Chapter Outline: Failure

How do Materials Break?

- Ductile vs. brittle fracture
- Principles of fracture mechanics
  - Stress concentration
- Impact fracture testing
IDEAL VS REAL MATERIALS

• Stress-strain behavior (Room T):

- Perfect material-no flaws
- Carefully produced glass fiber
- Typical ceramic
- Typical strengthened metal
- Typical polymer

• DaVinci (500 yrs ago!) observed...
  --the longer the wire, the smaller the load to fail it.

• Reasons:
  --flaws cause premature failure.
  --Larger samples are more flawed!

Fracture

Fracture: separation of a body into pieces due to stress, at temperatures below the melting point.

Steps in fracture:
- Crack formation
- Crack propagation

Depending on the ability of material to undergo plastic deformation before the fracture two fracture modes can be defined - ductile or brittle

• Ductile fracture - most metals (not too cold):
  - Extensive plastic deformation ahead of crack
  - Crack is “stable”: resists further extension unless applied stress is increased

• Brittle fracture - ceramics, ice, cold metals:
  - Relatively little plastic deformation
  - Crack is “unstable”: propagates rapidly without increase in applied stress

Ductile fracture is preferred in most applications
Brittle vs. Ductile Fracture

- **Ductile materials** - extensive plastic deformation and energy absorption ("toughness") before fracture
- **Brittle materials** - little plastic deformation and low energy absorption before fracture

**A.** Very ductile, soft metals (e.g. Pb, Au) at room temperature, other metals, polymers, glasses at high temperature.

**B.** Moderately ductile fracture, typical for ductile metals

**C.** Brittle fracture, cold metals, ceramics.
Ductile Fracture (Dislocation Mediated)

(a) Necking, (b) Cavity Formation,
(c) Cavity coalescence to form a crack,
(d) Crack propagation, (e) Fracture

Crack grows $90^\circ$ to applied stress

$45^\circ$ - maximum shear stress

Typical Cup-and-Cone fracture in ductile Al

Scanning Electron Microscopy: Fractographic studies at high resolution. Spherical “dimples” correspond to micro-cavities that initiate crack formation.
Brittle Fracture (Limited Dislocation Mobility)

- 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).

Brittle fracture in a mild steel

Brittle Fracture

A. Transgranular fracture: Fracture cracks pass through grains. Fracture surface have faceted texture because of different orientation of cleavage planes in grains.

B. Intergranular fracture: Fracture crack propagation is along grain boundaries (grain boundaries are weakened or embrittled by impurities segregation etc.)
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 \( \sim \frac{E}{10} \). But experimental fracture strength is normally \( \frac{E}{100} - \frac{E}{10,000} \).

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.

\[
\text{Stress Concentration}
\]

For a long crack oriented perpendicular to the applied stress the maximum stress near the crack tip is:

\[
\sigma_m \approx 2\sigma_0 \left( \frac{a}{\rho_t} \right)^{1/2}
\]

where \( \sigma_0 \) is the applied external stress, \( a \) is the half-length of the crack, and \( \rho_t \) the radius of curvature of the crack tip. (note that \( a \) is half-length of the internal flaw, but the full length for a surface flaw).

The stress concentration factor is:

\[
K_t = \frac{\sigma_m}{\sigma_0} \approx 2 \left( \frac{a}{\rho_t} \right)^{1/2}
\]
SIMULATION: DISLOCATION MOTION/GENERATION

- Tensile loading (horizontal dir.) of a FCC metal with notches in the top and bottom surface.
- Over 1 billion atoms modeled in 3D block.
- Note the large increase in disl. density.

Simulation courtesy of Farid Abraham. Used with permission from International Business Machines Corporation.

Impact Fracture Testing
(testing fracture characteristics under high strain rates)

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.
Ductile-to-brittle transition

As temperature decreases a ductile material can become brittle - ductile-to-brittle transition. Alloying usually increases the ductile-to-brittle transition temperature. FCC metals remain ductile down to very low temperatures. For ceramics, this type of transition occurs at much higher temperatures than for metals.

The ductile-to-brittle transition can be measured by impact testing: the impact energy needed for fracture drops suddenly over a relatively narrow temperature range – temperature of the ductile-to-brittle transition.