Breakage mechanism of materials

First of all we should define breakage or fracture of materials:-

Fracture or breakage of material is the separation of an object or material into two or more pieces under the action of stress. The fracture of a solid usually occurs due to the development of certain displacement discontinuity surfaces within the solid.

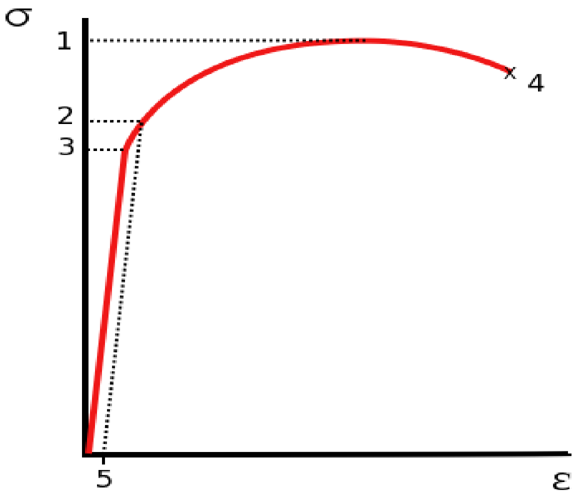
• The fracture of a solid usually occurs due to the development of certain displacement discontinuity surfaces within the solid.

• If a displacement develops perpendicular to the surface of displacement, it is called a normal tensile crack or simply a crack; if a displacement develops tangentially to the surface of displacement, it is called a shear crack, slip band, or dislocation.

Brittle fractures occur with no apparent deformation before fracture; *ductile* fractures occur when visible deformation does occur before separation. **Fracture strength** or **breaking strength** is the stress when a specimen fails or fractures. A detailed understanding of how fracture occurs in materials may be assisted by the study of fracture mechanics

Strength

Fracture strength, also known as **breaking strength**, is the stress at which a specimen fails via fracture.[2] This is usually determined for a given specimen by a tensile test, which charts the stress–strain curve (see image). The final recorded point is the fracture strength.



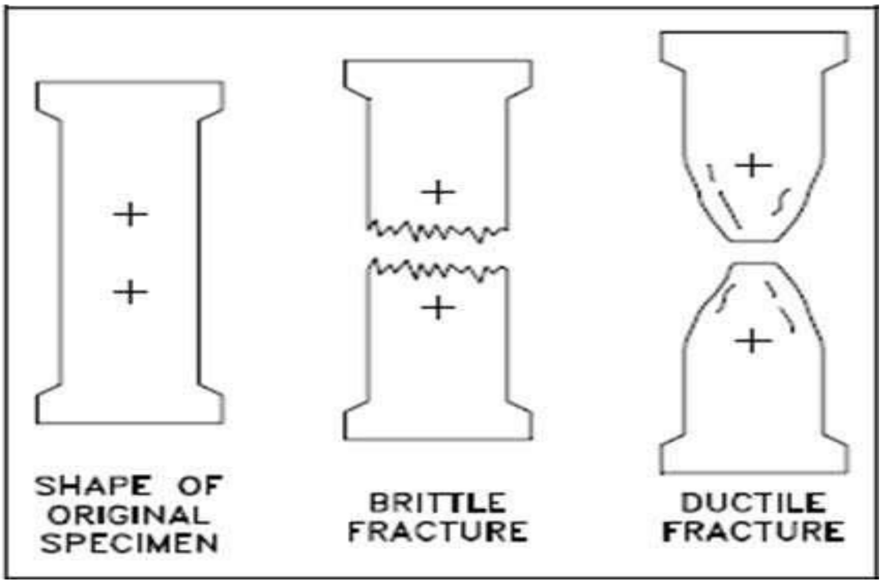
Stress vs. strain curve typical of aluminium.

1. Ultimate tensile strength
2. Yield strength.
3. Proportional limit stress
4. Fracture
5. Offset strain (typically 0.2%)

Ductile materials have a fracture strength lower than the ultimate tensile strength (UTS), whereas in brittle materials the fracture strength is equivalent to the UTS If a ductile material reaches its ultimate tensile strength in a load-controlled situation, it will continue to deform, with no additional load application, until it ruptures. However, if the loading is displacement-controlled the deformation of the material may relieve the load, preventing rupture.

<u>There are mainly two types of fracture:-</u>

1) **Brittle Fracture**
2) **Ductile Fracture**



1) Brittle fracture

In *brittle fracture*, no apparent plastic deformation takes place before fracture. Brittle fracture typically involves little energy absorption and occurs at high speeds—up to 2133.6 m/s (7000 ft/s) in steel. In most cases brittle fracture will continue even when loading is discontinued.

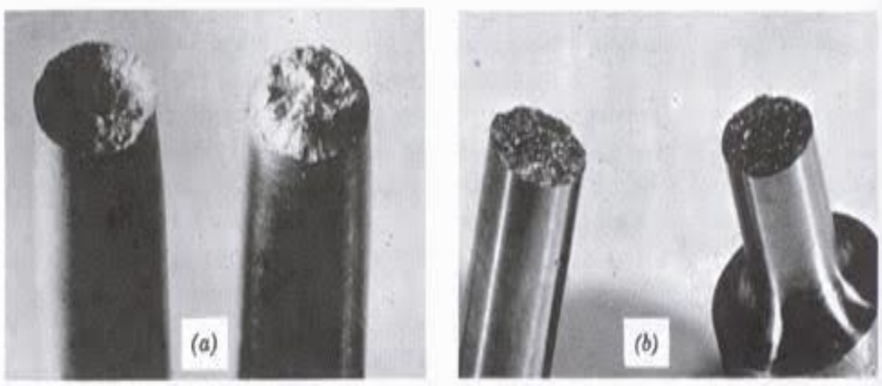


Figure 8.3 (*a*) Cup-and-cone fracture in aluminum. (*b*) Brittle fracture in a mild steel. (From H. W. Hayden, W. G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, p. 144. Copyright © 1965 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

• When gradual tensile load is applied on material in tensile test, at the end of elastic limit without any prior indication material breaks. This type of fracture is called as Brittle Fracture.

Brittle fracture in amorphous materials such as ceramic glass, yields relatively shiny and smooth surface for most brittle crystalline materials cracks propagation corresponds o he successive and repeated breaking of atomic bonds along specific crystallographic planes.

This is an example of Brittle fracture

In brittle crystalline materials, fracture can occur by *cleavage* as the result of tensile stress acting normal to crystallographic planes with low bonding (cleavage planes). In amorphous solids, by contrast, the lack of a crystalline structure results in a conchoidal fracture, with cracks proceeding normal to the applied tension.

The theoretical strength of a crystalline material is (roughly).

$$\sigma_{\text{(theoretical)}} = (E\,\gamma \div r_o)^{1/2}$$

Where : – **E** is the Young's modulus of the material,

γ is the surface energy, and

r_o is the equilibrium distance between atomic centres

.

On the other hand, a crack introduces a stress concentration modelled by

$$\sigma_{(elliptical\ crack)} = \sigma_{(applied)}[1+2(\alpha \div \rho)^{1/2}] = 2\,\sigma_{(applied)}[(\alpha \div \rho)^{1/2}]$$

{ for sharp crack}

Where: – $\sigma_{(applied)}$ is the loading stress,

α is half the length of the crack, and

ρ is the radius of curvature at the crack tip.

Putting these two equations together, we get

$$\sigma_{(fracture)} = (E\,\gamma\,\rho \div 4\,\alpha\,r_o)$$

Looking closely, we can see that sharp cracks (small) and large defects (large) both lower the fracture strength of the material.

Steps in Brittle Fracture

The basic sequence in a typical brittle fracture is: i) introduction of a flaw either before or after the material is put in service, ii) slow and stable crack propagation under recurring loading, iii) and sudden rapid failure when the crack reaches critical crack length based on the conditions defined by fracture mechanics.

How to avoid Brittle fracture

Brittle fracture may be avoided by controlling three primary factors:

1) Material fracture toughness (K_c),
2) Nominal stress level (σ),

3) Introduced flaw size

Residual stresses, temperature, loading rate, and stress concentrations also contribute to brittle fracture by influencing the three primary factors.

Ductile Materials behaving like Brittle

Under certain conditions, ductile materials can exhibit brittle behaviour. Rapid loading, low temperature, and triaxial stress constraint conditions may cause ductile materials to fail without prior deformation.

2) Ductile facture

• When a ductile material has a gradually increasing tensile stress, it behaves elastically up to a limiting stress & then plastic deformation occurs. As stress is increased, the cross sectional area of the material is reduced & a necked region is produced. With a ductile material, there is a considerable amount of plastic deformation before failure occurs in the material, extensive plastic deformation (necking) takes place before the fracture.

The terms rupture or ductile rupture describes the ultimate failure of ductile materials loaded in tension. The extensive plasticity causes the crack to propagate slowly due to the absorption of a large amount of energy before fracture.

Because ductile rupture involves a high degree of plastic deformation, the fracture behaviour of a propagating crack as modelled above changes fundamentally. Some of the energy from stress concentrations at the crack tips is dissipated by plastic deformation ahead of the crack as it propagates.
Ductile fracture is typically transgranular and deformation due to dislocation slip can cause the shear lip characteristic of cup and cone fracture.

Ductile fracture of a specimen strained axially. It is also an example of cup and cone fracture.

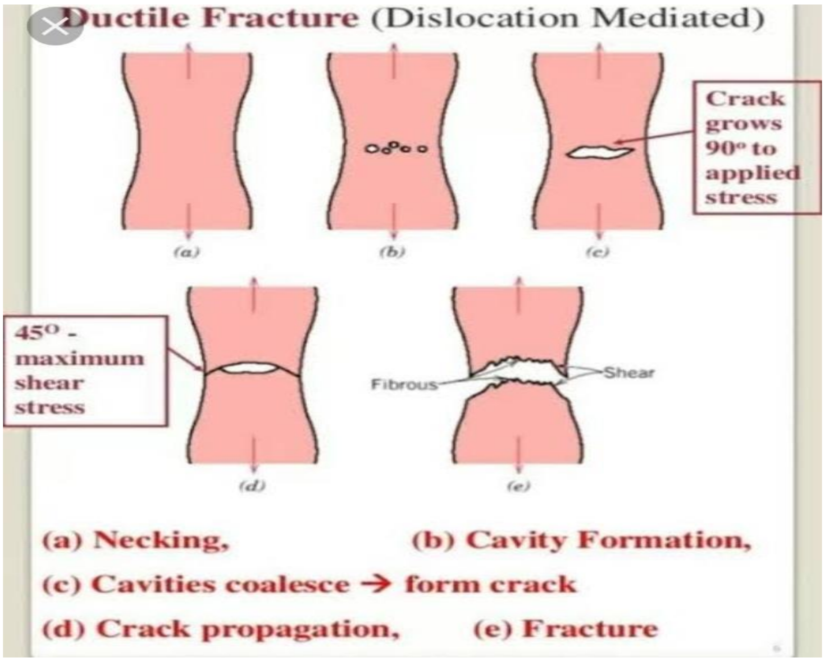
<u>Steps in Ductile Fracture</u>

1) Necking.

2) Small Cavities Formation.

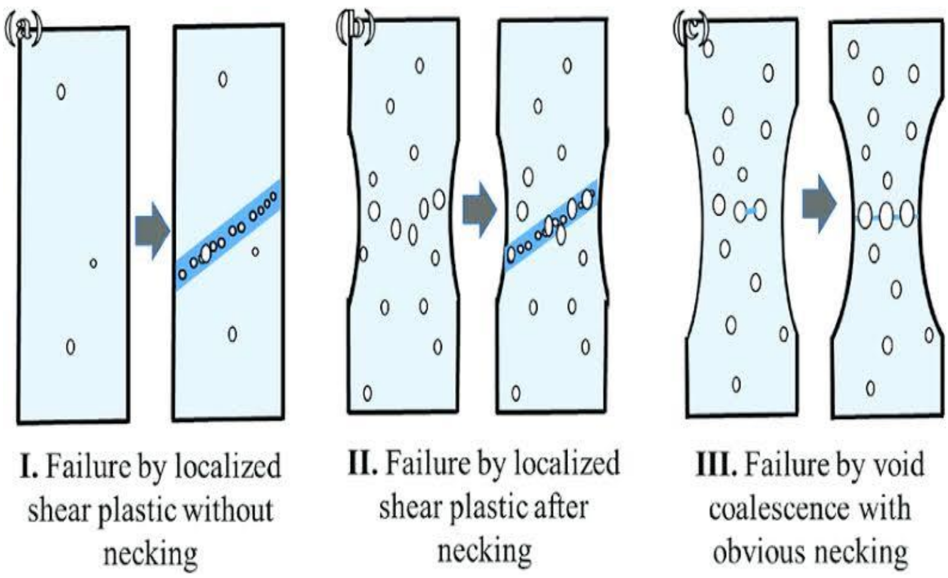
3) Formation of Crack.

3) Cup& Cone Fracture.



In this figure the various steps which are involved in ductile fracture are shown with their respective names.

NECKING

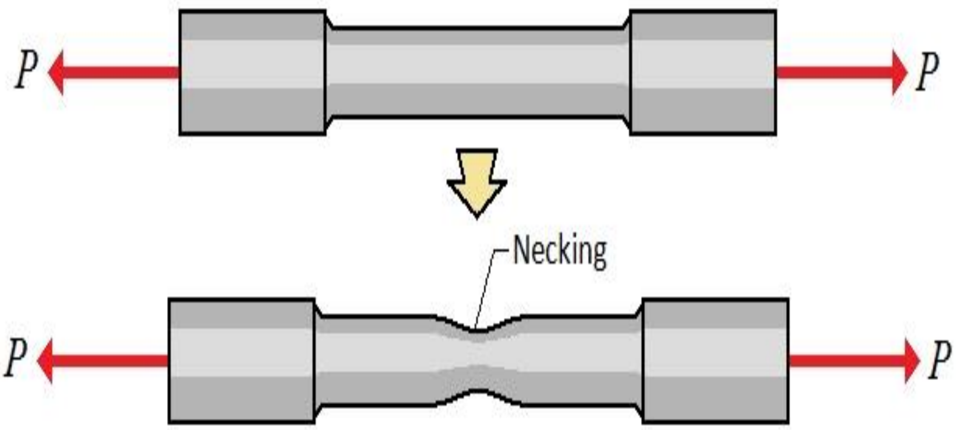


Necking, in engineering or materials science, is a mode of tensile deformation where relatively large amounts of strain localize disproportionately in a small region of the material.

With elastic strain the material becomes plastically deformed & neck formation process starts

• Deformation of material depends upon material purity.

These are some diagrams about formation of neck.

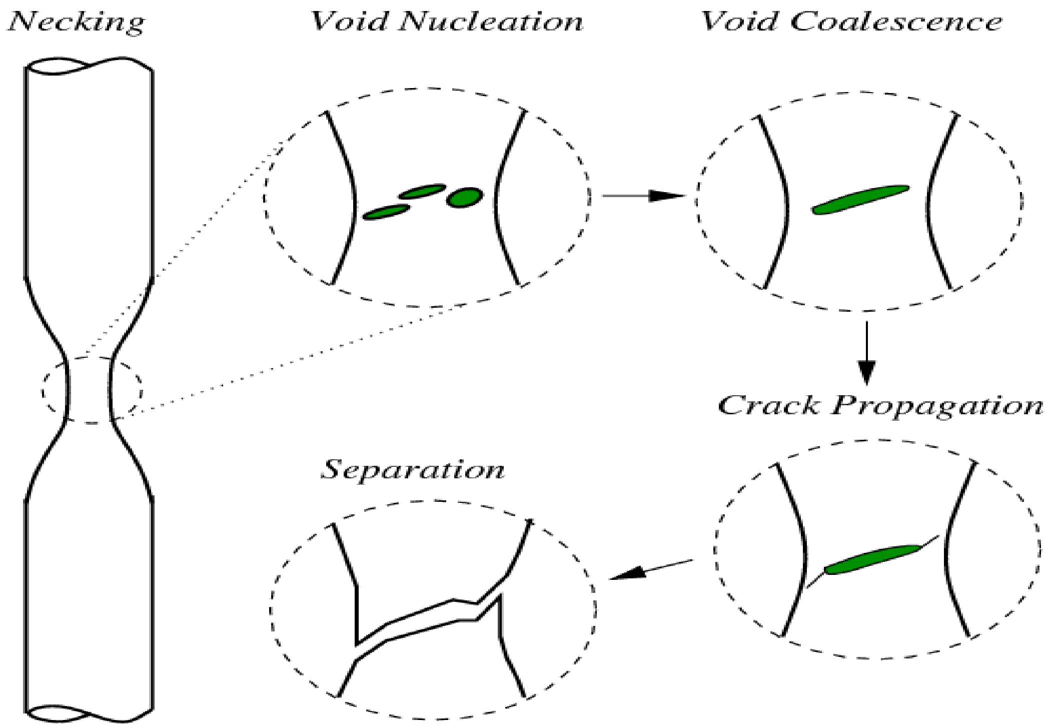


Small cavities forming

Within the neck, small cavities or voids are formed. These develop as a result of the stress causing small particle of impurities or other discontinuities in the material to either fracture or separate from metal matrix. More such nuclei are available to trigger the development of these cavities, the less the material will extend before fracture & less ductile the material. As purity of material increases, ductility of the material also increases.

Formation of Crack

Small cavities, or micro voids, form in the interior of the cross section enlarge, come together, & coalesce to form an elliptical crack, which has its long axis perpendicular to the stress direction. The crack continues to grow in a direction parallel to its major axis by this micro void coalescence process.

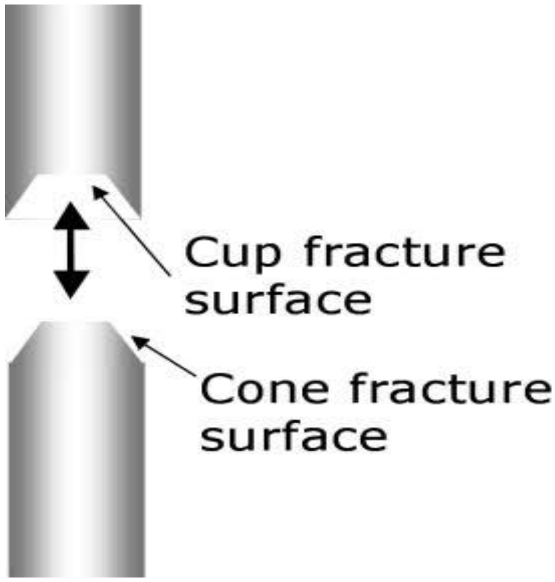


In this figure crack formation and its propagation is shown.

Cup & Cone Fracture

Finally, fracture ensues by the rapid propagation of a crack around the outer perimeter of the neck by shear deformation at an angle of about 45 degree with the tensile axis this is the angle at which the shear stress is a maximum.

• Sometimes a fracture having this characteristic surface contour is termed a cup-and cone fracture because one of the mating surfaces is



in the form of a cup, the other like a cone.

In this type of fractured specimen the central interior region of the surface has an irregular & fibrous appearance, which is indicative of plastic deformation.

Griffith Stress and its Derivation

In the study of fracture, a basic problem is to explain why it takes place at only a small fraction of the theoretical stress calculated for the fracture of a perfect crystal. It is believed that this happens due to the occurrence of inherent flaws such as cracks in the material. Fracture is the separation of a load-bearing body into two or more parts by the extension of a crack, and leading to a reduction in the load-bearing capacity to zero. These cracks cause the local concentration of stress to attain values as high as the theoretical (i.e., cohesive) strength; this results in the propagation of such cracks and eventually in the fracture of the material in a brittle manner. In Griffith's theory an energy balance is considered for estimating the stress required to cause a crack to propagate. The surface energy associated with a flat crack of length 2 *L* and unit thickness is 4 *L* γ, where γ is the surface energy per unit area of the crack surfaces. In general there will also be some plastic deformation of the surfaces of the crack, requiring an energy *P* per unit area, so that the total energy required for the creation of the crack is

$$W_L = 4L(\gamma + P)$$

This energy is considered to be supplied by the elastic strain energy, W_E, that is released per unit thickness by the formation of the crack and is given by

$$W_E = (\pi L^2 \sigma^2) \div E$$

Where, 1) σ is the tensile stress acting normal to the crack
2) *E* is the Young's modulus

Now, an existing crack will grow spontaneously under the action of a given stress, if the change in *W*e with increase in *L*, dW_E/dL, is at least equal to the corresponding change in *W*L, dWL/dL. From the two relationships provided, this equality can be expressed as

$$(2\pi L \sigma^2) \div E = 4(\gamma + P)$$

The value of σ is obtained from this equation is the critical value of the applied tensile stress normal to the crack (also known as the ***Griffith stress***) necessary to cause the crack to propagate and is given by

$$\sigma_f = [2E(\gamma + P) \div \pi L]^{0.5}$$

This result indicates that the stress necessary to cause brittle fracture is lower, the longer the existing crack and the smaller the energy, *P*, expended in plastic deformation. The quantity σ_f represents the smallest tensile stress that would be able to propagate the crack of length 2 *L*. The term $\sigma_f (\pi L)^{0.5}$ is generally denoted by the symbol *K* and is known as the stress-intensity factor (for a sharp elastic crack in an infinitely wide plate). Fracture occurs when the product of the nominal applied stress and the stress concentration factor of a flaw attain a value equal to that of the cohesive stress.

Besides Griffith's theory, the fracture of materials can be described in terms of a property known as fracture toughness. The fracture toughness of a material refers to its resistance to fracture in the presence of cracks or discontinuities. Fracture toughness is represented by the symbol *K*IC (pronounced "kay-one-cee") and is the critical value of the stress intensity factor (*K*) at a crack tip necessary to produce catastrophic failure under simple uniaxial loading. In general, the value of fracture toughness is given by

$$K\mathrm{IC} = Y\, \sigma\, (\pi\, L\mathrm{C})^{0,5}$$

Where, *Y* is a dimensionless geometric factor and *L*c is the critical crack length. The initiation of unstable fracture in a material takes place as soon as the applied stress intensity (*K*) attains the critical value, *K*IC, either because of increasing stress or due to increasing crack length, or both. It should be noted that a properly determined value of *K*IC represents the fracture toughness of the material under consideration irrespective of crack length, geometry or loading system; *K*IC is a material property in the same sense that yield strength is a material property.

The manner in which a particle fractures depends on (i) the nature of the particle; and (ii) the manner in which the fracture force is applied. A number of terms have been used to describe the different mechanisms of single particle fracture. The different terms considered here are abrasion, cleavage, shatter, and chipping. It may be pointed out that in practice these events do not occur in isolation. Real breakage involves a combination of these processes, with the proportions changing, depending on the equipment, and on the manner each particle is stressed within it.

Abrasion fracture occurs when sufficient energy is not supplied to cause significant fracture of the particle. In such circumstances only a localized stressing occurs and a small area is fractured to result in a distribution to be essentially the original particle, together with a small amount of very fine particles.

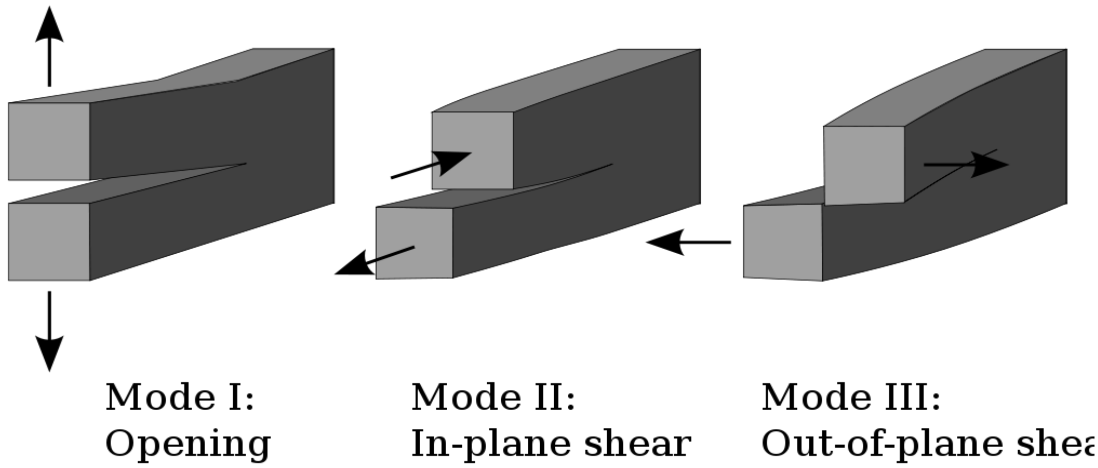
Cleavage fracture is said to take place when the applied energy is just sufficient to load a few regions of the particle to the point of fracture. Only a few particles result, and their size is comparatively close to that of the original particle. This situation typically arises under conditions of slow compression where fracture immediately relieves the loading on the particle. The term shatter fracture applies to a situation where the applied energy is well in excess of that necessary for fracture. Many regions of the particle are overloaded under these conditions, yielding a comparatively large number of particles with a wide distribution of sizes.

This type of fracture occurs under conditions of rapid loading such as those obtained in a high-velocity impact.

The term chipping implies breaking of the edges or the corners of a particle. The process may be considered to be a special case of cleavage. It should not be overlooked that the principal terms, abrasion, cleavage, and shatter used here have been so arranged as to qualify the order of increasing energy intensity.

Fracture Mode and Characteristics

There are three standard conventions for defining relative displacements in elastic materials in order to analyze crack propagation as proposed by Irwin. In addition fracture can involve uniform strain or a combination of these modes.



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

The manner in which a crack propagates through a material gives insight into the mode of fracture. With ductile fracture a crack moves slowly and is accompanied by a large amount of plastic deformation around the crack tip.

A ductile crack will usually not propagate unless an increased stress is applied and generally cease propagating when loading is removed. In a ductile material, a crack may progress to a section of the material where stresses are slightly lower and stop due to the blunting effect of plastic deformations at the crack tip.

On the other hand, with brittle fracture, cracks spread very rapidly with little or no plastic deformation. The cracks that propagate in a brittle material will continue to grow once initiated.

Crack propagation is also categorized by the crack characteristics at the microscopic level. A crack that passes through the grains within the material is undergoing transgranular fracture. A crack that propagates along the grain boundaries is termed an intergranular fracture. Typically, the bonds between material grains are stronger at room temperature than the material itself, so transgranular fracture is more likely to occur. When temperatures increase enough to weaken the grain bonds, intergranular fracture is the more common fracture mode.

Micro-mechanism of fracture

Cleavage

At sufficiently low temperature, cleavage usually dominates the fracture for most crystalline solids because the temperature limits the plasticity of the material and makes it brittle. Generally, cleavage is controlled by nucleation and propagation of cracks either of which can determine the stress at which the specimen fails.

Ductile fracture at low temperature

Ductile fracture requires holes nucleate at inclusion which concentrates stress. Applied stress and plastic strain make holes grow and when, eventually, they are large enough coarsening happens and the material fails.

Transgranular creep fracture

This mechanism happens when the temperature is above 0.3Tm and is the adaptation of low temperature ductile fracture but follows the strain-rate power law in which the creep stabilizes the flow and there by postpone the coalescence of holes.

Intergranular creep fracture

At low stress, fracture mechanism transfer from transgranular to intergranular which depends on voids and cracks grow at grain boundaries. This regime is determined by diffusion and power-law creep because small voids grow by diffusion at the grain boundary but the space between voids is controlled by deformation creep.

Diffusion fracture

At very low stresses and high temperatures, the diffusion field dominates growing voids and power-law creep is negligible.

Rupture

At very high temperatures, the high rates of recovery relieve the stress at inclusion and suppress the nucleation of internal voids. Therefore, with no other fracture mechanism intervenes, deformation continues until the cross-section area becomes zero.

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