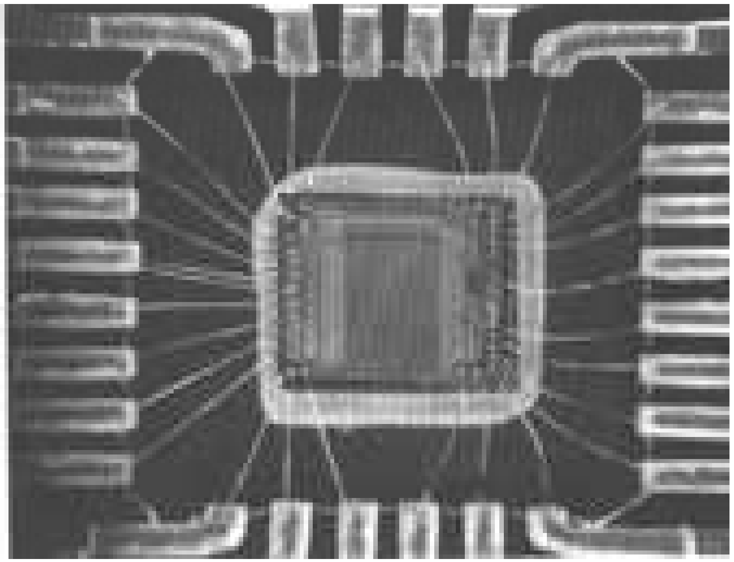
Chapter 5

Failure

Ship-cyclic loading from waves.



Computer chip-cyclic thermal loading.

Outline

- How do Materials Break?

Ductile vs. brittle fracture

- **Principles of fracture mechanics**
  - Stress concentration
- **Impact fracture testing**
- **Fatigue** (cyclic stresses)
  - Cyclic stresses, the S—N curve
  - Crack initiation and propagation
  - Factors that affect fatigue behavior
- **Creep** (time dependent deformation)
  - Stress and temperature effects
  - Alloys for high-temperature use

Fracture

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

Steps in fracture:

- crack formation
- crack propagation

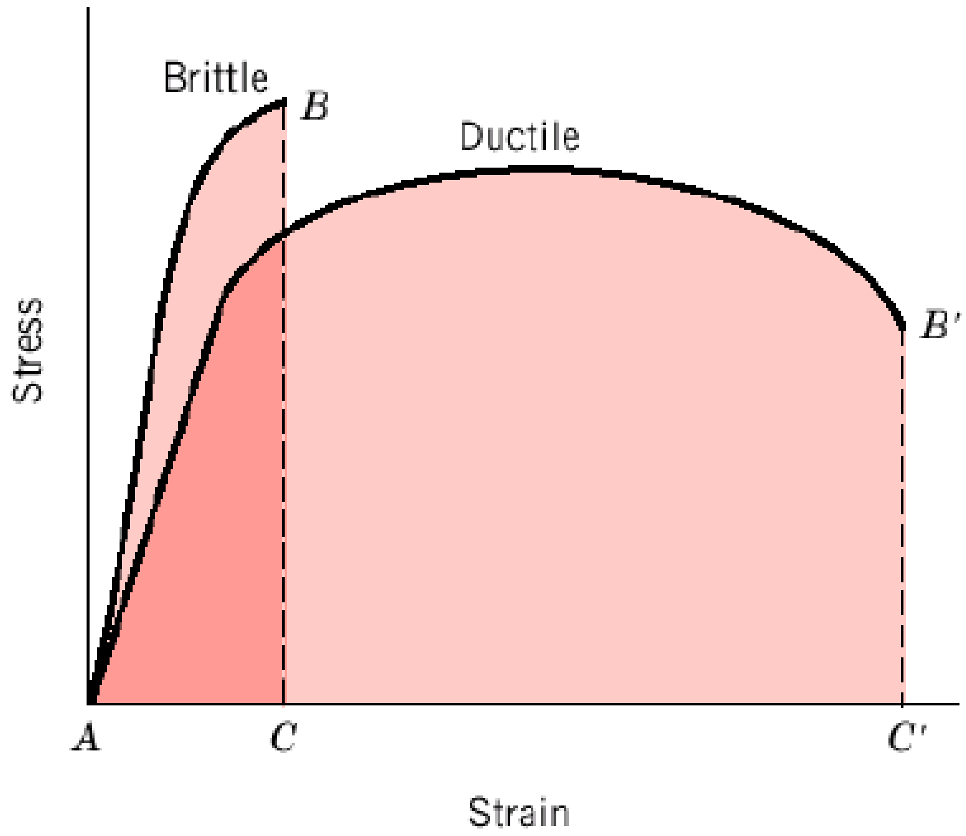
Depending on the ability of material to undergo plastic deformation before the fracture two fracture modes can be defined - **ductile or brittle**

- **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

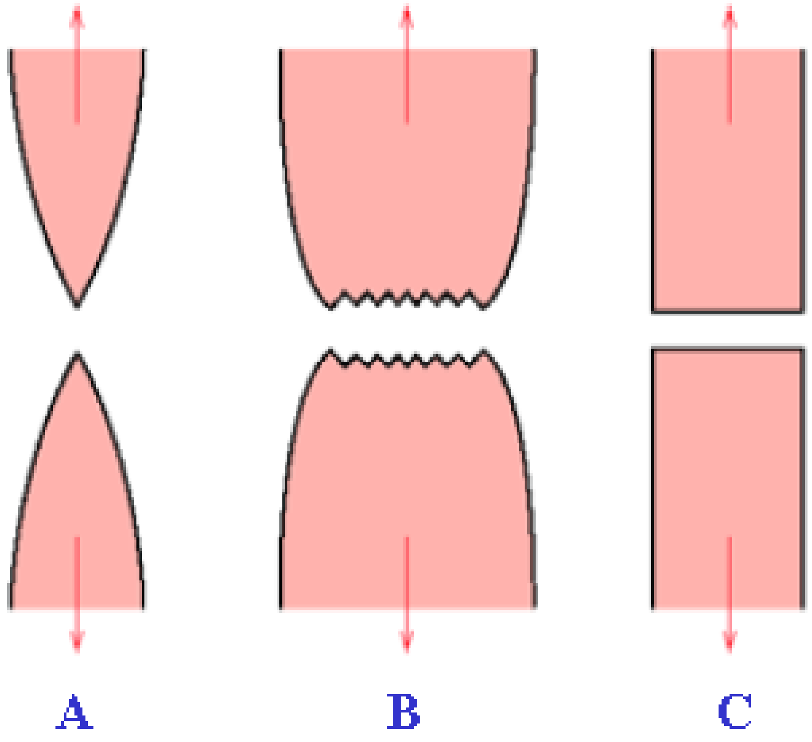
Ductile fracture is preferred in most applications

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



Brittle vs. Ductile Fracture

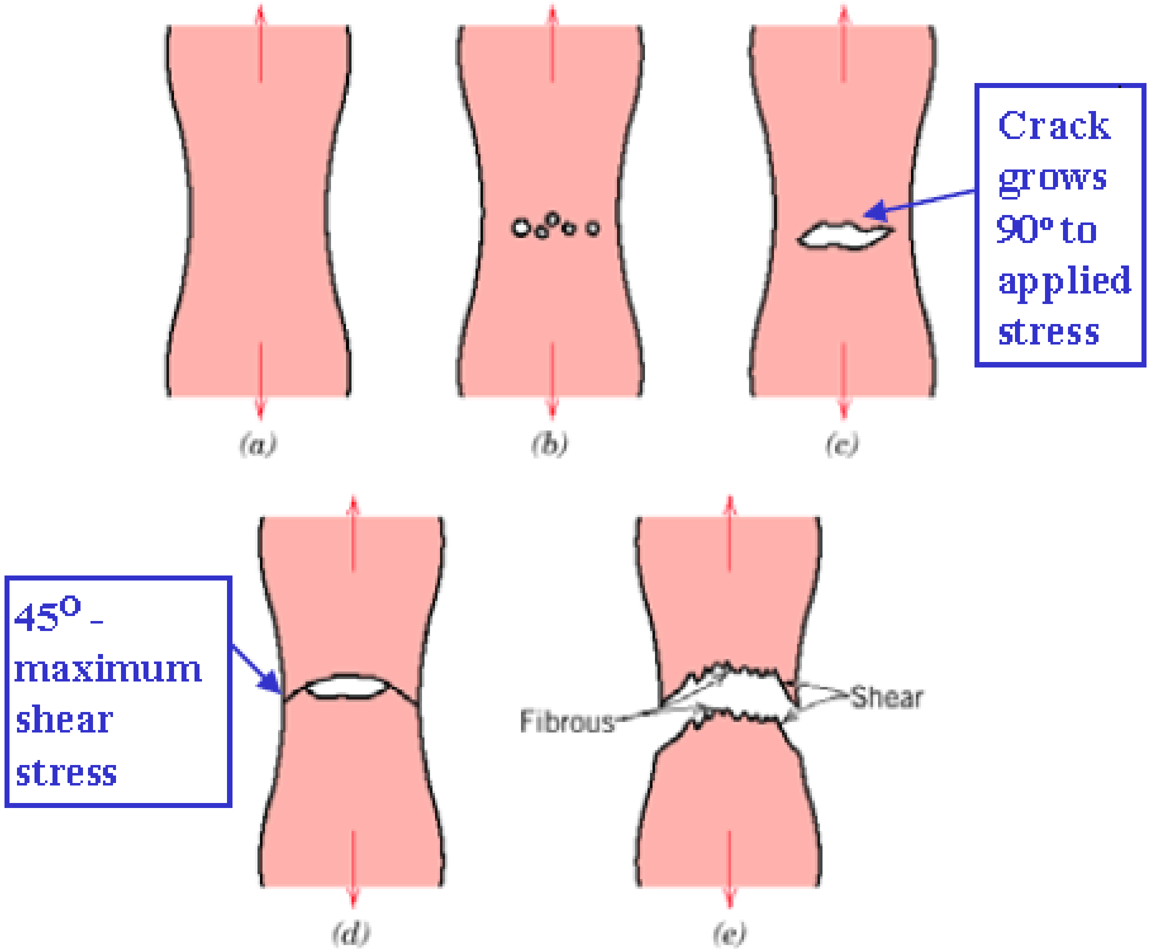


A. **Very ductile**, soft metals (e.g. Pb, Au) at room temperature, other metals, polymers, glasses at high temperature.

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

C. **Brittle fracture**, cold metals, ceramics.

Ductile Fracture (Dislocation Mediated)

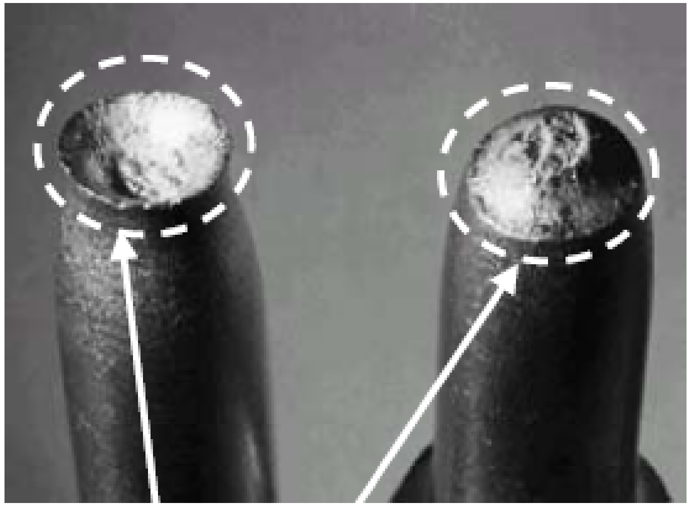


(a) Necking, (b) Cavity Formation,

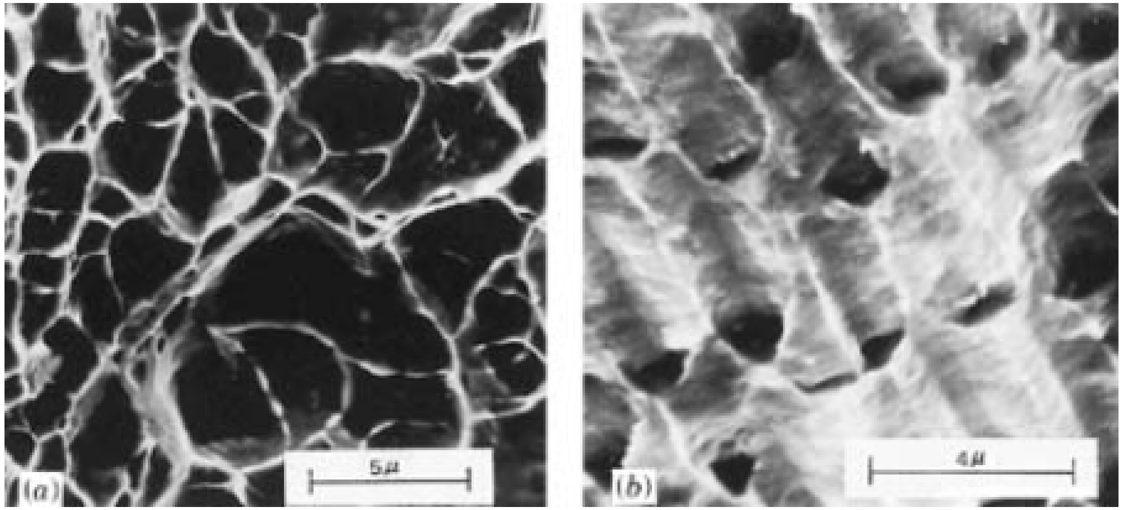
(c) Cavity coalescence to form a crack,

(d) Crack propagation, (e) Fracture

Ductile Fracture



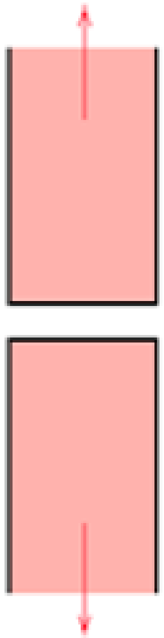
Typical Cup-and-Cone fracture in ductile Al



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).

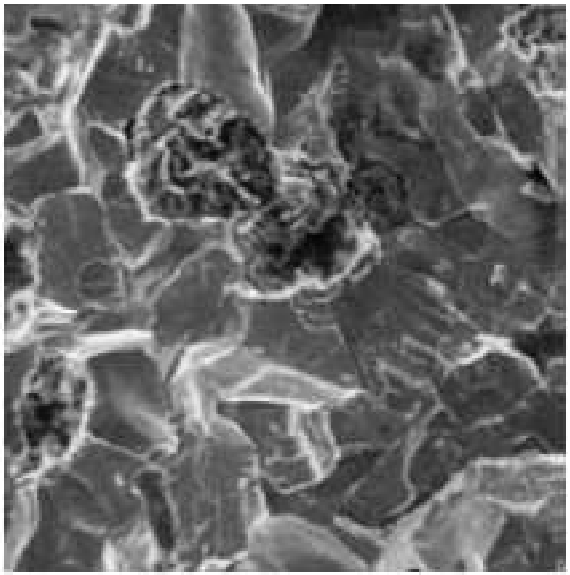


Brittle fracture in a mild steel

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.)



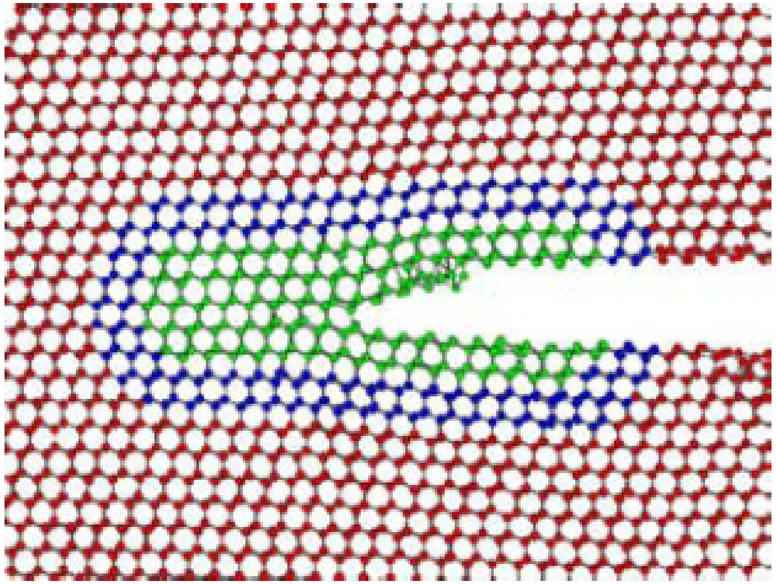
A

B

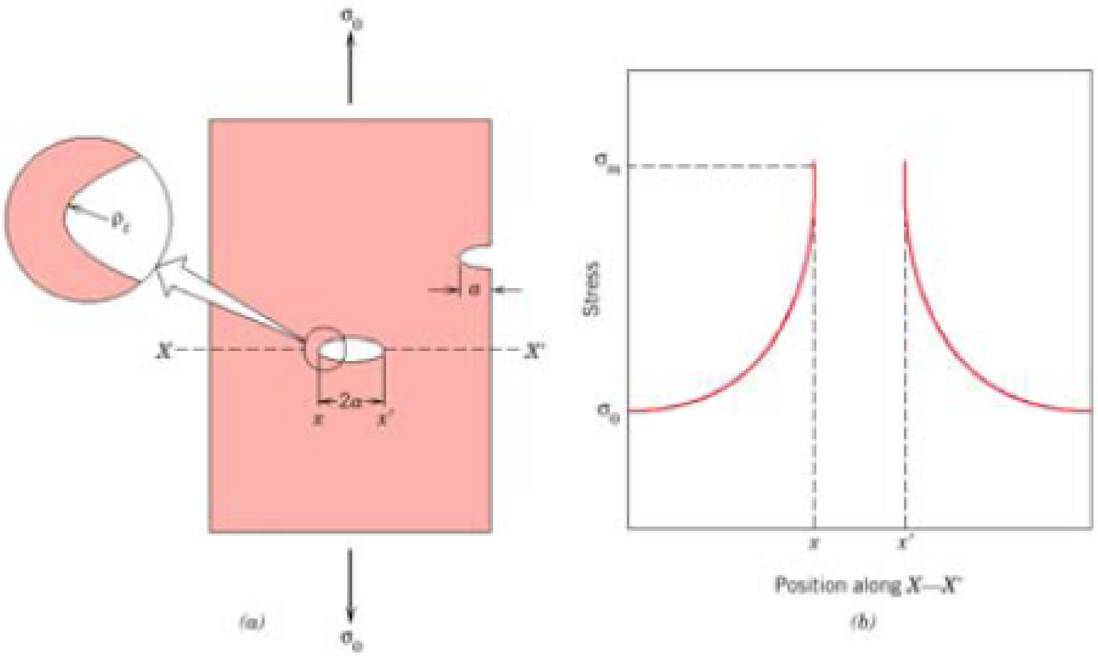
Stress Concentration

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.



Stress Concentration



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

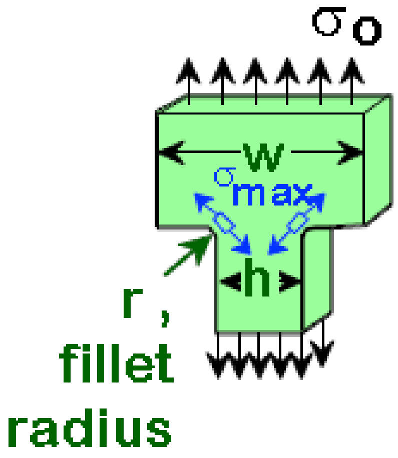
$$\sigma_m \approx 2\sigma_0 \left(\frac{a}{\rho_t} \right)^{1/2}$$

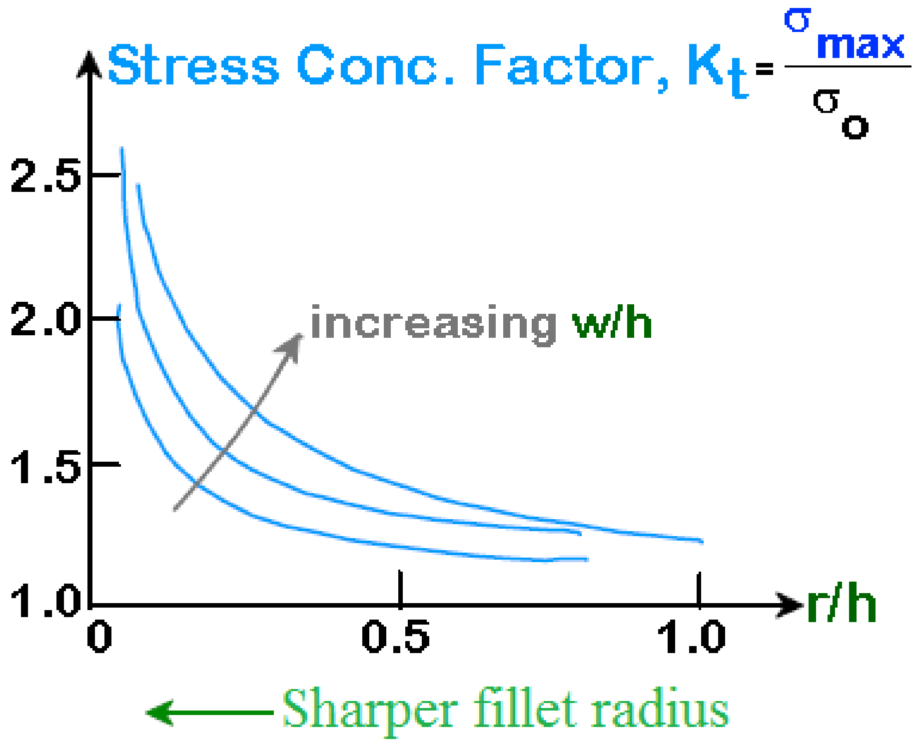
where $\boldsymbol{\sigma_0}$ is the applied external stress, **a** is the half-length of the crack, and $\boldsymbol{\rho_t}$ the radius of curvature of the crack tip. (note that **a** is half-length of the internal flaw, but the full length for a surface flaw).

The **stress concentration factor** is: $K_t = \dfrac{\sigma_m}{\sigma_0} \approx 2 \left(\dfrac{a}{\rho_t} \right)^{1/2}$

ENGINEERING FRACTURE DESIGN

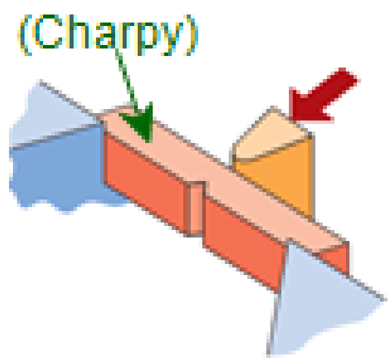
- Avoid sharp corners!

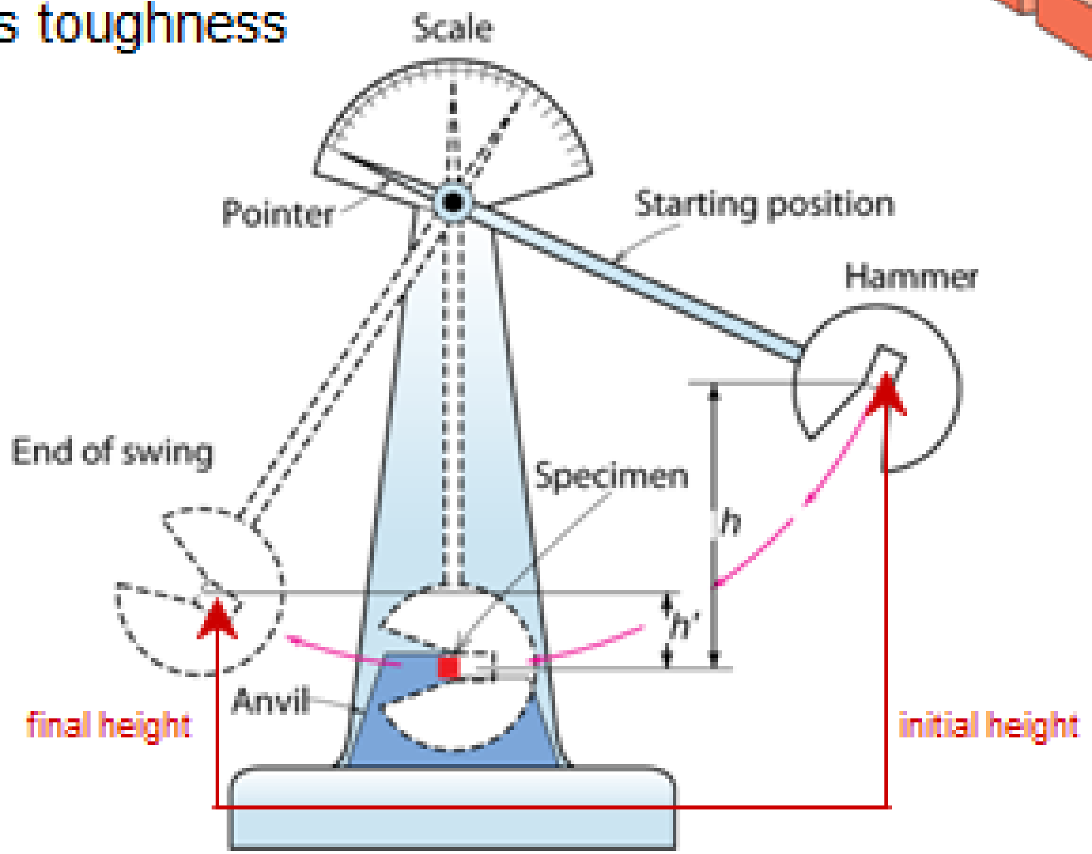




Impact Testing

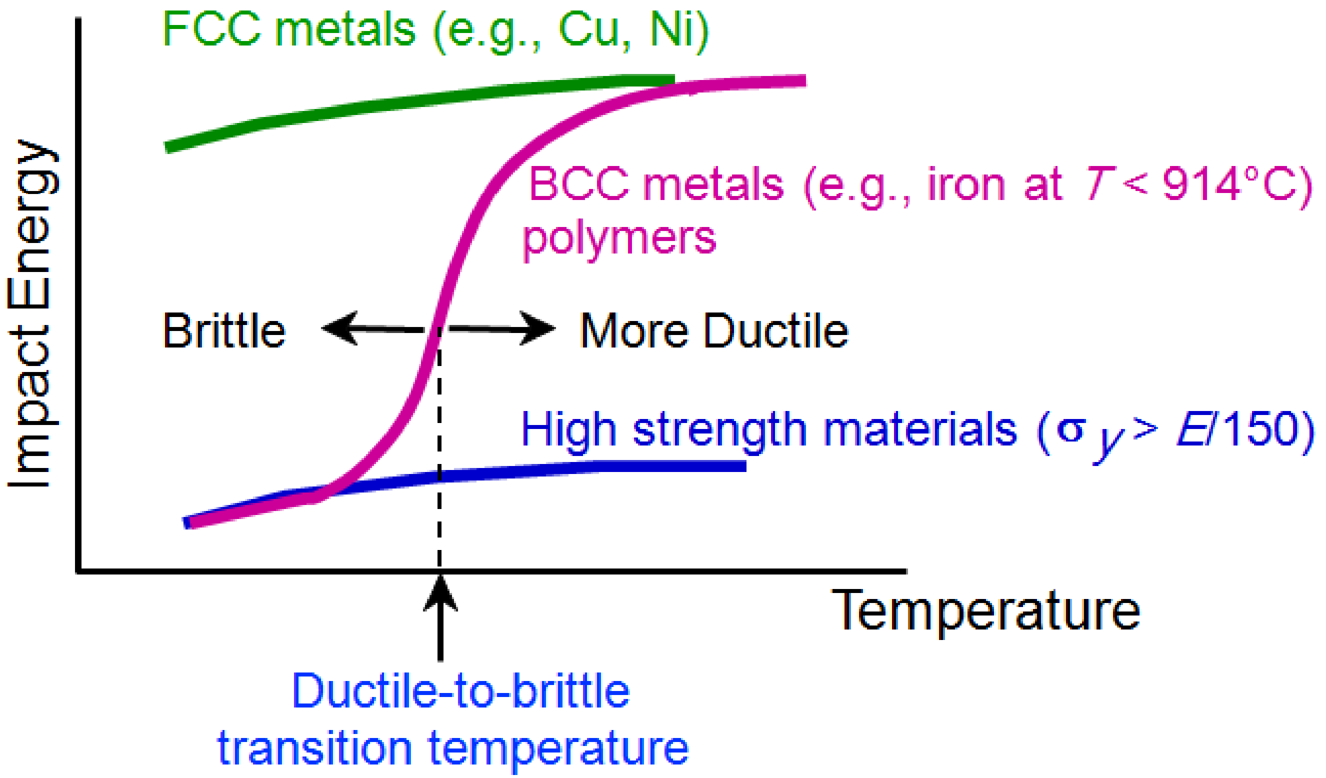
- Impact loading:
  -- severe testing case
  -- makes material more brittle
  -- decreases toughness





Temperature

- **Increasing temperature...**
  --increases %*EL* and K_c
- **Ductile-to-Brittle Transition Temperature (DBTT)...**

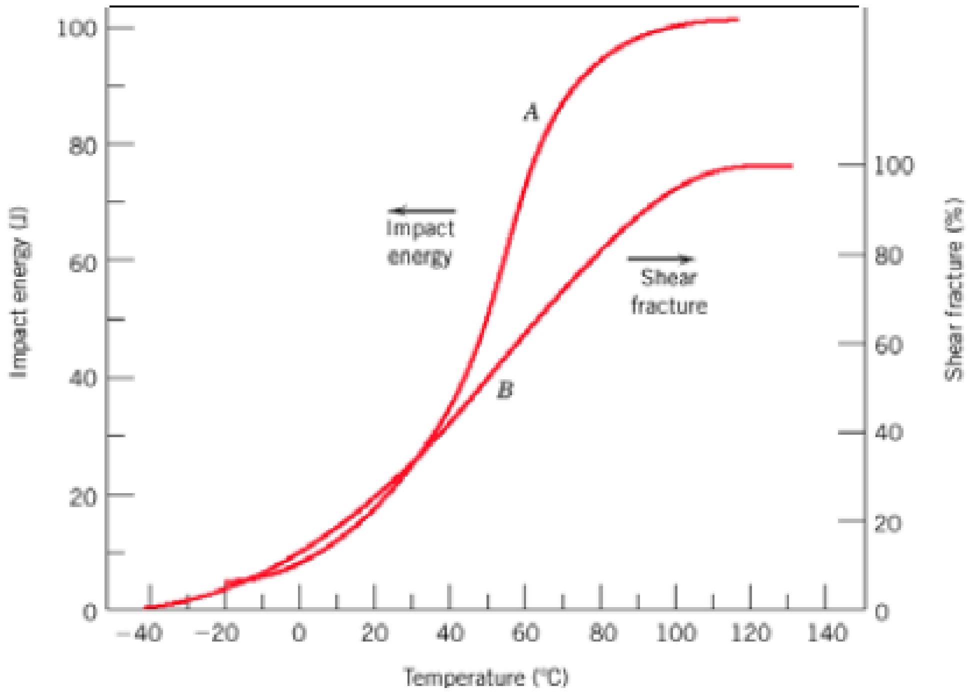


Ductile-to-brittle transition

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.



Fatigue

(Failure under fluctuating / cyclic stresses)

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.)

Fatigue failure is brittle-like (relatively little plastic deformation) - even in normally ductile materials. Thus sudden and catastrophic!

Applied stresses causing fatigue may be axial (tension or compression), flextural (bending) or torsional (twisting).

Fatigue failure proceeds in three distinct stages: crack initiation in the areas of stress concentration (near stress raisers), incremental crack propagation, final catastrophic failure.

Fatigue: Cyclic Stresses (I)

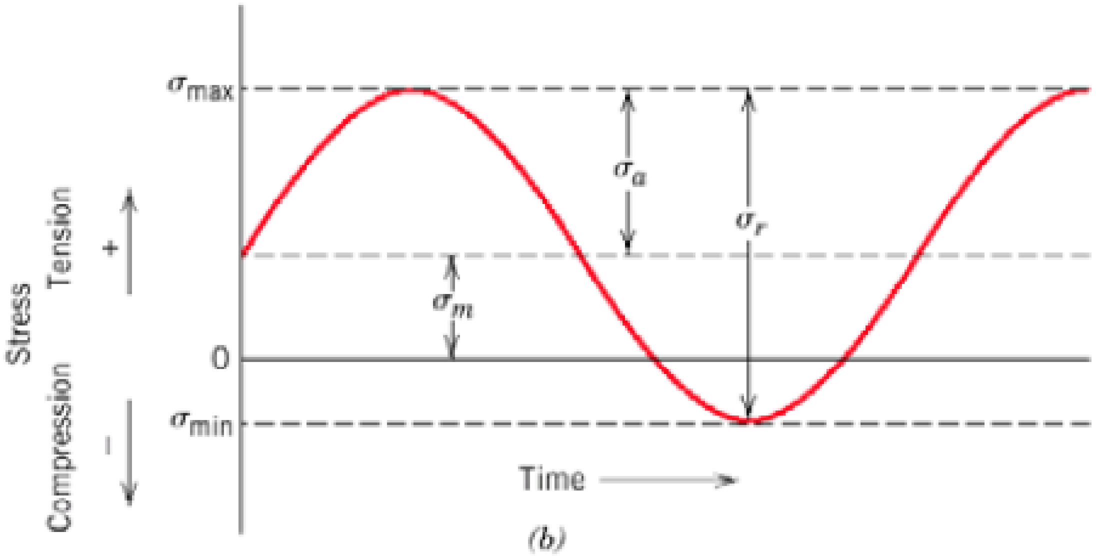
Cyclic stresses are characterized by maximum, minimum and mean stress, the range of stress, the stress amplitude, and the stress ratio

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

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

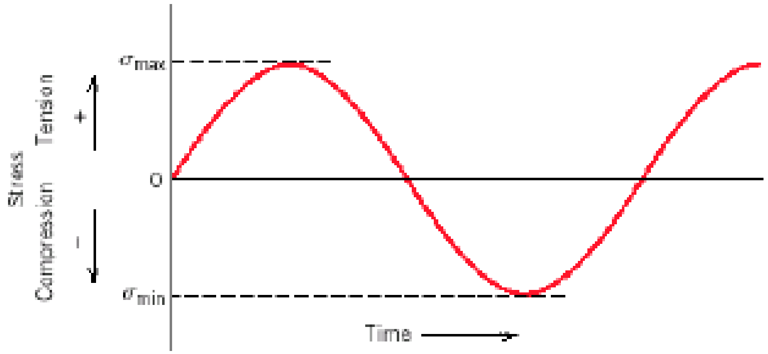
Stress amplitude: $\sigma_a = \sigma_r/2 = (\sigma_{max} - \sigma_{min}) / 2$

Stress ratio: $R = \sigma_{min} / \sigma_{max}$



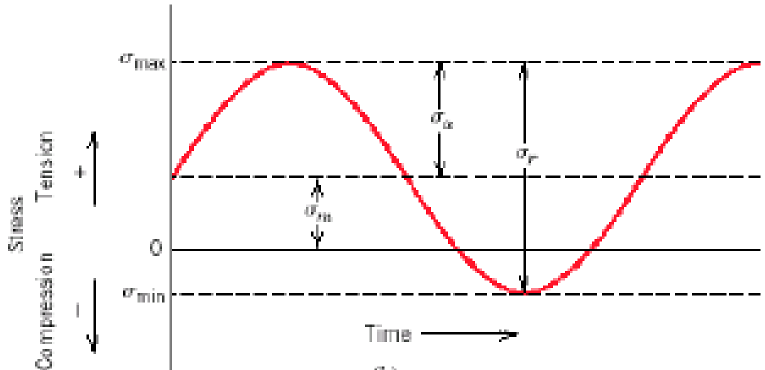
Remember the convention that tensile stresses are positive, compressive stresses are negative

Fatigue: Cyclic Stresses (II)



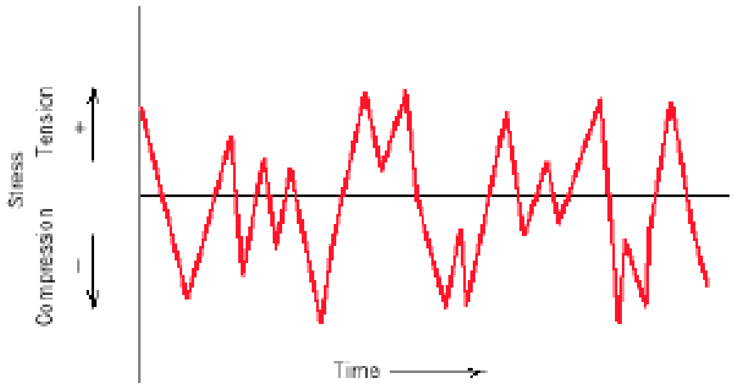
(a)

Periodic and symmetrical about zero stress



(b)

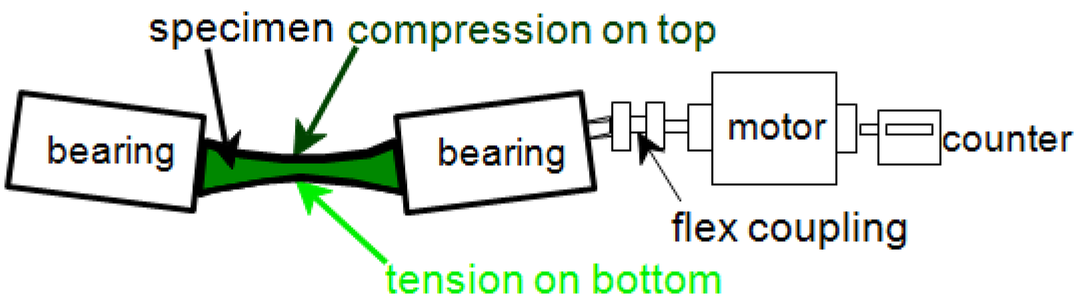
Periodic and asymmetrical about zero stress



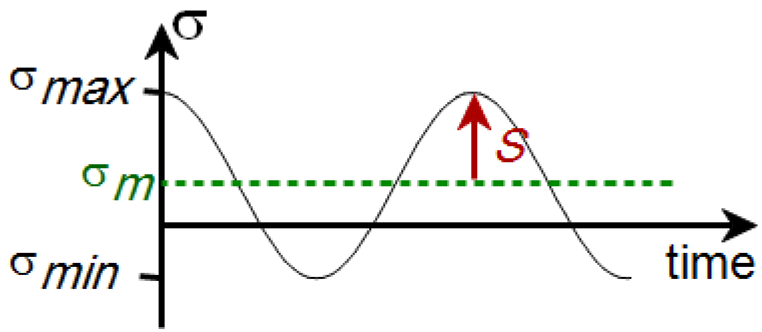
Random stress fluctuations

Fatigue

- Fatigue = failure under cyclic stress.



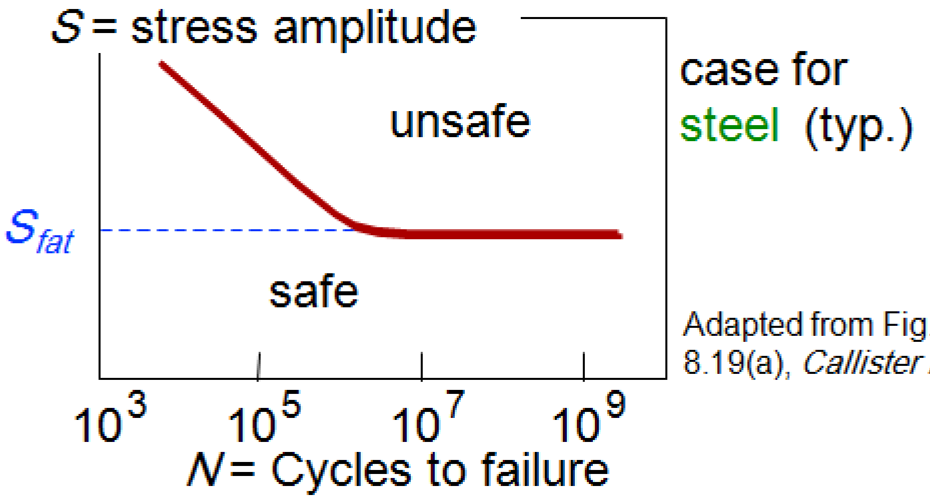
- Stress varies with time.
  -- key parameters are S, σ_m, and frequency



- Key points: Fatigue...
  --can cause part failure, even though $\sigma_{max} < \sigma_c$.
  --causes ~ 90% of mechanical engineering failures.

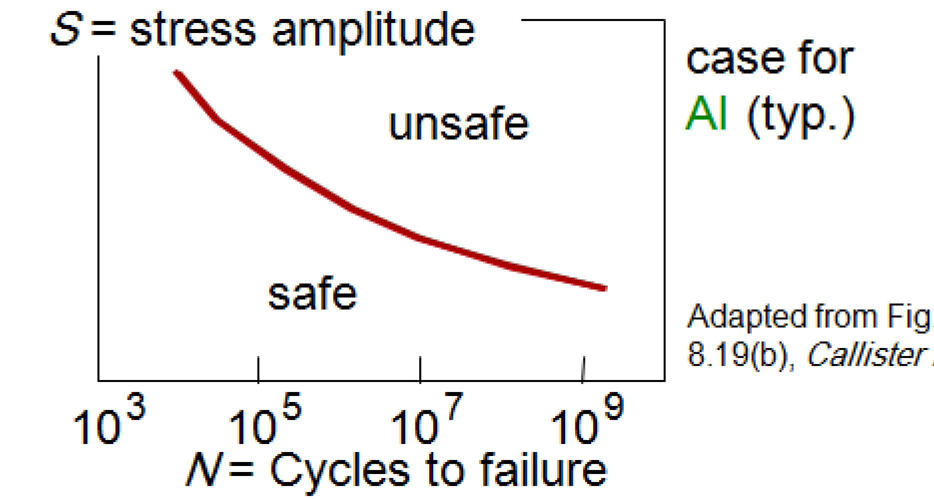
Fatigue Design Parameters

- Fatigue limit, S_{fat}:
  --no fatigue if $S < S_{fat}$



Adapted from Fig. 8.19(a), *Callister 7e.*

- Sometimes, the fatigue limit is zero!



Adapted from Fig. 8.19(b), *Callister 7e.*

Fatigue Mechanism

- Crack grows *incrementally*

$$\frac{da}{dN} = (\Delta K)^m$$

m: typ. 1 to 6

$\Delta K \sim (\Delta\sigma)\sqrt{a}$

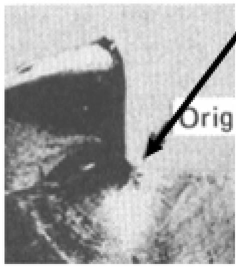
$\frac{da}{dN}$: increase in crack length per loading cycle

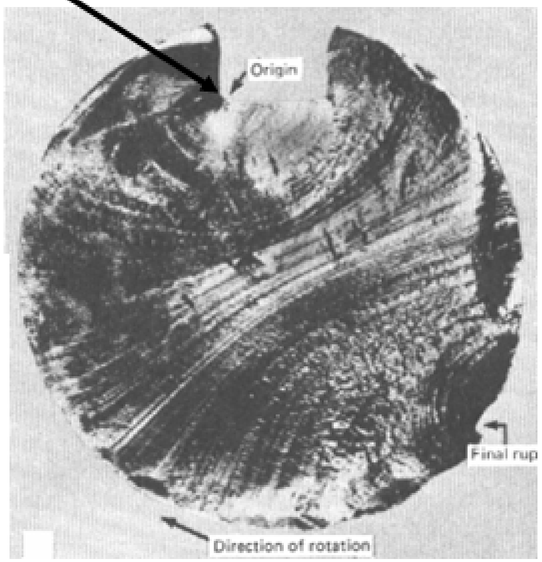
- Failed rotating shaft
  --crack grew even though

  $K_{max} < K_c$

  --crack grows faster as
  - $\Delta\sigma$ increases
  - crack gets longer
  - loading freq. increases.

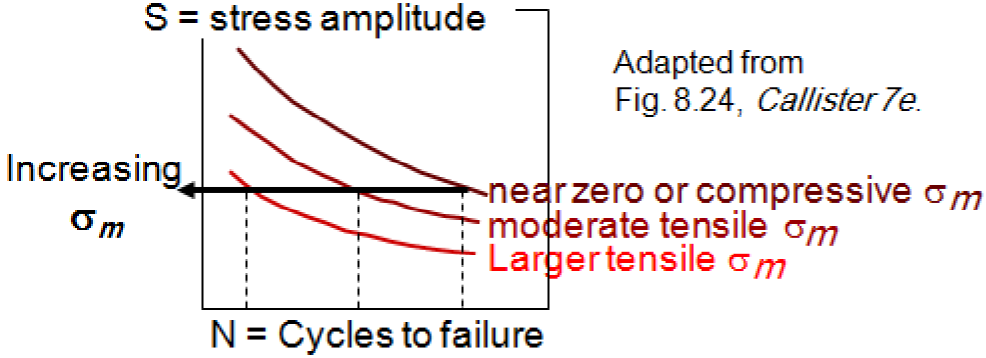
crack origin





Improving Fatigue Life

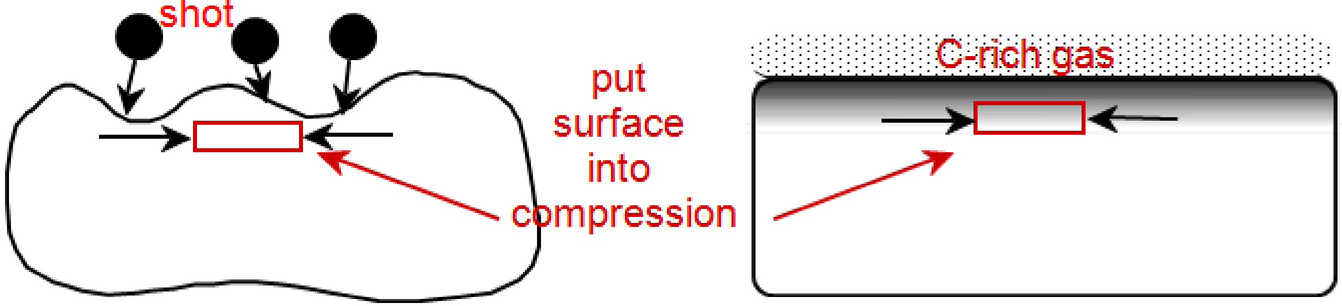
1. Impose a compressive surface stress (to suppress surface cracks from growing)



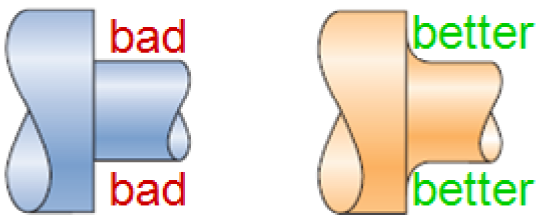
Adapted from Fig. 8.24, *Callister 7e.*

--Method 1: shot peening

--Method 2: carburizing

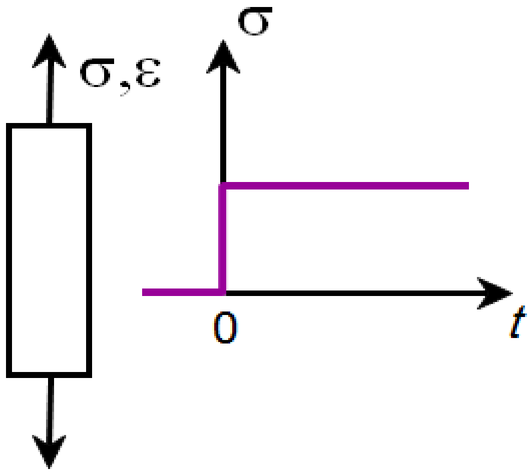


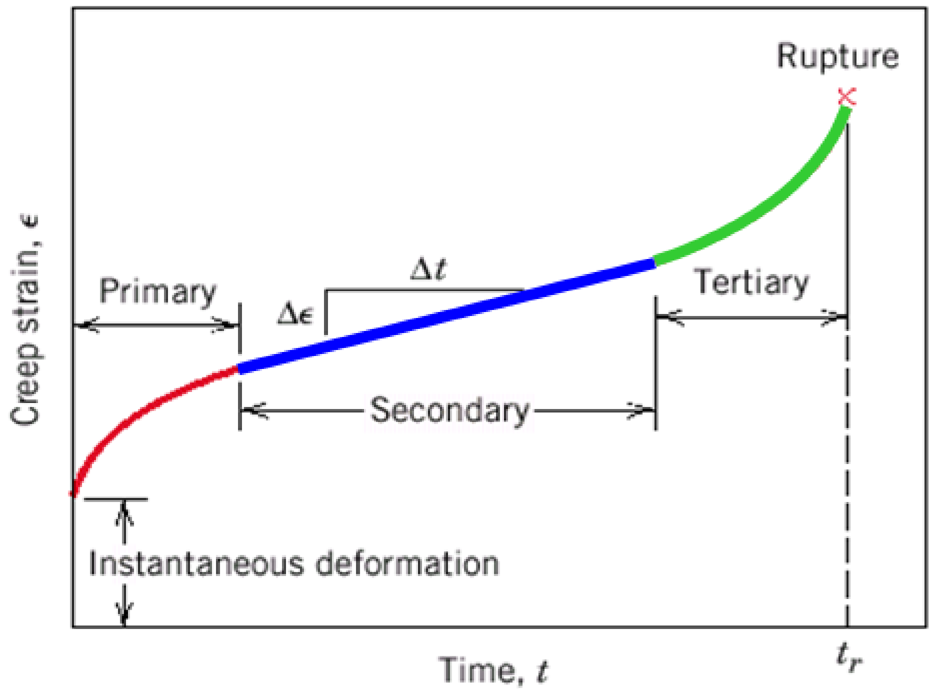
2. Remove stress concentrators.



Creep

Sample deformation at a constant stress (σ) vs. time





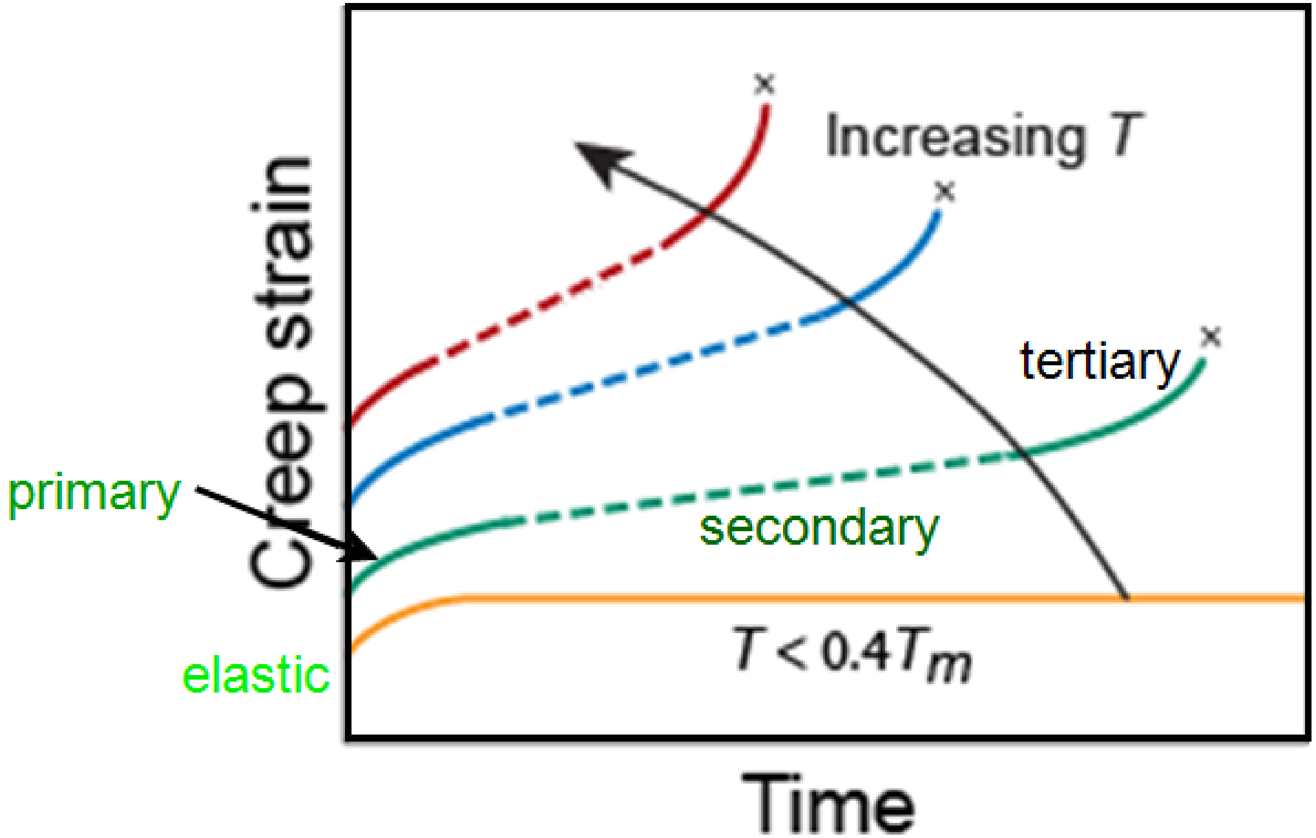
Primary Creep: slope (creep rate) decreases with time.

Secondary Creep: steady-state i.e., constant slope.

Tertiary Creep: slope (creep rate) increases with time, i.e. acceleration of rate.

Creep

- Occurs at elevated temperature, $T > 0.4\ T_m$



Secondary Creep

- Strain rate is constant at a given T, σ
  -- strain hardening is balanced by recovery

$$\dot{\varepsilon}_s = K_2 \sigma^n \exp\left(-\frac{Q_c}{RT}\right)$$

stress exponent (material parameter)

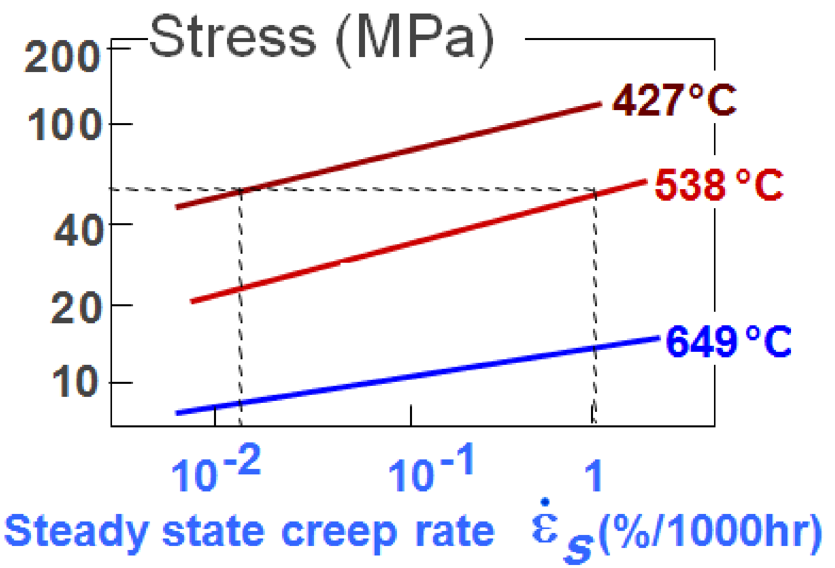
strain rate

material const.

applied stress

activation energy for creep (material parameter)

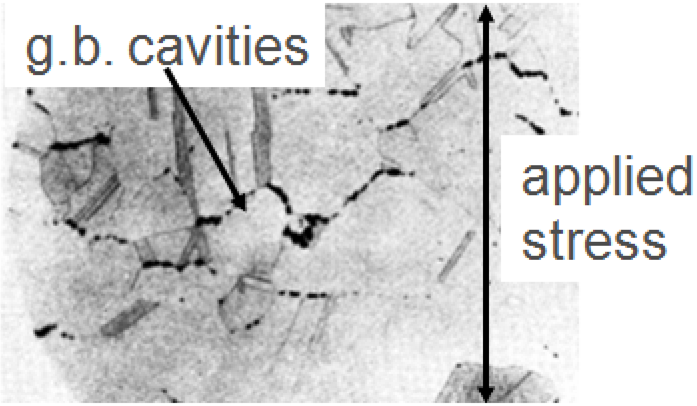
- Strain rate increases for higher T, σ



Creep Failure

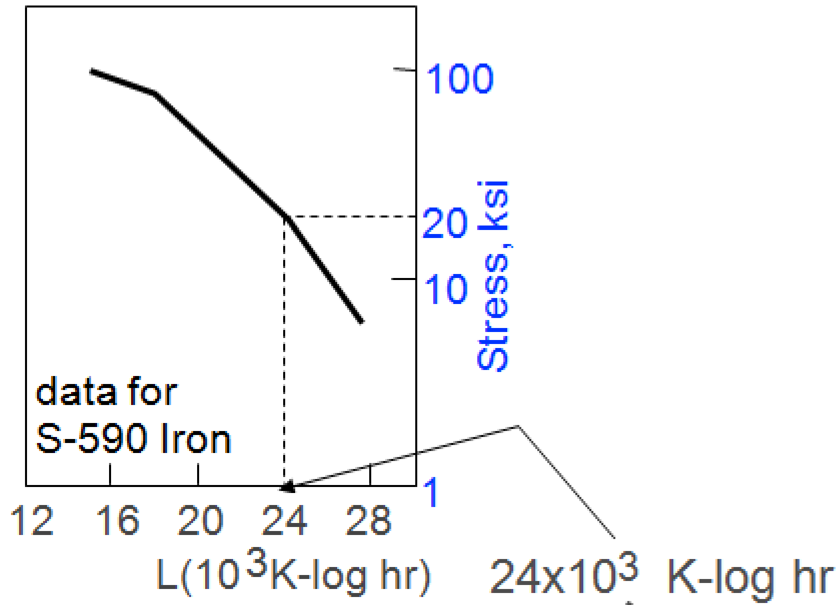
- Failure:

  along grain boundaries.



- Estimate rupture time

  S-590 Iron, $T = 800°C$, $\sigma = 20$ ksi



- Time to rupture, t_r

$$T(20+\log t_r)=L$$

temperature (T)

time to failure (rupture) (t_r)

function of applied stress (L)

$$T(20+\log t_r)=L$$

1073K

Ans: t_r = 233 hr