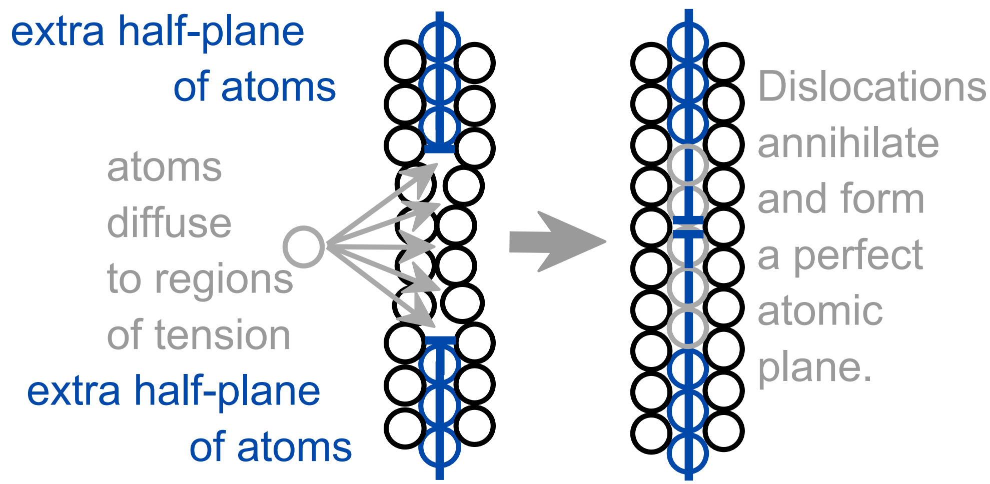
Recovery

Recovery: Rearrangement of dislocations, annihilation reduces dislocation density.

- **Scenario 1**

  Results from diffusion

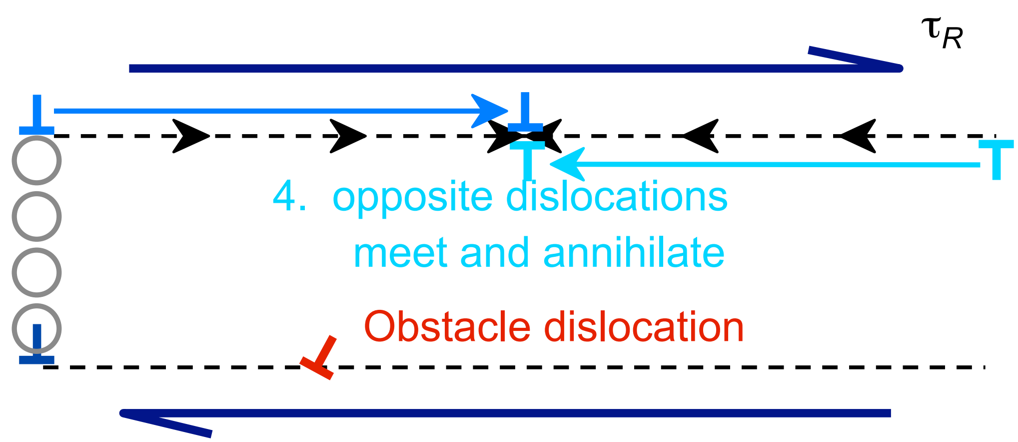


- **Scenario 2**

  3. "Climbed" disl. can now move on new slip plane

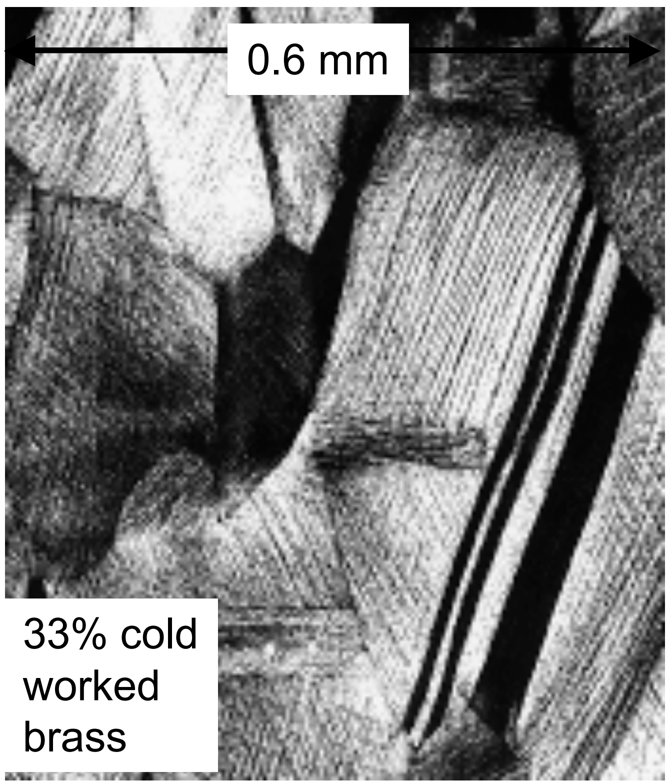
  2. grey atoms leave by vacancy diffusion allowing disl. to "climb"

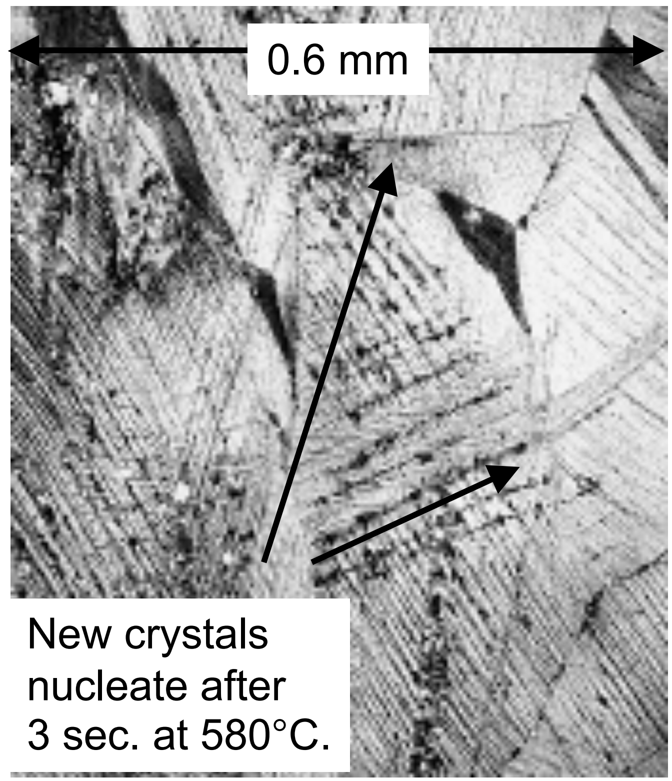
  1. dislocation blocked; can't move to the right



Recrystallization

- New grains are formed that:
  -- have a small dislocation density
  -- are small
  -- consume cold-worked grains.

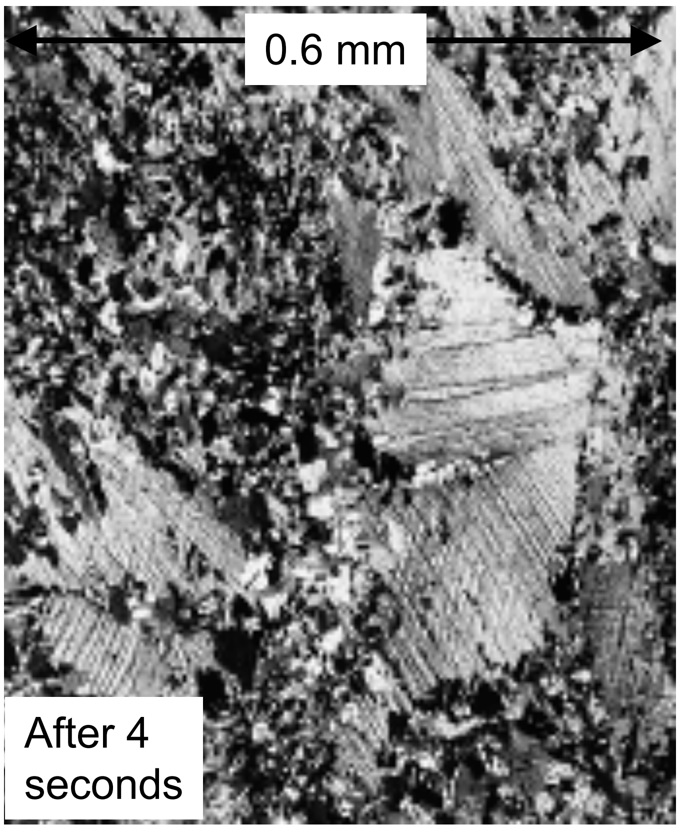


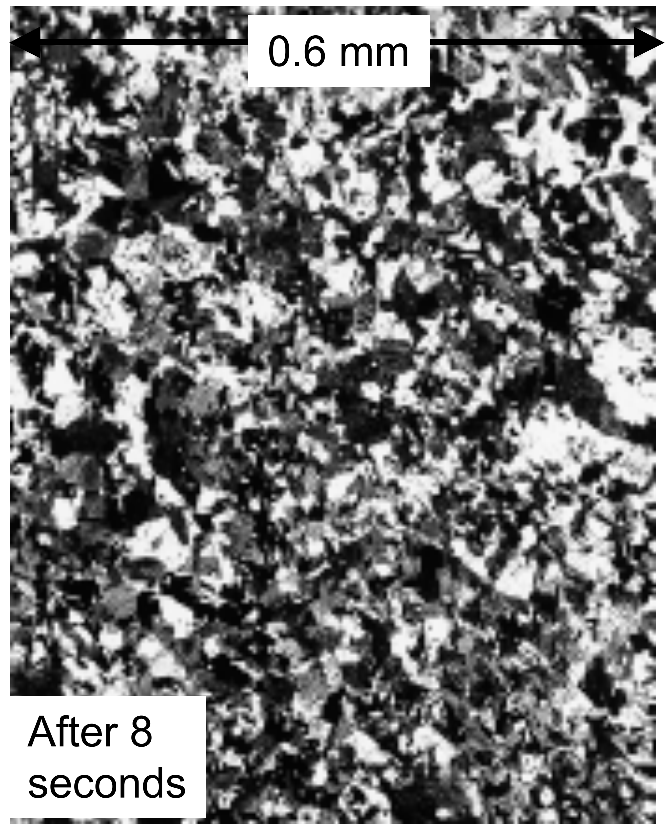


Adapted from Fig. 7.21 (a),(b), *Callister 7e.* (Fig. 7.21 (a),(b) are courtesy of J.E. Burke, General Electric Company.)

Further recrystallization

- All cold-worked grains are consumed.

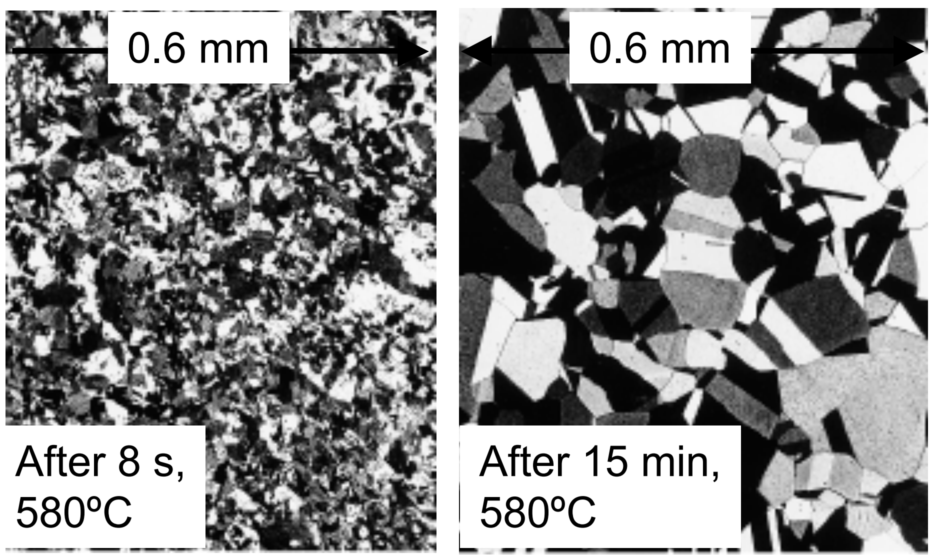




Adapted from Fig. 7.21 (c),(d), *Callister 7e.* (Fig. 7.21 (c),(d) are courtesy of J.E. Burke, General Electric Company.)

Grain growth

- At longer times, larger grains consume smaller ones.
- Why? Grain boundary area (and therefore energy) is reduced.



Adapted from Fig. 7.21 (d),(e), *Callister 7e.* (Fig. 7.21 (d),(e) are courtesy of J.E. Burke, General Electric Company.)

- Empirical Relation:

coefficient dependent on material and *T*.

exponent typ. ~ 2

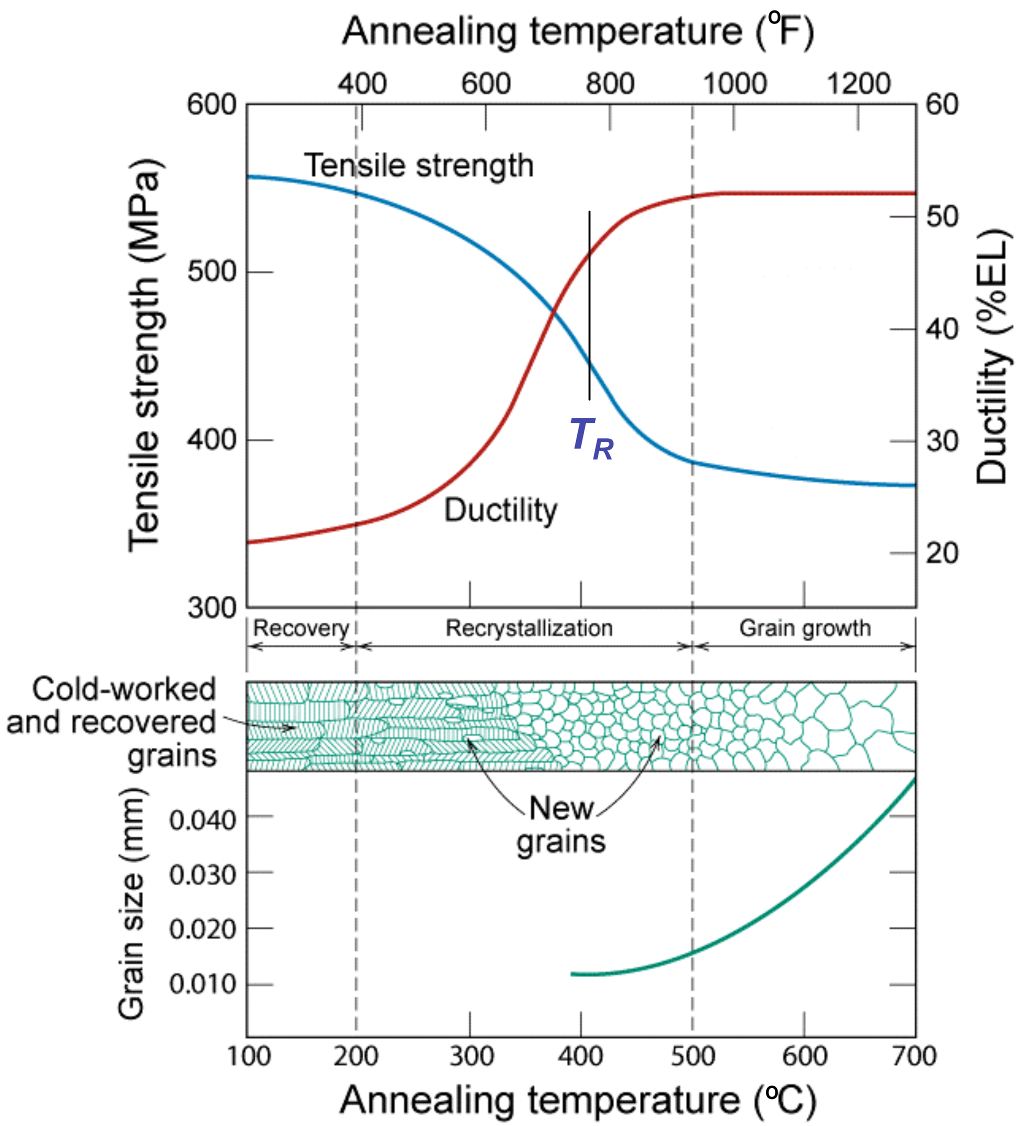
grain diam. at time t.

elapsed time

$$d^n - d_o^n = Kt$$

Ostwald Ripening

Influence of temperature on strength and ductility



T_R = recrystallization temperature

Adapted from Fig. 7.22, *Callister 7e.*

Influence of temperature on strength and ductility

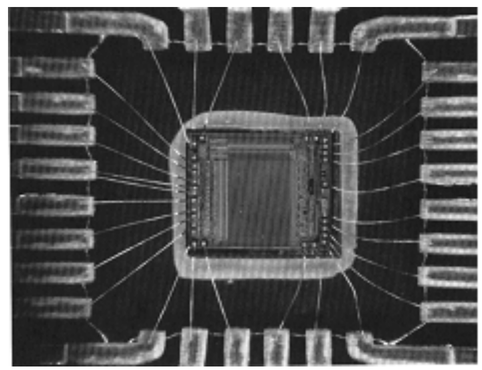
- **T_R = recrystallization temperature = point of highest rate of property change**
  - T_m => $T_R \approx 0.3\text{-}0.6\ T_m$ (K)
  - Due to diffusion → annealing time→ $T_R = f(t)$ shorter annealing time => higher T_R
  - Higher %CW => lower T_R – strain hardening
  - Easier to move in pure metals => lower T_R

Mechanical failure

- How do flaws in a material initiate failure?
- How is fracture resistance quantified; how do different material classes compare?
- How do we estimate the stress to fracture?
- How do loading rate, loading history, and temperature affect the failure stress?

Ship-cyclic loading from waves.

Adapted from chapter-opening photograph, Chapter 8, *Callister 7e.* (by Neil Boenzi, *The New York Times.*)



Computer chip-cyclic thermal loading.

Adapted from Fig. 22.30(b), *Callister 7e.* (Fig. 22.30(b) is courtesy of National Semiconductor Corporation.)

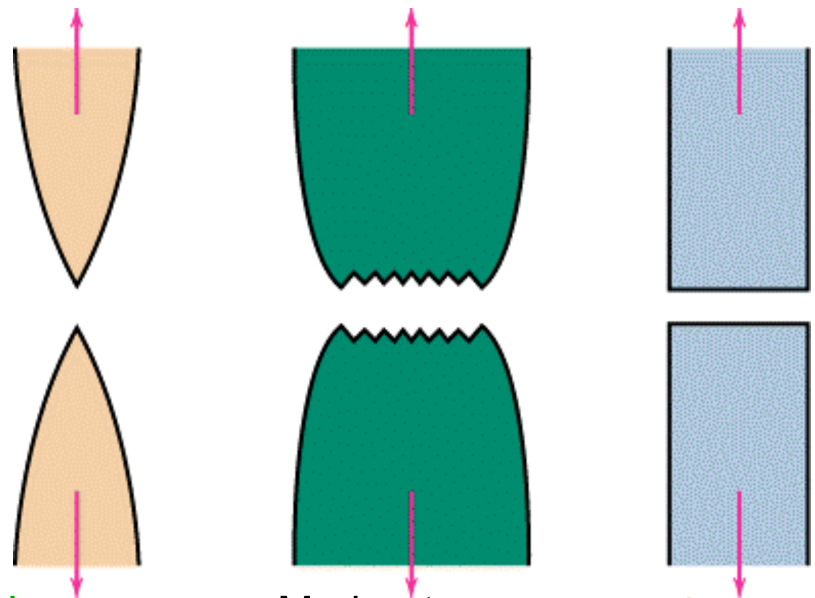
Hip implant-cyclic loading from walking.

Adapted from Fig. 22.26(b), *Callister 7e.*

Ductile vs. brittle failure

- Classification:

Fracture behavior:	Very Ductile	Moderately Ductile	Brittle



Adapted from Fig. 8.1, *Callister 7e.*

%AR or *%EL*	Large	Moderate	Small

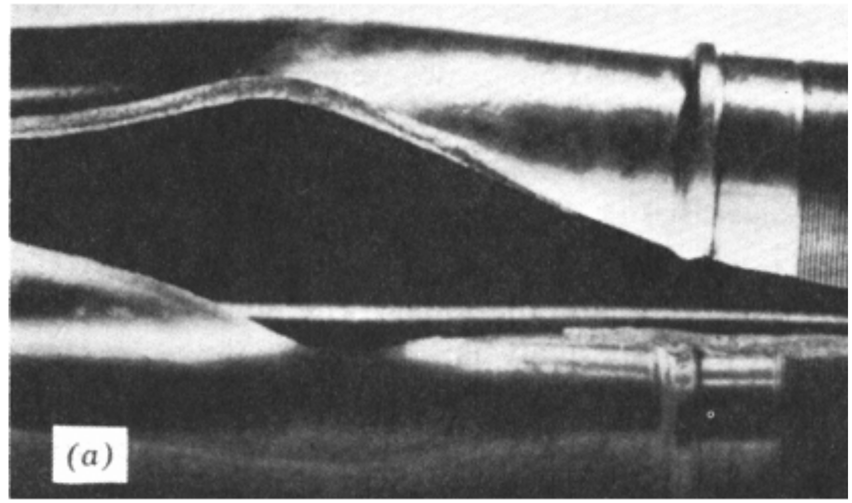
- Ductile fracture is usually desirable!

Ductile: warning before fracture

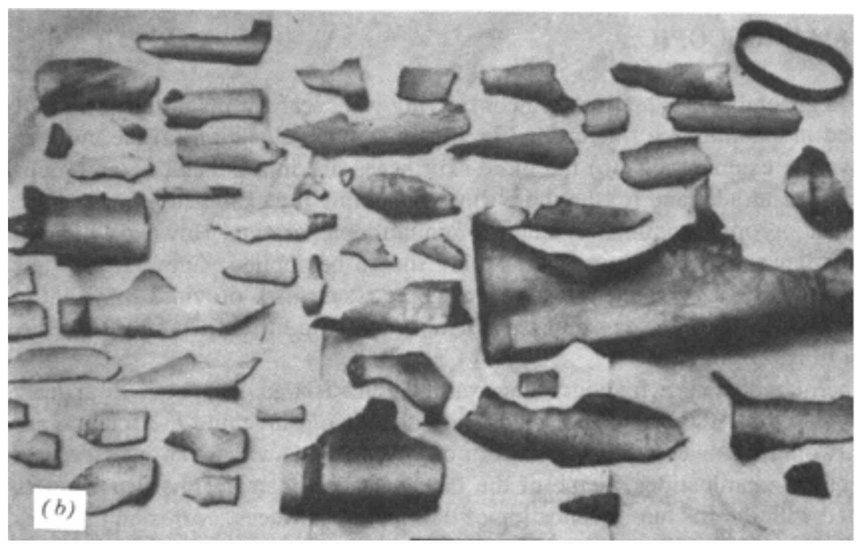
Brittle: No warning

Example: failure of a pipe

- **Ductile failure:**
  --one piece
  --large deformation



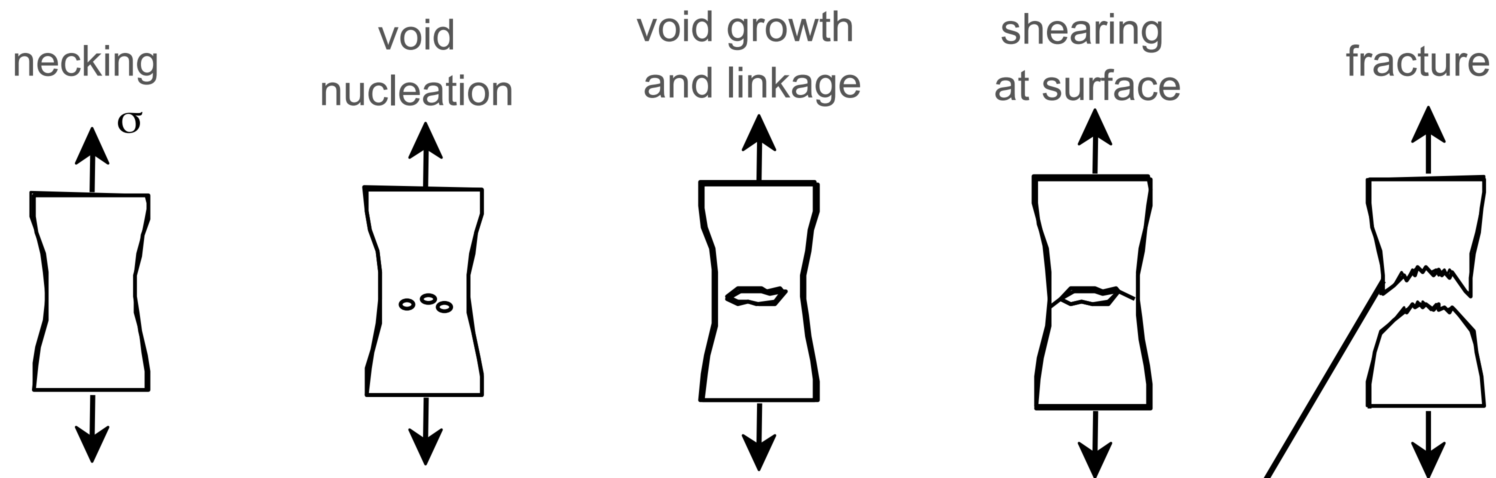
- **Brittle failure:**
  --many pieces
  --small deformation



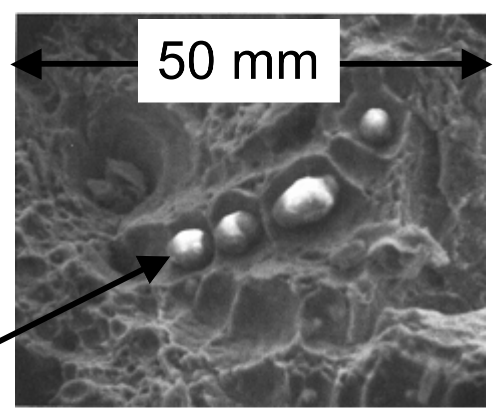
Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66 John Wiley and Sons, Inc., 1987. Used with permission.

Moderately ductile failure

- Evolution to failure:

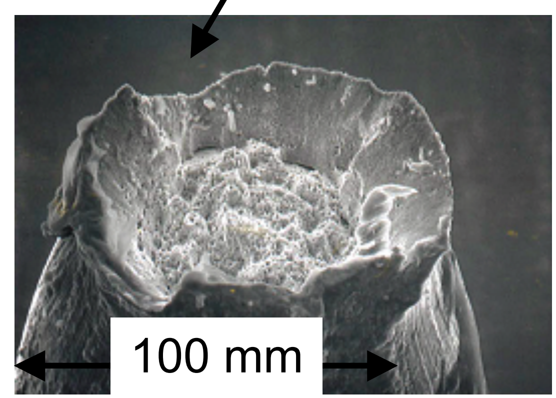


- Resulting fracture surfaces (steel)



particles serve as void nucleation sites.

From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 11.28, p. 294, John Wiley and Sons, Inc., 1987. (Orig. source: P. Thornton, *J. Mater. Sci*., Vol. 6, 1971, pp. 347-56.)



Fracture surface of tire cord wire loaded in tension. Courtesy of F. Roehrig, CC Technologies, Dublin, OH. Used with permission.

Ductile vs. brittle failure

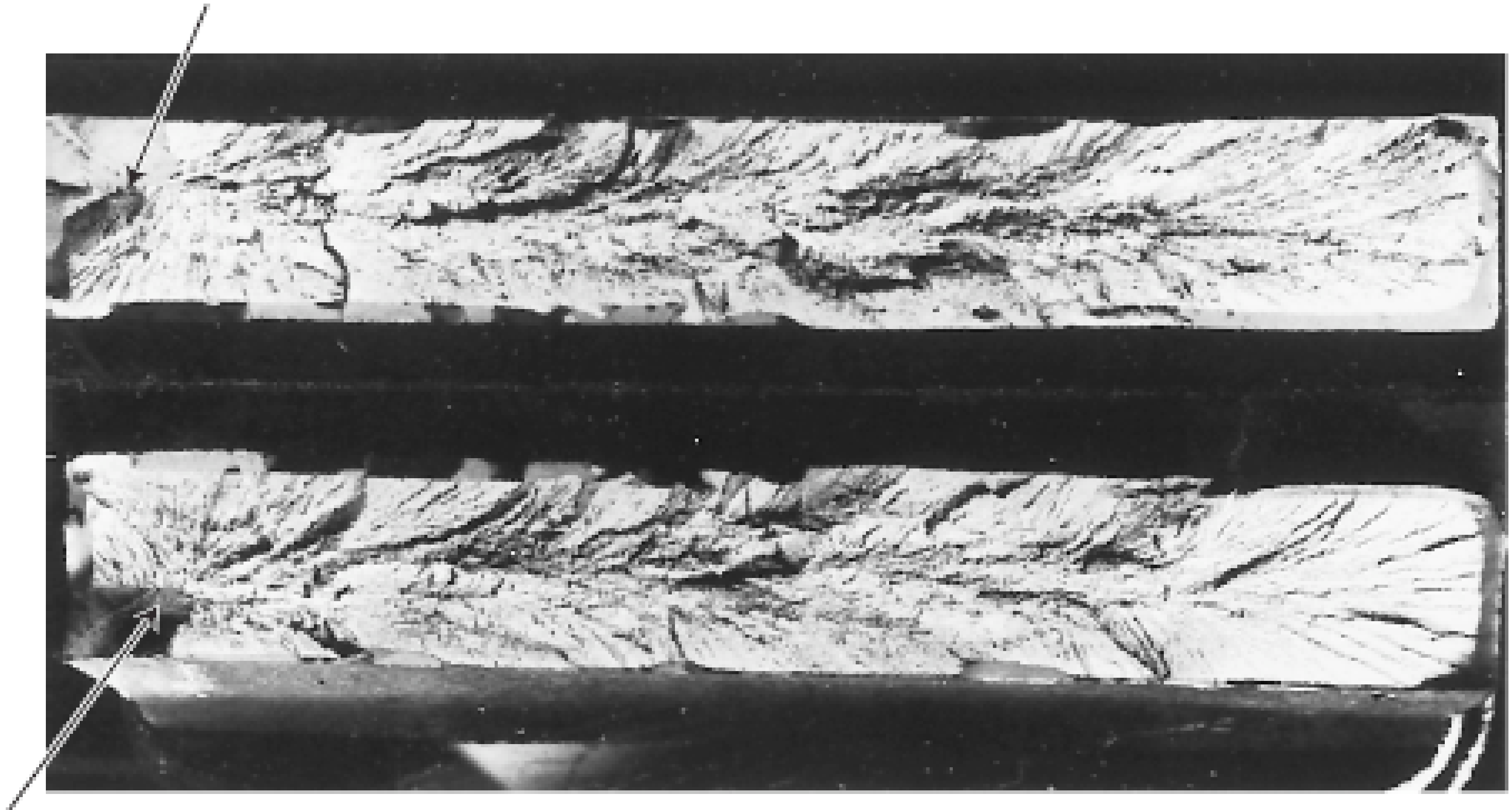
cup-and-cone fracture

brittle fracture

Adapted from Fig. 8.3, *Callister 7e.*

Brittle failure

Arrows indicate point at which failure originated

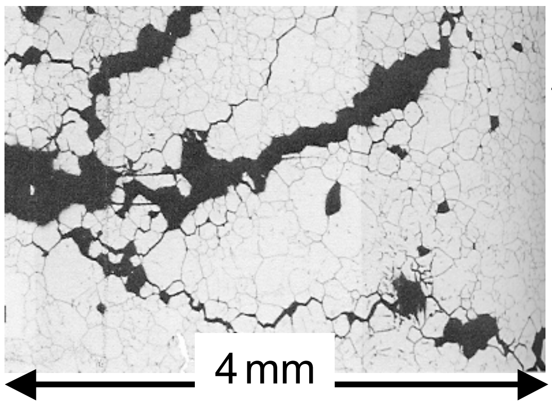


(a)

Adapted from Fig. 8.5(a), *Callister 7e.*

Brittle fracture surfaces

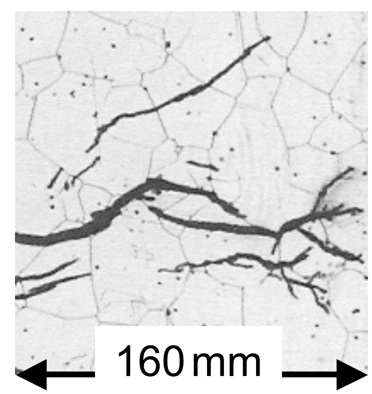
- Intergranular (between grains)



304 S. Steel (metal)
Reprinted w/permission from "Metals Handbook", 9th ed, Fig. 633, p. 650. Copyright 1985, ASM International, Materials Park, OH. (Micrograph by J.R. Keiser and A.R. Olsen, Oak Ridge National Lab.)

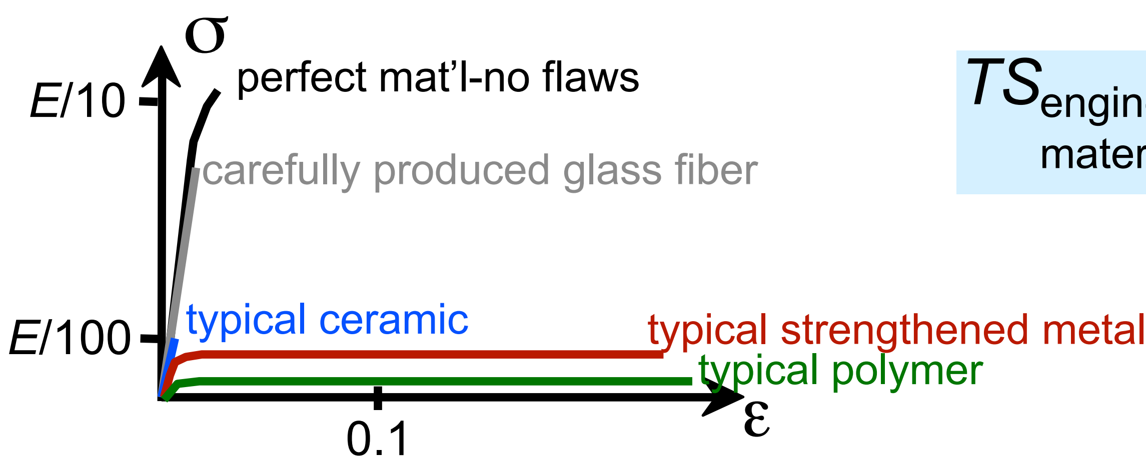
- Intragranular (within grains)

316 S. Steel (metal)
Reprinted w/ permission from "Metals Handbook", 9th ed, Fig. 650, p. 357. Copyright 1985, ASM International, Materials Park, OH. (Micrograph by D.R. Diercks, Argonne National Lab.)



Ideal vs. real materials

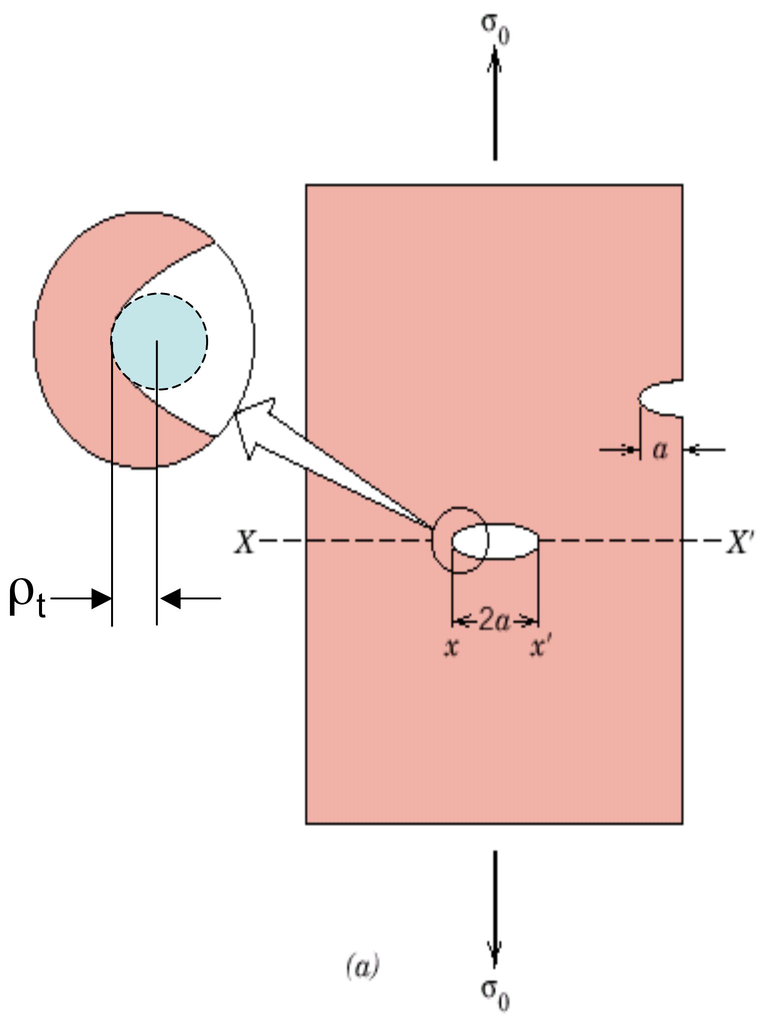
- Stress-strain behavior (Room *T*):



$TS_{\text{engineering materials}} << TS_{\text{perfect materials}}$

Flaws are Stress Concentrators!

Ideal vs. real materials



Adapted from Fig. 8.8(a), *Callister 7e.*

Griffith Crack

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

where

ρ_t = radius of curvature
σ_o = applied stress
σ_m = stress at crack tip

Crack propagation

Crack propagates if above critical stress

i.e., $\sigma_m > \sigma_c$

or $K_t > K_c$

$$\sigma_c = \left(\frac{2E\gamma_s}{\pi a}\right)^{1/2}$$

where

E = modulus of elasticity

γ_s = specific surface energy

a = one half length of internal crack

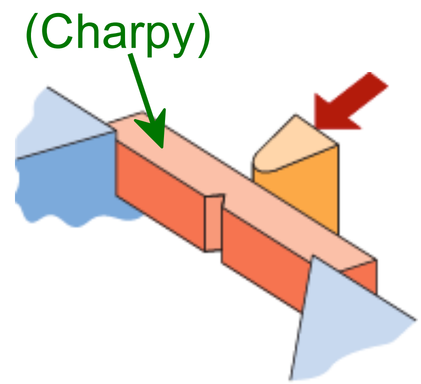
$K_c = \sigma_c/\sigma_0$

For ductile => replace γ_s by $\gamma_s + \gamma_p$

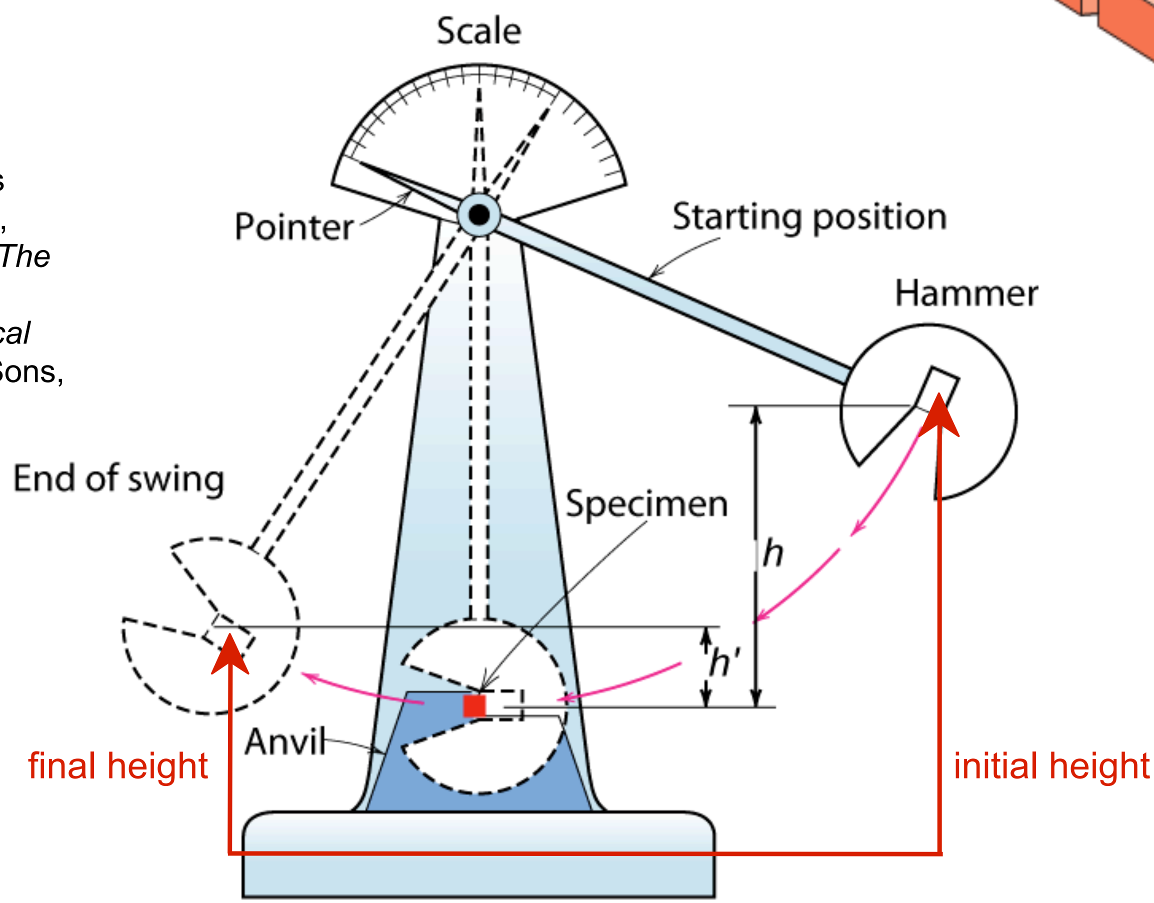
where γ_p is plastic deformation energy

Impact testing

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



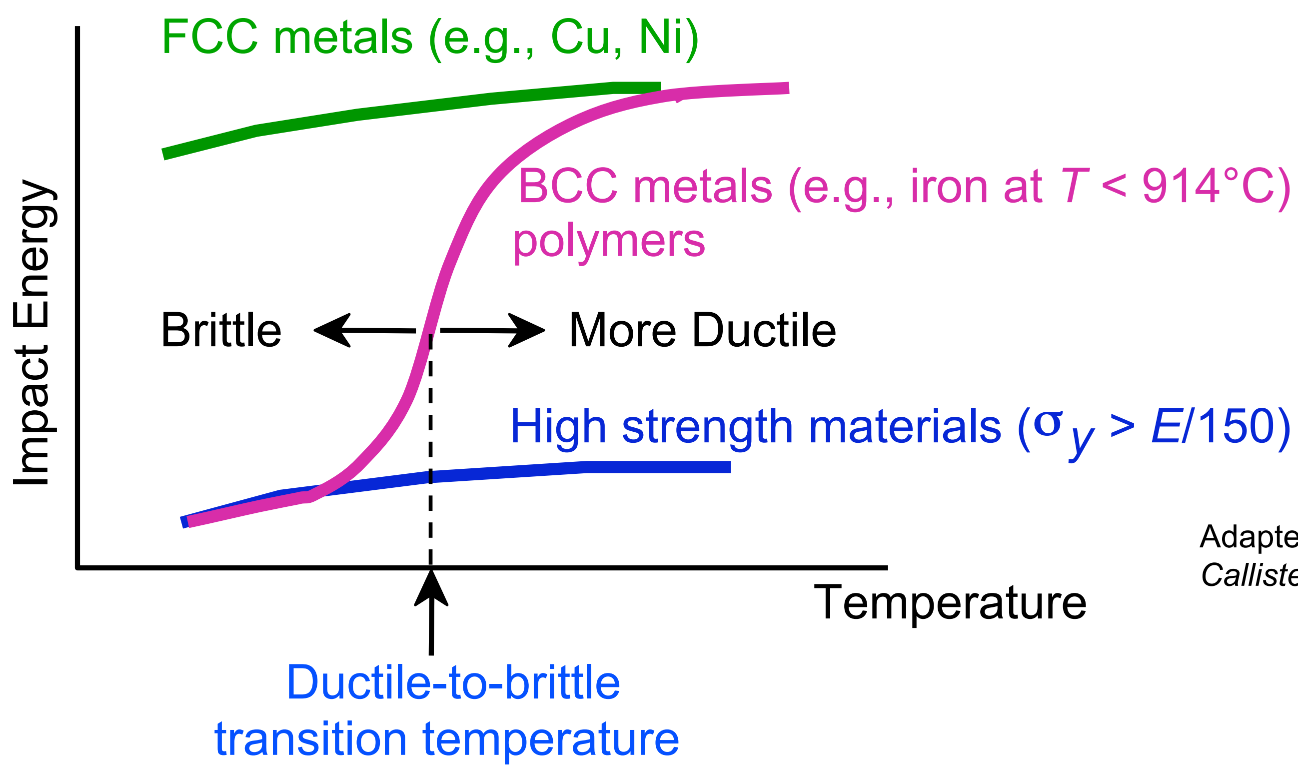
Adapted from Fig. 8.12(b), *Callister 7e.* (Fig. 8.12(b) is adapted from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, John Wiley and Sons, Inc. (1965) p. 13.)



Temperature effects

- **Increasing temperature...**
  --increases %*EL* and K_c

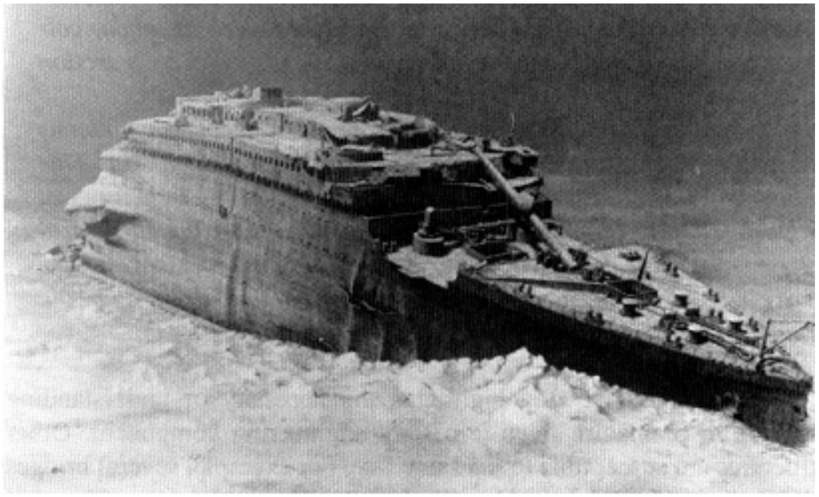
- **Ductile-to-Brittle Transition Temperature (DBTT)...**



Adapted from Fig. 8.15, *Callister 7e.*

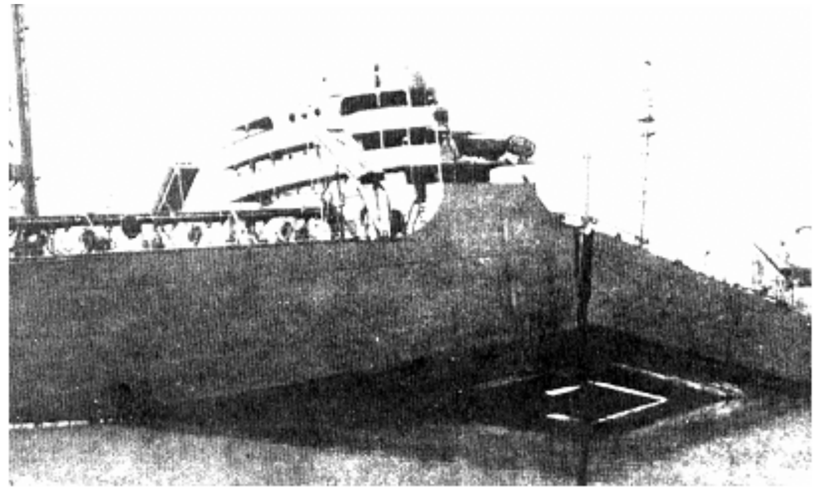
Stay above DBTT

- **Pre-WWII: The Titanic**



Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(a), p. 262, John Wiley and Sons, Inc., 1996. (Orig. source: Dr. Robert D. Ballard, *The Discovery of the Titanic*.)

- **WWII: Liberty ships**

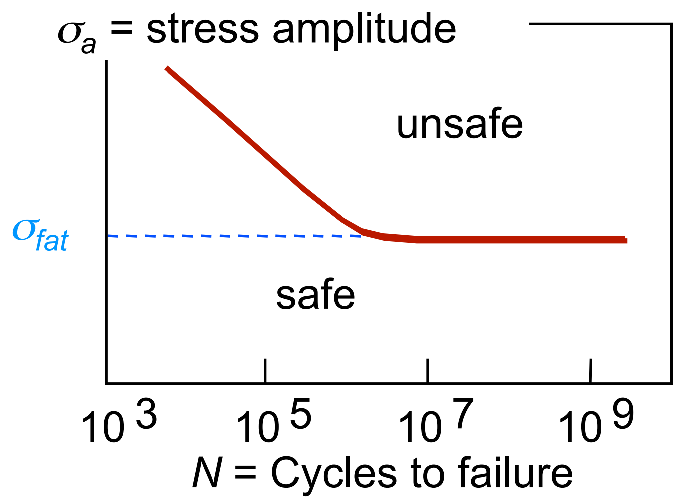


Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(b), p. 262, John Wiley and Sons, Inc., 1996. (Orig. source: Earl R. Parker, "Behavior of Engineering Structures", Nat. Acad. Sci., Nat. Res. Council, John Wiley and Sons, Inc., NY, 1957.)

- Problem: Used a type of steel with a DBTT ~ Room temp.

Fatigue

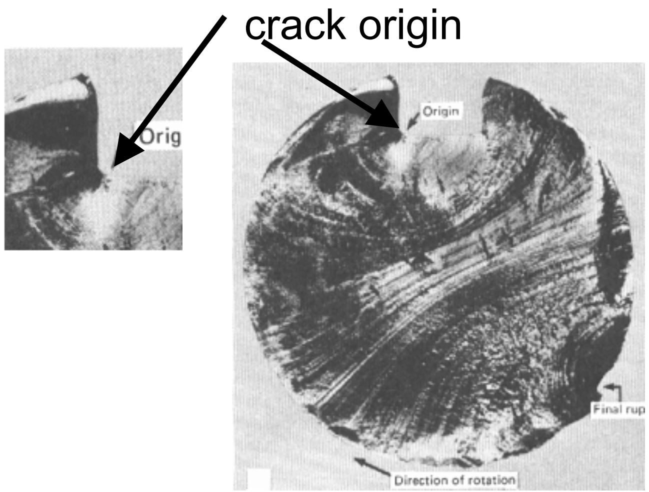
- Fatigue limit, σ_{fat}:
  --no fatigue if $\sigma < \sigma_{fat}$

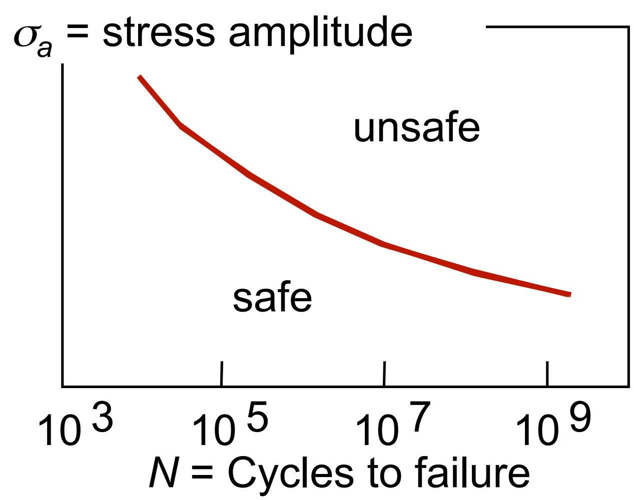


case for
steel (typ.)

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

- Sometimes, the
  fatigue limit is zero!



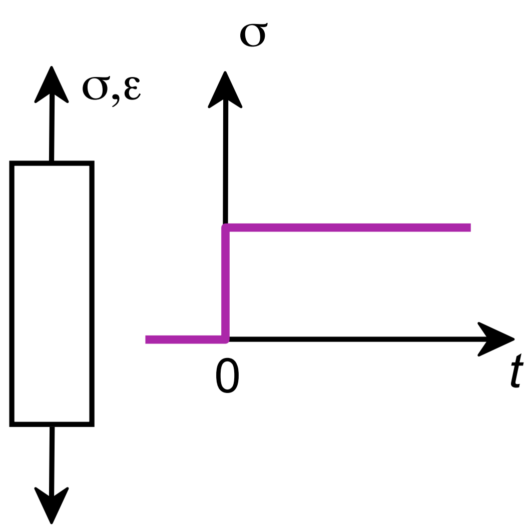


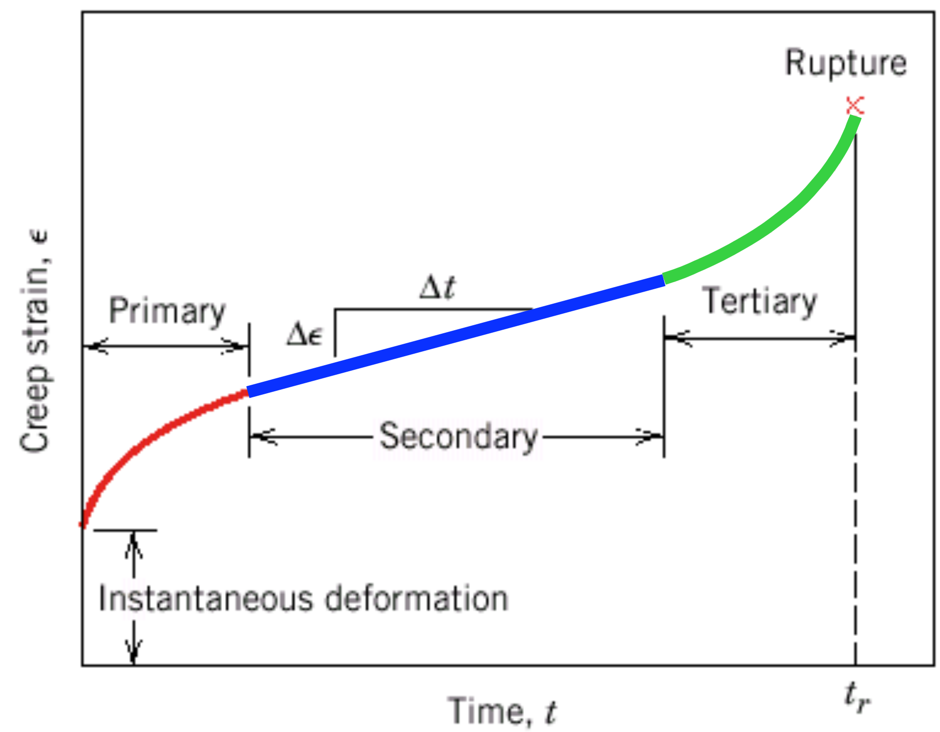
case for
Al (typ.)

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

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.

Adapted from
Fig. 8.28, *Callister 7e.*

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)

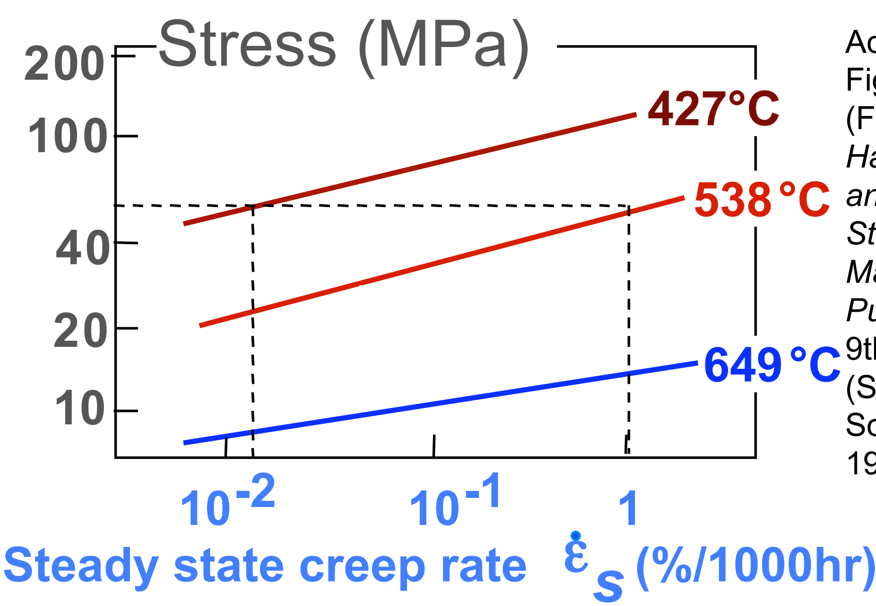
strain rate

material const.

applied stress

activation energy for creep (material parameter)

- Strain rate increases for higher T, σ



Adapted from Fig. 8.31, *Callister 7e.* (Fig. 8.31 is from *Metals Handbook: Properties and Selection: Stainless Steels, Tool Materials, and Special Purpose Metals*, Vol. 3, 9th ed., D. Benjamin (Senior Ed.), American Society for Metals, 1980, p. 131.)