Chapter 3

Fracture

Cracks in Metals

Theoritical and Practical strength

Fast Fracture

1. **Introduction**

Failure of materials may have huge costs. Causes included improper materials selection or processing, the improper design of components, and improper use.

Ductile material (such as steel) generally exhibits a very linear stress-strain relationship up to a well defined yield point . The linear portion of the curve is the elastic region and the slope is the modulus of elasticity or Young's Modulus. After the yield point the curve typically decreases slightly due to dislocations escaping from Cottrell atmospheres. As deformation continues the stress increases due to strain hardening until it reaches the ultimate strength. Until this point the cross-sectional area decreases uniformly due to Poisson contractions. However, beyond this point a *neck* forms where the local cross-sectional area decreases more quickly than the rest of the sample resulting in an increase in the true stress. On an engineering stress-strain curve this is seen as a decrease in the stress. Conversely, if the curve is plotted in terms of *true stress* and *true strain* the stress will continue to rise until failure. Eventually the neck becomes unstable and the specimen ruptures (fractures).
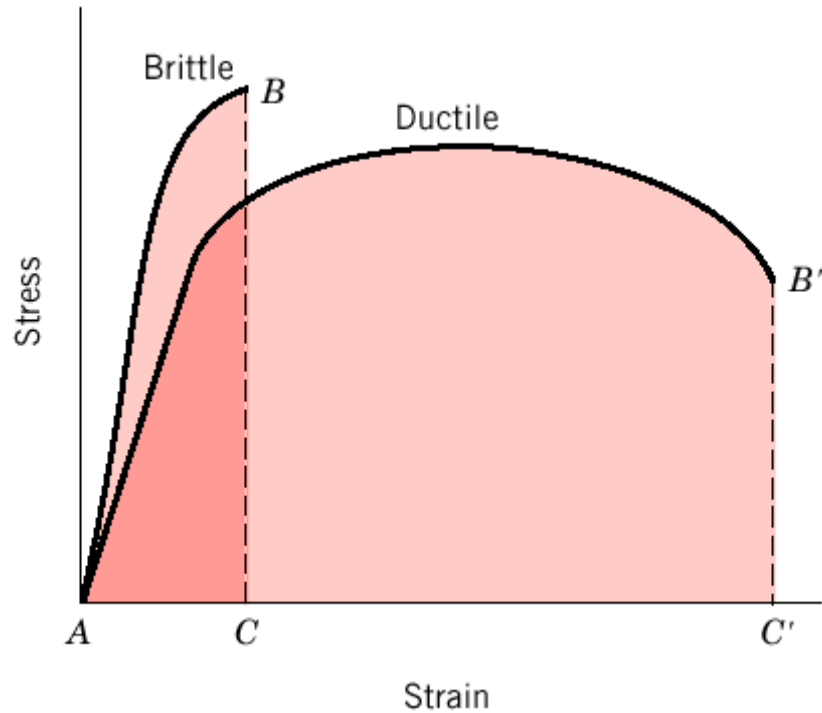
Most ductile metals other than steel do not have a well-defined yield point. For these materials the yield strength is typically determined by the "offset yield method", by which a line is drawn parallel to the linear elastic portion of the curve and intersecting the abscissa at some arbitrary value (most commonly .2%). The intersection of this line and the stress-strain curve is reported as the yield point.

4.2.   Material Types

Brittle materials such as concrete or ceramics do not have a yield point. For these materials the rupture strength and the ultimate strength are the same.

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a- Ductile materials - extensive plastic deformation and energy absorption "toughness") before fracture. Ductile materials can be classified into various classifications; 1- Very ductile, soft metals (e.g. Pb, Au) at room temperature, other metals, polymers, glasses at high temperature., 2- Moderately ductile fracture, typical for ductile metals, 3- Brittle fracture, cold metals, ceramics.
b- Brittle materials – has a little plastic deformation and low energy absorption before fracture
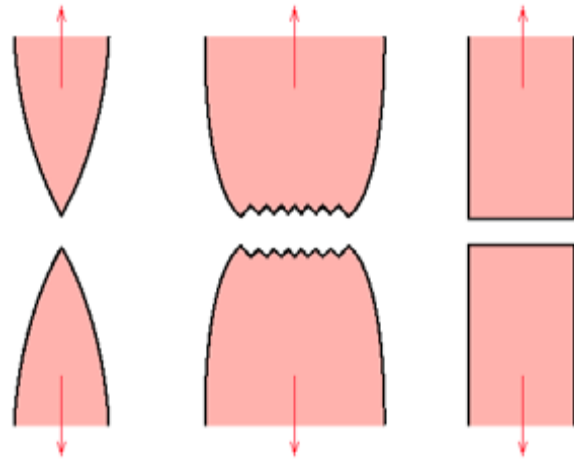
Brittle fracture in glass.   **Ductile- brittle fracture**

Brittle fracture

no apparent plastic deformation takes place before 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)

$$\sigma_{\text{theoretical}} = \sqrt{\frac{E\gamma}{r_o}}$$

where E is the Young's elastic modulus of the material, γ is the surface energy, and r_o is the equilibrium distance between atomic centers.

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

$$\sigma_{\text{elliptical crack}} = \sigma_{\text{applied}}\left(1 + 2\sqrt{\frac{a}{\rho}}\right) = 2\sigma_{\text{applied}}\sqrt{\frac{a}{\rho}} \text{ (for sharp crack)}$$

where σ_{applied} is the loading stress, a 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

$$\sigma_{\text{fracture}} = \sqrt{\frac{E\gamma\rho}{4ar_o}}$$

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

Recently, scientists have discovered supersonic fracture , the phenomenon of crack motion faster than the speed of sound in a material. This phenomenon was recently also verified by experiment of fracture in rubber-like materials.


In Brittle Fracture, No appreciable plastic deformation, Crack propagation is very fast, Crack propagates nearly perpendicular to the direction of the applied stress and   Crack often   propagates by cleavage – breaking of atomic bonds along specific crystallographic planes (cleavage planes). **Brittle Fracture occurs at Limited Dislocation Mobility.**

Stress Concentration
Fracture strength of a brittle solid is related to the cohesive forces between atoms. One can estimate that the theoretical cohesive strength of a brittle material should

be ~ E/10. But experimental fracture strength is normally E/100 - E/10,000. 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.** The magnitude of this amplification depends on micro-crack orientations, geometry and dimensions.
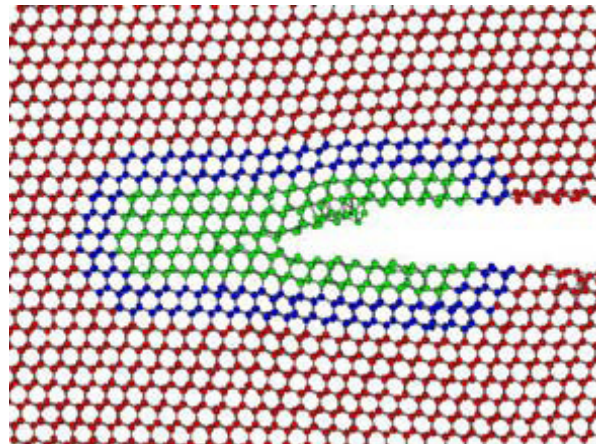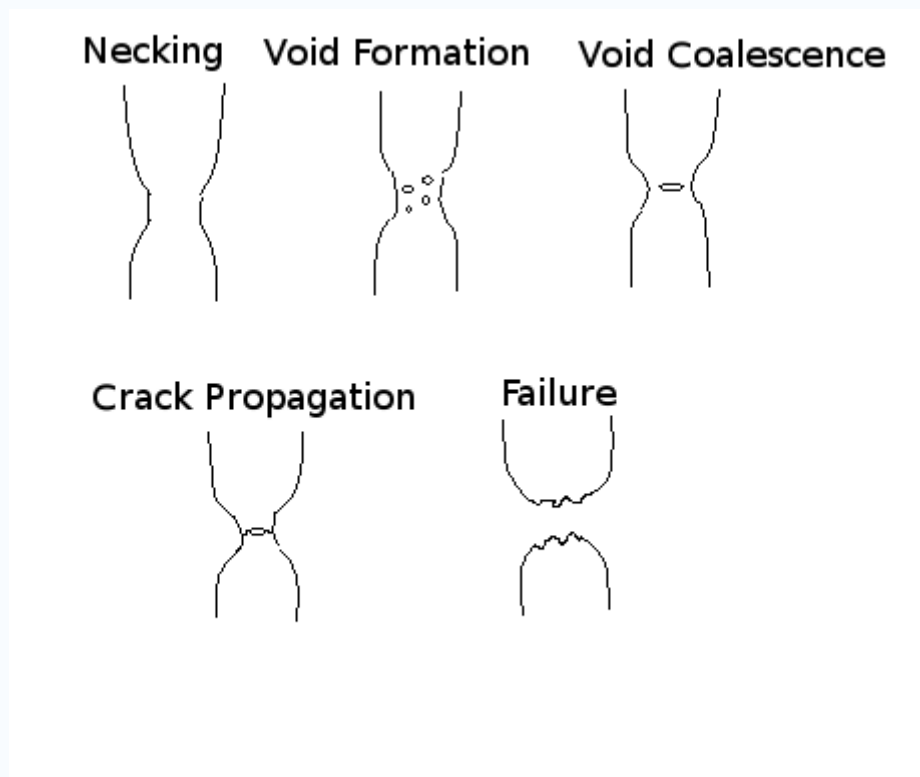

Ductile fracture

In *ductile fracture*, extensive plastic deformation takes place before fracture. Many ductile metals, especially materials with high purity, can sustain very large deformation of 50–100% or more strain before fracture under favorable loading condition and environmental condition. The strain at which the fracture happens is controlled by the purity of the materials. At room temperature, pure iron can undergo deformation up to 100% strain before breaking, while cast iron or high-carbon steels can barely sustain 3% of strain.
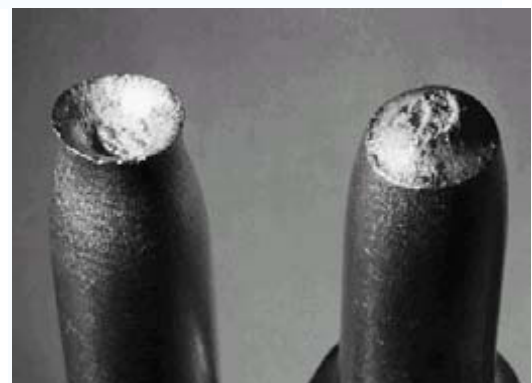
Ductile failure of a specimen strained axially.

Because ductile rupture involves a high degree of plastic deformation, the fracture behavior of a propagating crack as modeled above changes fundamentally. Some of the energy from stress concentrations at the crack tips is dissipated by plastic deformation before the crack actually propagates.

The basic steps of ductile fracture are necking (which results in stress localization at the point on the sample of smallest cross-sectional area), void formation, void coalescence (also known as crack formation), crack propagation, and failure, often resulting in a cup-and-cone shaped failure surface.

Schematic representation of the steps in ductile fracture.
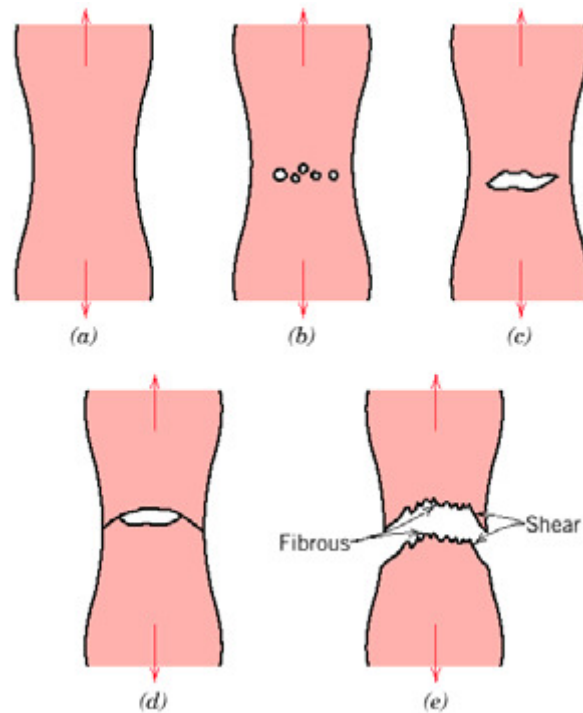
**(a) Necking, (b) Cavity Formation,
(c) Cavity coalescence to form a crack (d) Crack propagation, (e) cup and cone**

Fundamentals of Fracture

Fracture is a form of failure where the material separates in pieces due to stress, at temperatures below the melting point. The fracture is termed ductile or brittle depending on whether the elongation is large or small.

Steps in fracture (response to stress):

- crack formation

- crack propagation

Ductile vs. brittle fracture

	Ductile	**Brittle**
Deformation	extensive	little
track propagation	slow, needs stress	fast
type of materials	most metals (not too cold)	ceramics, ice, cold metals
Warning	permanent elongation	none
strain energy	higher	lower
fractured surface	rough	smoother
Necking	yes	no

Ductile Fracture

Stages of ductile fracture

- Initial necking
- small cavity formation (microvoids)
- void growth (elipsoid) by coalescence into a crack
- fast crack propagation around neck. Shear strain at 45°
- final shear fracture (cup and cone)

The interior surface is fibrous, irregular, which signify plastic deformation.

Brittle Fracture

There is no appreciable deformation, and crack propagation is very fast. In most brittle materials, crack propagation (by bond breaking) is along specific crystallographic planes (*cleavage* planes). This type of fracture is transgranular (through grains) producing grainy texture (or faceted texture) when cleavage direction changes from grain to grain. In some materials, fracture is intergranular.

5.   Principles of Fracture Mechanics

Fracture occurs due to *stress concentration* at flaws, like surface scratches, voids, etc. If a is the length of the void and ρ the radius of curvature, the enhanced stress near the flaw is:

$$\sigma_m \approx 2\ \sigma_0\ (a/\rho)^{1/2}$$

where σ_0 is the applied macroscopic stress. Note that a is 1/2 the length of the flaw, not the full length for an internal flaw, but the full length for a surface flaw. The stress concentration factor is:

$$K_t = \sigma_m/\sigma_0 \approx 2\ (a/\rho)^{1/2}$$

Because of this enhancement, flaws with small radius of curvature are called *stress raisers*.

6.   Impact Fracture Testing

Normalized tests, like the Charpy and Izod tests measure the impact energy required to fracture a notched specimen with a hammer mounted on a pendulum. The energy is measured by the change in potential energy (height) of the pendulum. This energy is called notch toughness.

Ductile to brittle transition occurs in materials when the temperature is dropped below a transition temperature. Alloying usually increases the ductile-brittle transition temperature (Fig. 8.19.) For ceramics, this type of transition occurs at much higher temperatures than for metals.

Failure Analysis

When a specimen is loaded until its failure point in the tensile test, a distinct surface is formed on each of the resulting two pieces. In general, it is possible to

predict the failure surface given the state of stress and the material characterization. Upon knowing whether the material is brittle or ductile, we can predict the failure surface reasonably well. Failure takes place along the plane of **maximum shear stress** for ductile materials. Brittle materials fail on planes of maximum tensile normal stress.