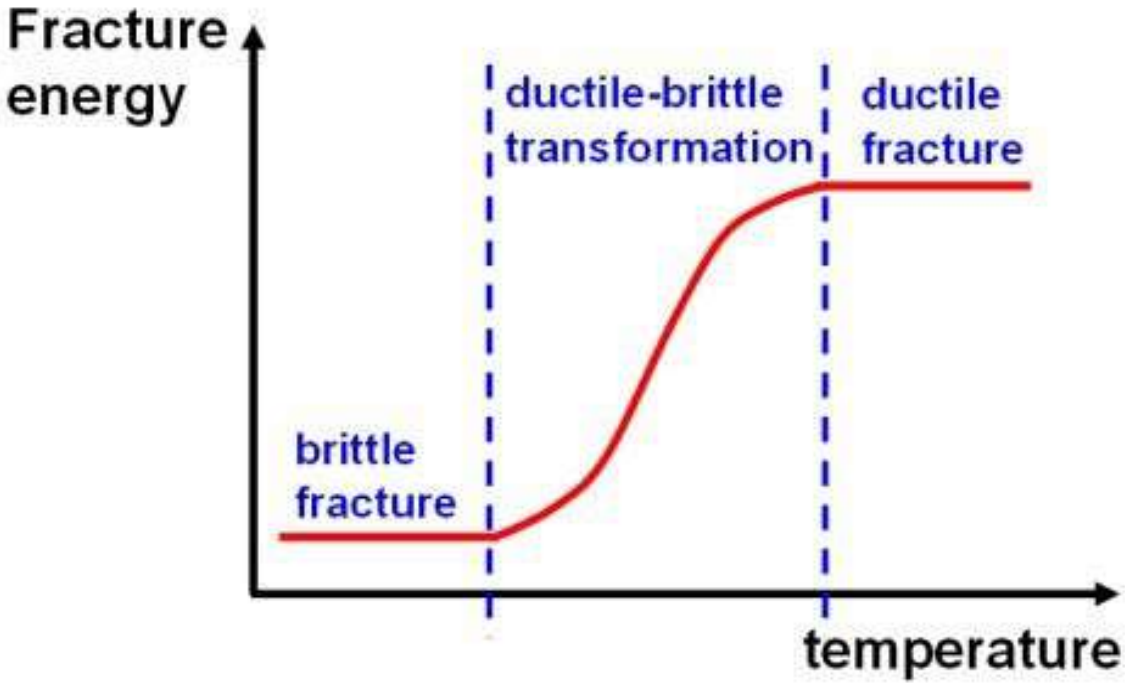
Two standard tests, the **Charpy** and **Izod,** measure the **impact energy** (the energy required to fracture a test piece under an impact load), also called the notch toughness.

Application in forging

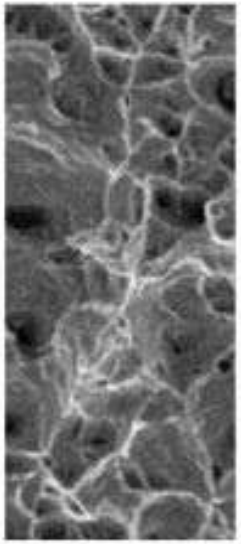
- In forging process the forces are applied on the raw material such that the stresses induced are greater than yield and less than ultimate strength so that material is experiencing plastic or permanent deformation to get required shape.
- But in forging operation force applied can be either continuous or intermittent impact loads.
- There are two kinds of **forging** process, **impact forging** and press **forging**. In the former, the **load** is applied by **impact**, and deformation takes place over a very short time. Press **forging**, on the other hand, involves the gradual build up of pressure to cause the metal to yield. The time of **application** is relatively long.

Ductile to brittle transition temperature

- The **ductile to brittle transition temperature** is the temperature at which the failure mode of a material changes from ductile to brittle fracture.
- This temperature may be defined by the average energy between the ductile and brittle regions, at some specific absorbed energy, or by some characteristic fracture appearance.
- **A material subjected to an impact blow during service should have a transition temperature below the temperature of the material's surroundings.**
- Not all materials have a distinct transition temperature.
- BCC metals have transition temperatures, but most FCC metals do not. FCC metals have high absorbed energies, with the energy decreasing gradually and, sometimes, even increasing as the temperature decreases.
- The effect of this transition in steel may have contributed to the failure of the Titanic.
- In polymeric materials, the ductile to brittle transition temperature is related closely to the glass-transition temperature and for practical purposes is treated as the same.
- The transition temperature of the polymers used in booster rocket O-rings and other factors led to the Challenger disaster.



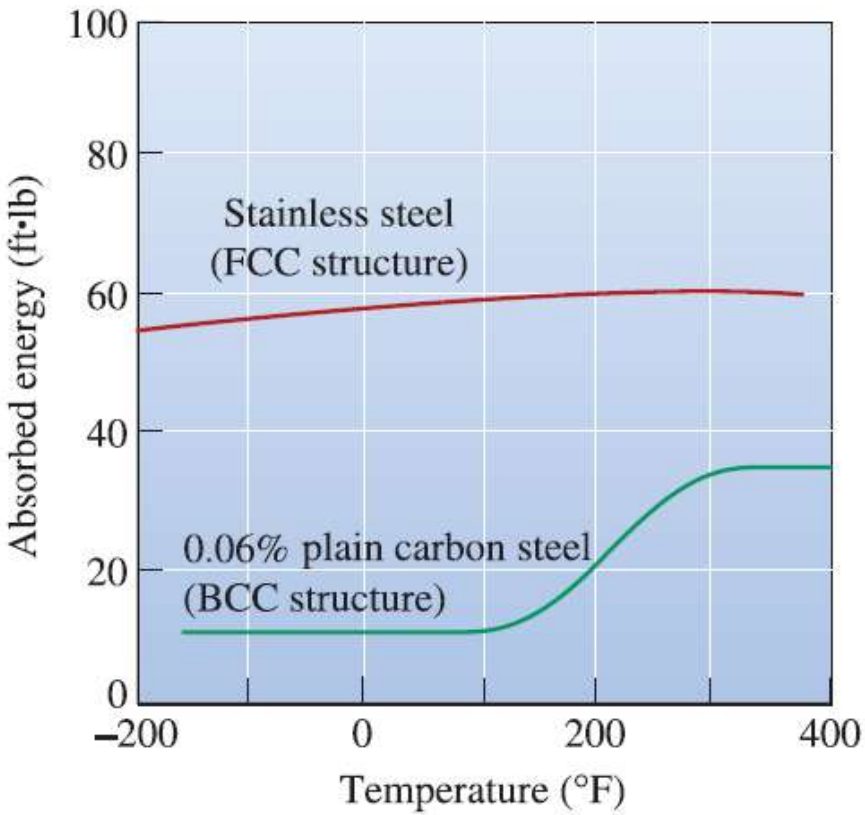
brittle fracture surface



ductile fracture surface

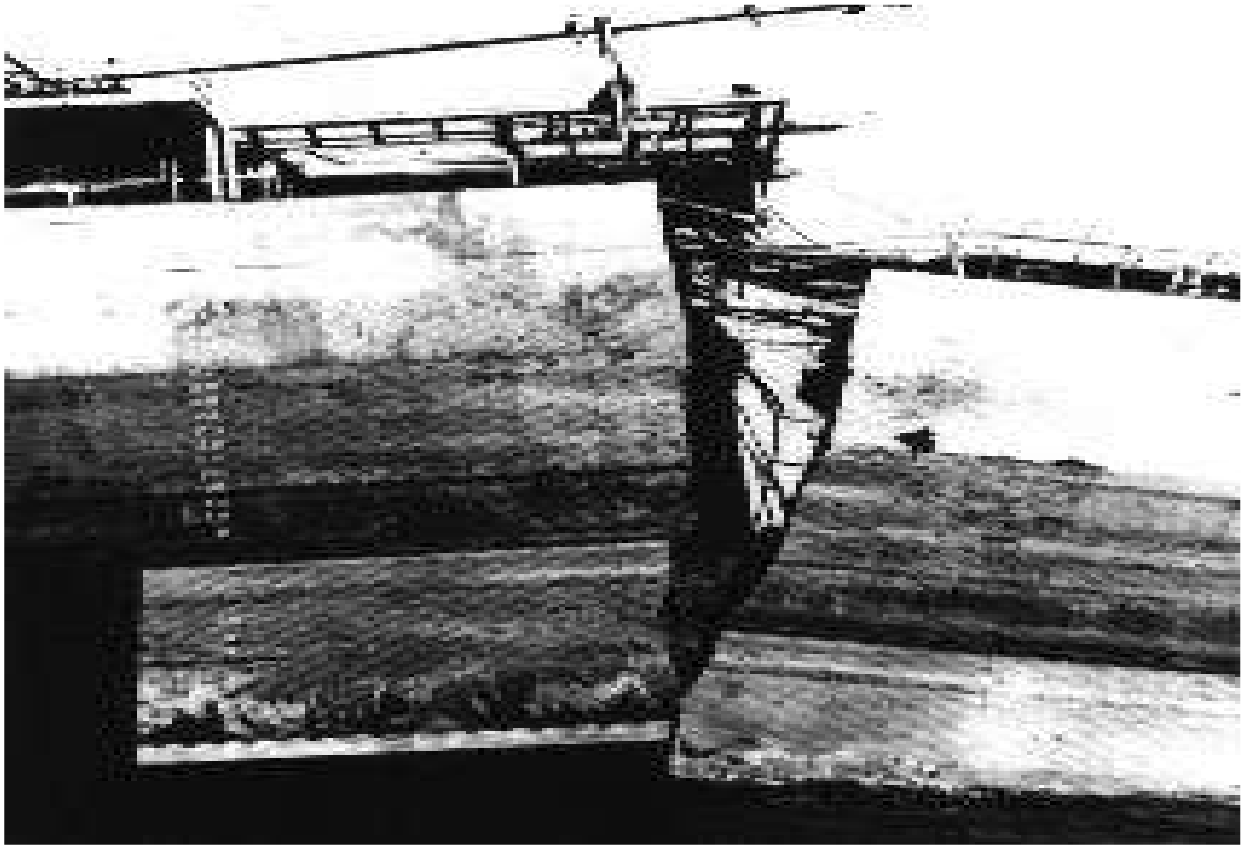
Ductile to brittle transition temperature in steels

- In materials with a BCC structure – steels mostly – an extreme change in fracture energy is observed within a certain temperature range.
- Above a certain temperature, the material is ductile, requiring relatively high energy to fracture it; below this point, the material becomes brittle and requires very low energy to fracture.
- This material behavior is called ductile-to-brittle transition. The temperature at which this phenomenon occurs is called ductile-to-brittle transition temperature.
- Thus, in BCC steels, under conditions of sudden load and low temperatures, brittle fracture without deformation occurs.
- Ductile-to-brittle transitions have also been observed in polymers, due to elasticity loss.
- On the other hand, in FCC-structured crystalline materials, the fracture energy changes with temperatures in a gradual fashion.



The Charpy V-notch properties for a BCC carbon steel and an FCC stainless steel. The FCC crystal structure typically leads to higher absorbed

Ductile-to-brittle transition



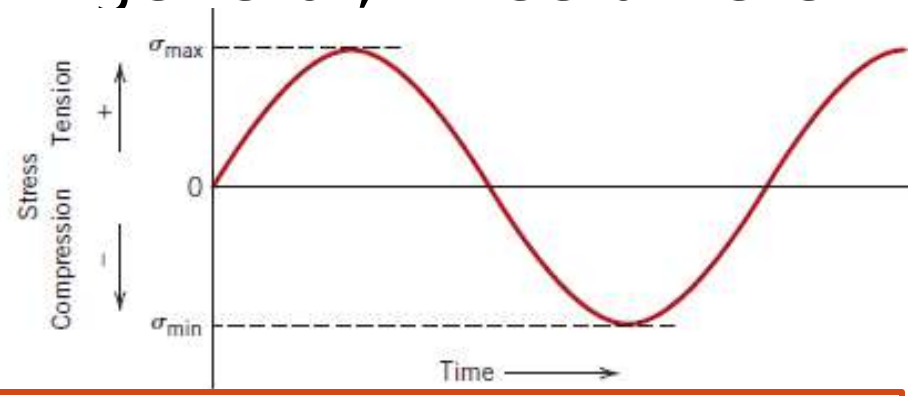
Low temperatures can severely embrittle steels. The Liberty ships, produced in great numbers during the WWII were the first all-welded ships. A significant number of ships failed by catastrophic fracture. Fatigue cracks nucleated at the corners of square hatches and propagated rapidly by brittle fracture.

Fatigue

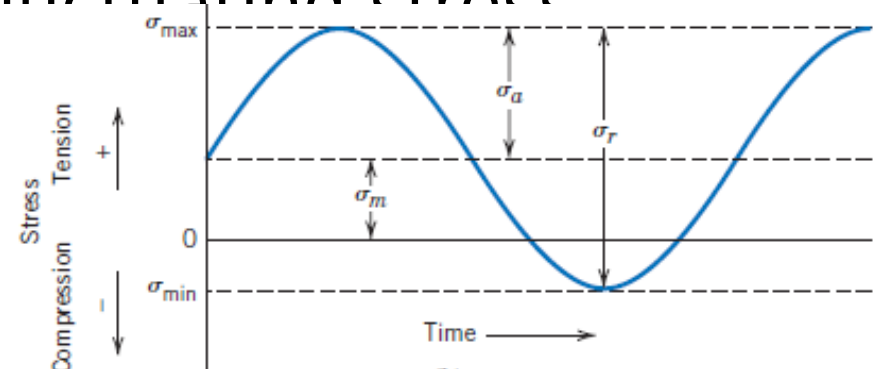
- Under fluctuating / cyclic stresses, failure can occur at loads considerably lower than tensile or yield strengths of material under a static load: **Fatigue.**
- Estimated to causes 90% of all failures of metallic structures (bridges, aircraft, machine components, etc.) are by cyclic stress
- Fatigue failure is brittle-like (relatively little plastic deformation) - even in normally ductile materials. Thus sudden and catastrophic!
- The term “fatigue” is used because this type of failure normally occurs after a lengthy period of repeated stress or strain cycling.
- Fatigue failure proceeds in three distinct stages: crack initiation in the areas of stress concentration (near stress raisers), incremental crack propagation, final catastrophic failure.

Cyclic stresses

- The applied stress may be axial (tension-compression), flexural (bending), or torsional (twisting) in nature.
- In general, three different fluctuating stress



Periodic and symmetrical about zero stress



Periodic and asymmetrical about zero stress

Fatigue: Cyclic Stresses (II)

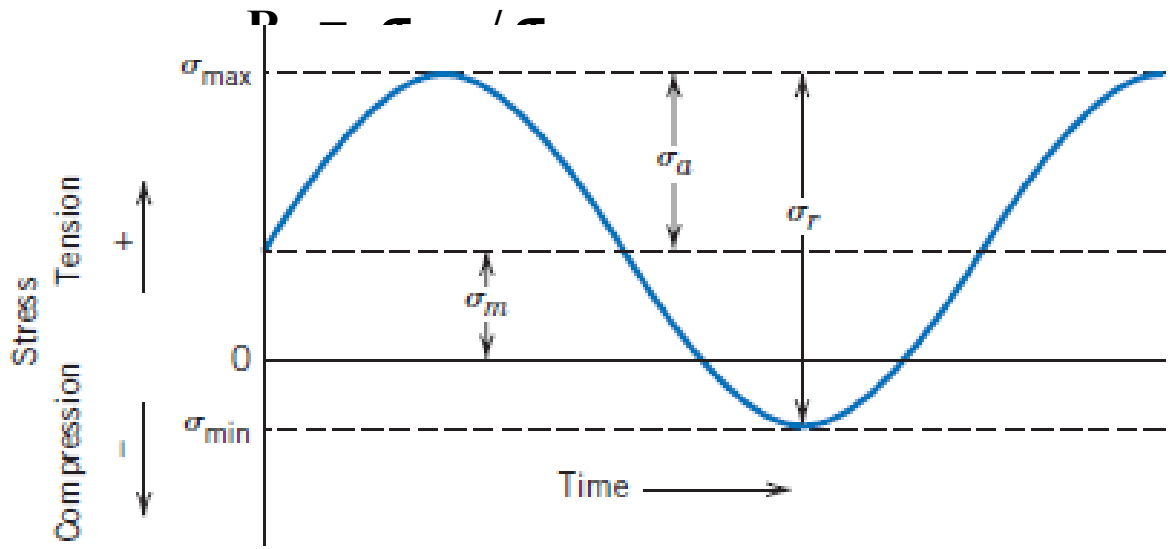
Cyclic stresses are characterized by maximum, minimum and mean stress, the range of stress, the stress amplitude, and the stress ratio

Mean stress: Range of $\sigma_m = (\sigma_{max} + \sigma_{min}) / 2$

stress: Stress $\sigma_r = (\sigma_{max} - \sigma_{min})$

Stress amplitude: $\sigma_a = \sigma_r/2 = (\sigma_{max} - \sigma_{min}) / 2$

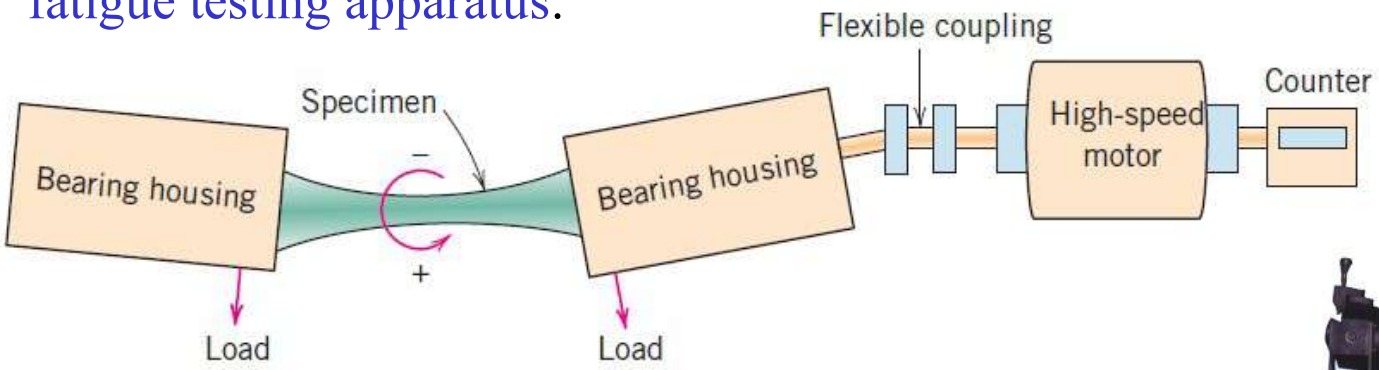
Stress ratio:



Remember the convention that tensile stresses are positive, compressive

Fatigue: Testing

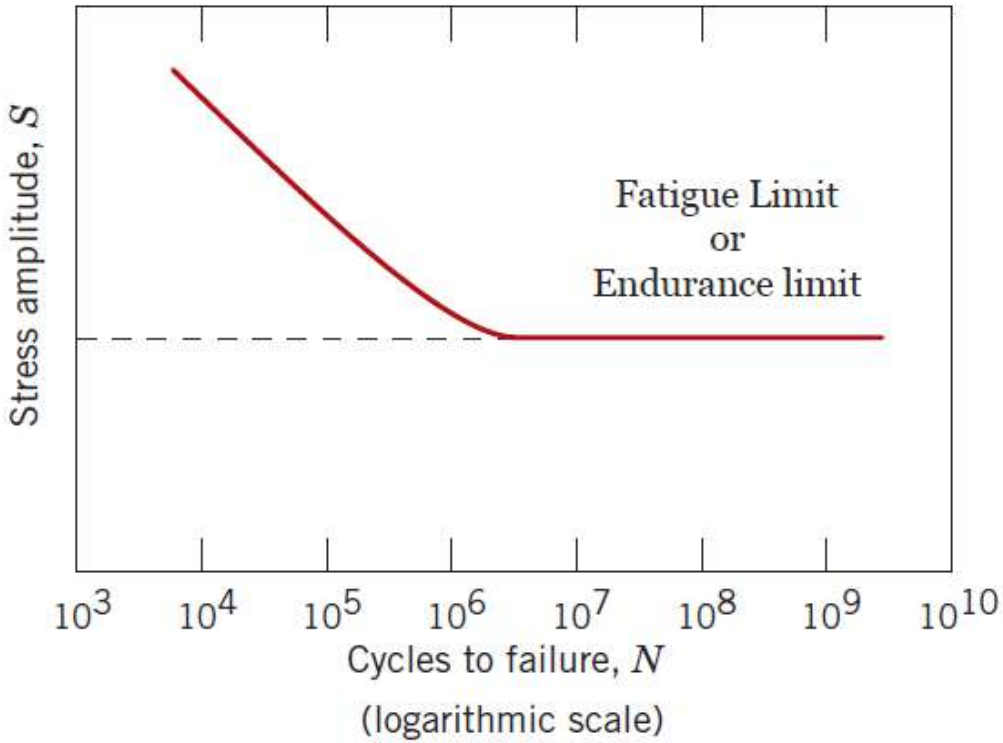
Fatigue properties of a material (S-N curves) are tested in rotating-bending tests in fatigue testing apparatus:



- Fatigue test are performed to determine the capacity of a material to withstand repeated cyclic stresses.
- The machine has an electric motor, bearings and collects to support and hold the machine for test.
- A revolution counter, counts the number of rotations.
- A dead weight is attached at the center of the specimen.

- The number of cycles for failure, depend on the value of applied stress.
- For a high stress the number of cycles will be less and for a lower stress, the number of cycles before failure will be more or large in number.
- Below a certain ultimate value of stress; the failure will not happen even after infinite number of cycles, this value of stress is called ***endurance limit*** or ***fatigue limit***.
- A series of tests are commenced by subjecting a specimen to the stress cycling at a relatively large maximum stress amplitude (σ_{max}), usually on the order of two-thirds of the static tensile strength; the number of cycles to failure is counted.
- This procedure is repeated on other specimens at progressively decreasing maximum stress amplitudes.
- Data are plotted as ***stress* (S)** versus the logarithm of ***the number of cycles to failure* (N)** for each of the specimens.

Fatigue: S-N curves



- **Fatigue limit** (endurance limit) occurs for some materials (e.g. some Fe and Ti alloys). In this case, the S—N curve becomes horizontal at large N.
- The fatigue limit is a maximum stress amplitude below which the material never fails, no matter how large the number of cycles is.
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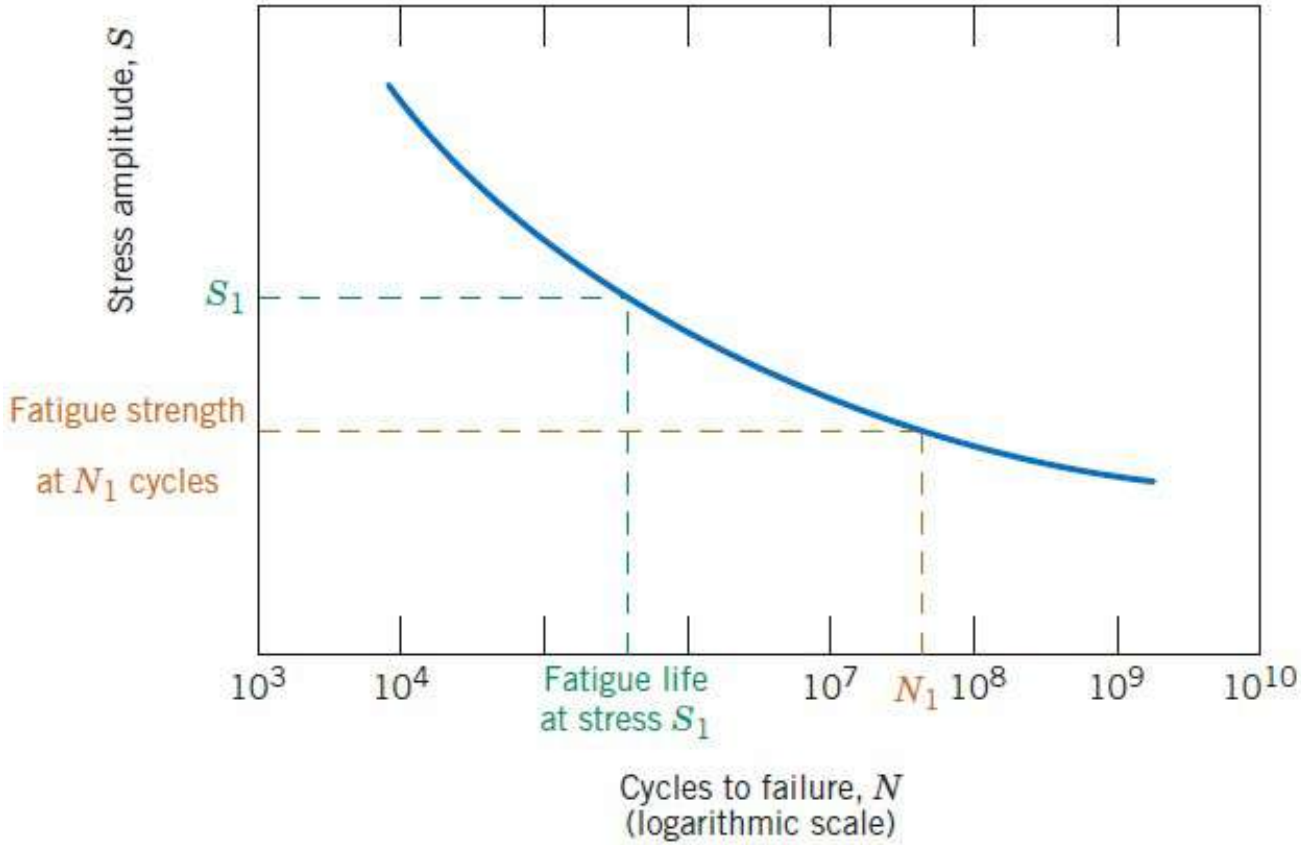
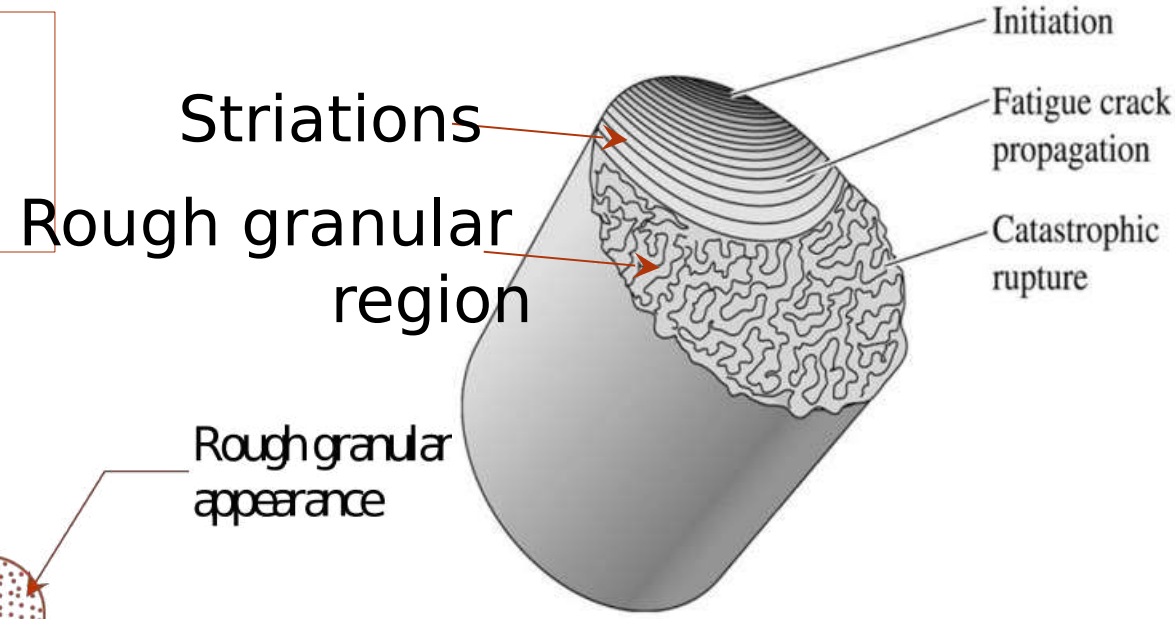


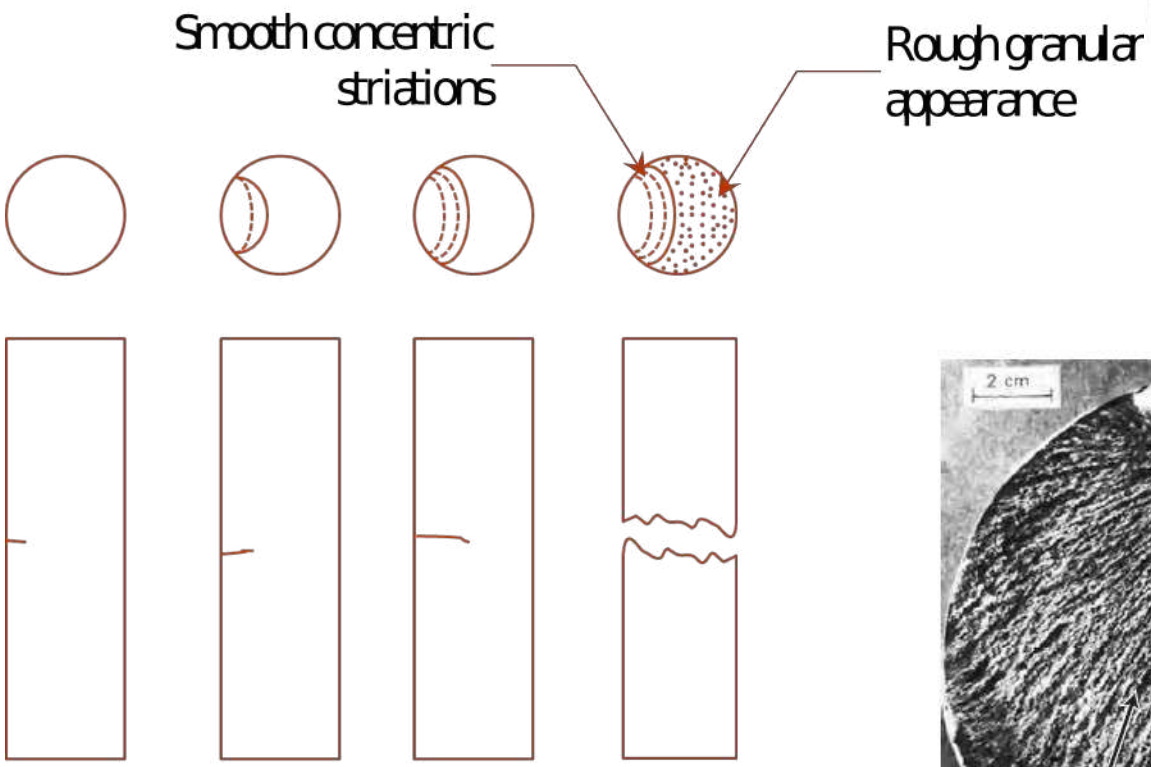
- For materials not having fatigue limit, fatigue will ultimately take place regardless of the magnitude of stress.
- **Fatigue strength,** which is defined as the stress level at which failure will occur for some specified number of cycles.
- A material's fatigue behavior is also characterized by **fatigue life** N_f, a measure of on the number of cycles to cause failure at a specified stress level, as taken from the S–N plot

Mechanism of fatigue

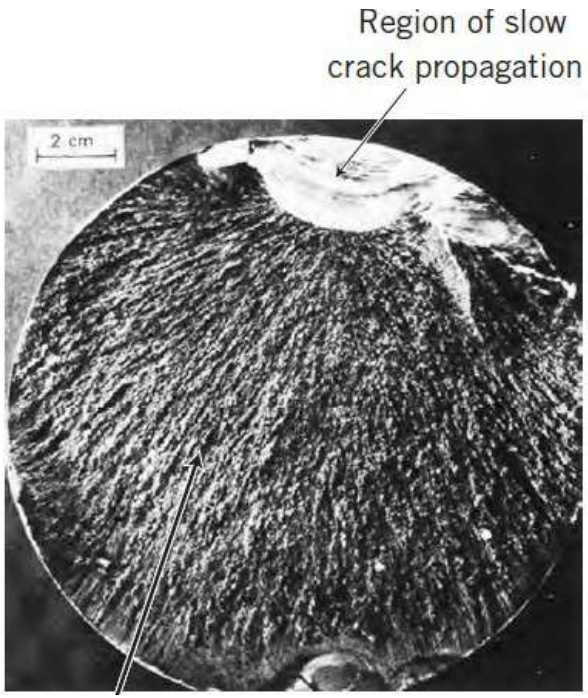
- The process of fatigue failure is characterized by three distinct steps:
  1. **Crack initiation**, wherein a small crack forms at some point of high stress concentration;
  2. **Crack propagation**, during which this crack advances incrementally with each stress cycle;
  3. **Final failure**, which occurs very rapidly once the advancing crack has reached a critical size.
- Cracks associated with fatigue failure almost always initiate (or nucleate) from the surface of a component at some point of stress concentration.
- Crack nucleation sites include surface scratches, sharp fillets, keyways, threads, dents, and the like.
- In addition, cyclic loading can produce microscopic surface discontinuities resulting from dislocation slip steps that may also act as stress raisers, and therefore as crack

Mechanism of Fatigue





Stages of fatigue failure



Factors affecting fatigue life

Mean Stress or stress gradient

- The dependence of fatigue life on stress amplitude is represented on the S–N plot.
- Such data are taken for a constant mean stress σ_m,. Mean stress, will also affect fatigue life, an increase in the mean stress level leads to a decrease in fatigue life.

Surface Effects

- For many common loading situations, the maximum stress within a component or structure occurs at its surface.
- Most cracks leading to fatigue failure originate at surface positions, specifically at stress amplification sites. Therefore, the fatigue life is especially sensitive to the condition and configuration of the component surface.

Design Factors

- The design of a component can have a significant influence on its fatigue characteristics.

Factors affecting fatigue life

Size effect

- Size of the component has no effect on fatigue life, however as the size increases, large components have less fatigue life because of the large number of defects present in them.

Rate of cycling

- This has small effect on fatigue life, fatigue strength generally increase with the rate of cycling due to the increased strain rate during rapid cycling.

High temperature

- An increase in temperature above room temperature can reduce fatigue life.
- This increment is due to an increase in the crack growth rate at high temperature

Environment factors

- Environmental factors have a remarkable effect on fatigue life.

Protection against fatigue

Surface Treatments

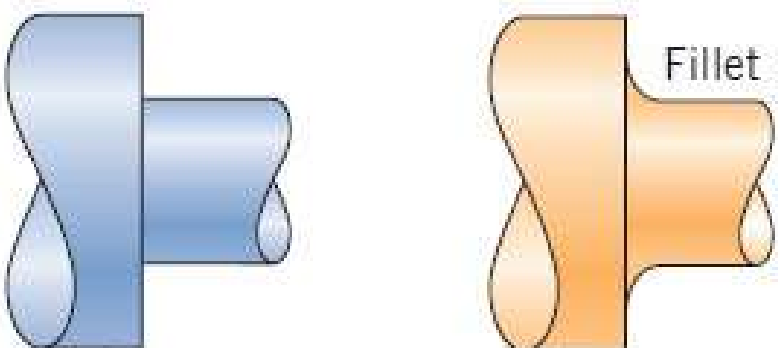
- During machining operations, small scratches and grooves are invariably introduced into the work piece surface by cutting tool action. These surface markings can limit the fatigue life.
- It has been observed that improving the surface finish by polishing will enhance fatigue life significantly.
- One of the most effective methods of increasing fatigue performance is by imposing residual compressive stresses within a thin outer surface layer. Thus, a surface tensile stress of external origin will be partially nullified and reduced in magnitude by the residual compressive stress. The net effect is that the likelihood of crack formation and therefore of fatigue failure is reduced.
- Residual compressive stresses are commonly introduced into ductile metals mechanically by localized plastic deformation within the outer surface region.
  - Commercially, this is often accomplished by a process termed shot peening. Small, hard particles (or shot) having diameters within the range of 0.1 to 1.0 mm are projected at high velocities onto the surface to be treated. The resulting deformation induces compressive stresses to a depth of between one-quarter and one-half of the shot diameter.
- Case hardening is a technique by which both surface hardness and fatigue life are enhanced for steel alloys. This is accomplished by a carburizing or nitriding process whereby a component is exposed to a carbonaceous or

Protection against fatigue

Proper design

- The design of a component can have a significant influence on its fatigue characteristics. Any notch or geometrical discontinuity can act as a stress raiser and fatigue crack initiation site; these design features include grooves, holes, keyways, threads, and so on.
- The sharper the discontinuity (i.e., the smaller the radius of curvature), the more severe the stress concentration.
- The probability of fatigue failure may be reduced by avoiding these structural irregularities, or by making design modifications whereby sudden contour changes leading to sharp corners are eliminated—for example, calling for rounded fillets with large radii of curvature at the point where there is a change in diameter for a rotating shaft.

Grain refinement *is also an alternate method for achieving*



Thermal fatigue

- Stresses which produce fatigue failure at high temperature need nit always result from mechanical sources.
- Thermal stresses result when the change in dimension of a member as a result of temperature change is prevented by some kind of constraint.
- If a bar with fixed support is heated, thermal stresses will develop by temperature change, which is given by;

$$\sigma = \alpha E \Delta T$$

  - Where, α-linear thermal coefficient of expansion
    E- Elastic modulus
    ΔT-Change in temperature
- If the failure occurs by a single application of stress, then it is called thermal shock.
- If the failure occurs by repeated application of thermal stress of a lower magnitude, then it is called as thermal fatigue.

Application of thermal fatigue in machining

- Principle of thermal fatigue is made use of in thermo mechanical machining.
- This method is used for the removal of burrs and fins by exposing the material to hot corrosive gases for a short period of time.
- Hot gases are formed by detonating an explosive mixture of oxygen, hydrogen and natural gas in a chamber with the material.
- A thermal shock wave vaporizes the burrs found on gears, die castings, valves and so on.
- Thermo chemical machining (TCM) will remove burrs and fins from a wide range of materials, but it is particularly effective with materials of low thermal conductivity.

Effect of thermal fatigue on metal cutting tool life

- Another area where thermal fatigue becomes significant is in metal cutting tool life.
- In machining operations in which there is interrupted cutting, such as milling, heat is generated at each cut.
- Thus the tool is subjected to a heating and a cooling cycle.
- If the thermal conductivity of the tool is low, and the coefficient of thermal expansion is high, tool failure can take place soon.
- Similar situation can happen in the case of hot forging dies.
- To avoid such situation, tool failure due to