Cracks in Metals

Theoretical 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, \(\gamma\) 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

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

where $\sigma_{\text{applied}}$ is the loading stress, $a$ is half the length of the crack, and $\rho$ 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 $\rho$) 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

<table>
<thead>
<tr>
<th></th>
<th><strong>Ductile</strong></th>
<th><strong>Brittle</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Deformation</td>
<td>extensive</td>
<td>little</td>
</tr>
<tr>
<td>track propagation</td>
<td>slow, needs stress</td>
<td>fast</td>
</tr>
<tr>
<td>type of materials</td>
<td>most metals (not too cold)</td>
<td>ceramics, ice, cold metals</td>
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<tr>
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<td>strain energy</td>
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<tr>
<td>fractured surface</td>
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<td>smoother</td>
</tr>
<tr>
<td>Necking</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>

**Ductile Fracture**

Stages of ductile fracture

- Initial necking
- small cavity formation (microvoids)
- void growth (ellipsoid) 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 $\rho$ the radius of curvature, the enhanced stress near the flaw is:

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

where $\sigma_0$ 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 \textit{maximum shear stress} for ductile materials. Brittle materials fail on planes of maximum tensile normal stress.