Recovery
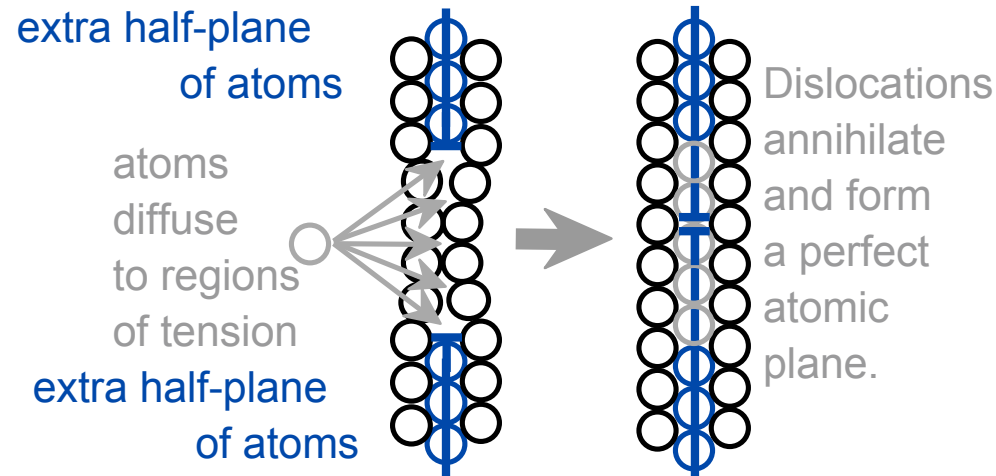
Recovery: Rearrangement of dislocations, annihilation reduces dislocation density.

- **Scenario 1**

  Results from diffusion

  extra half-plane of atoms

  atoms diffuse to regions of tension

  extra half-plane of atoms

  Dislocations annihilate and form a perfect atomic plane.
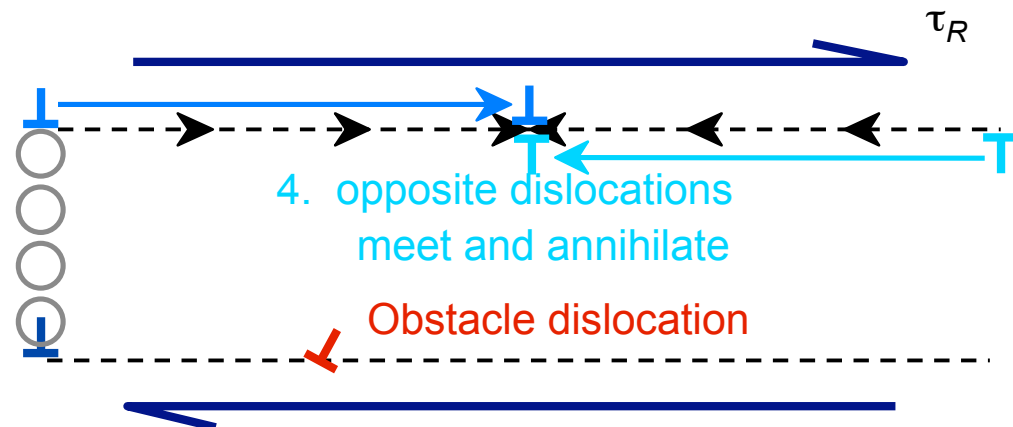
- **Scenario 2**

  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

  τ_R

  4. opposite dislocations meet and annihilate

  Obstacle dislocation

Recrystallization

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

0.6 mm

33% cold worked brass

0.6 mm

New crystals nucleate after 3 sec. at 580°C.
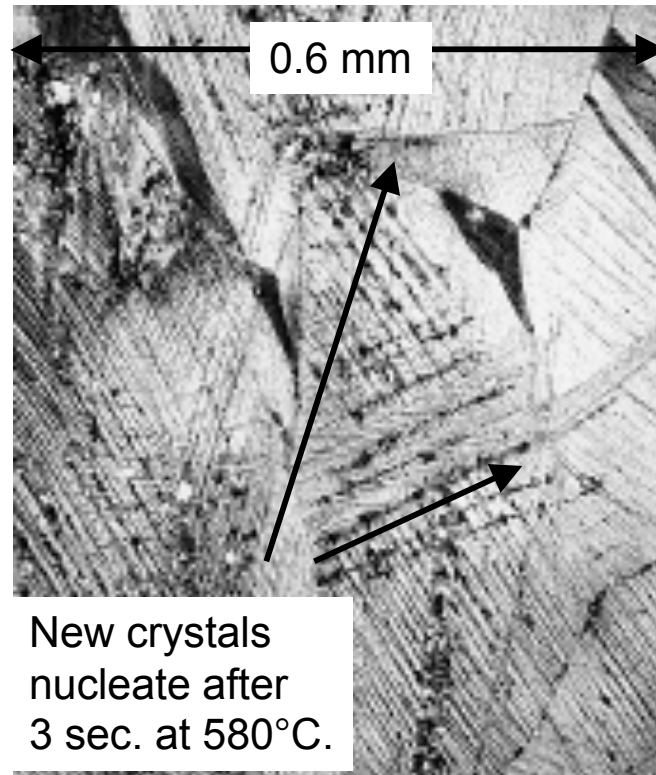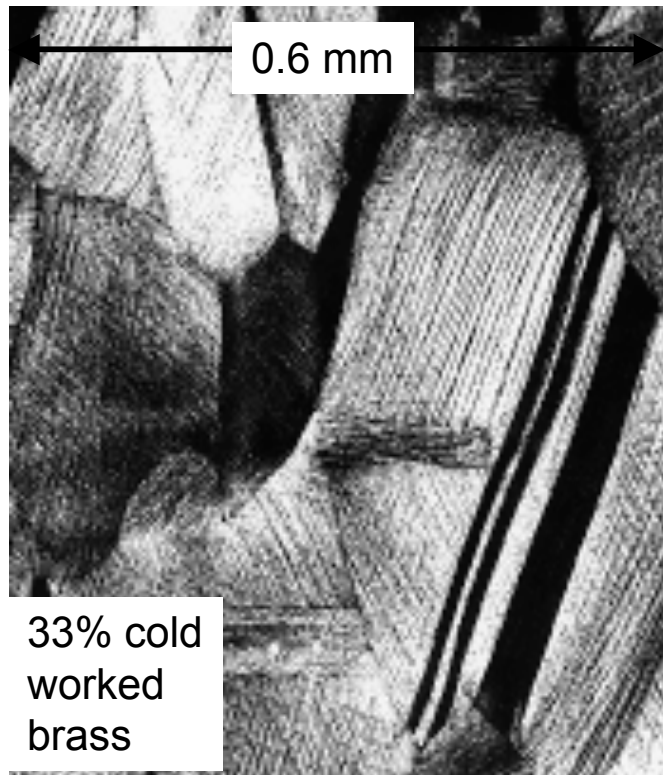
Adapted from Fig. 7.21 (a),(b), *Callister* 7e. (Fig. 7.21 (a),(b) are courtesy of J.E. Burke, General Electric Company.)

Further recrystallization

- All cold-worked grains are consumed.

0.6 mm

After 4 seconds

0.6 mm

After 8 seconds
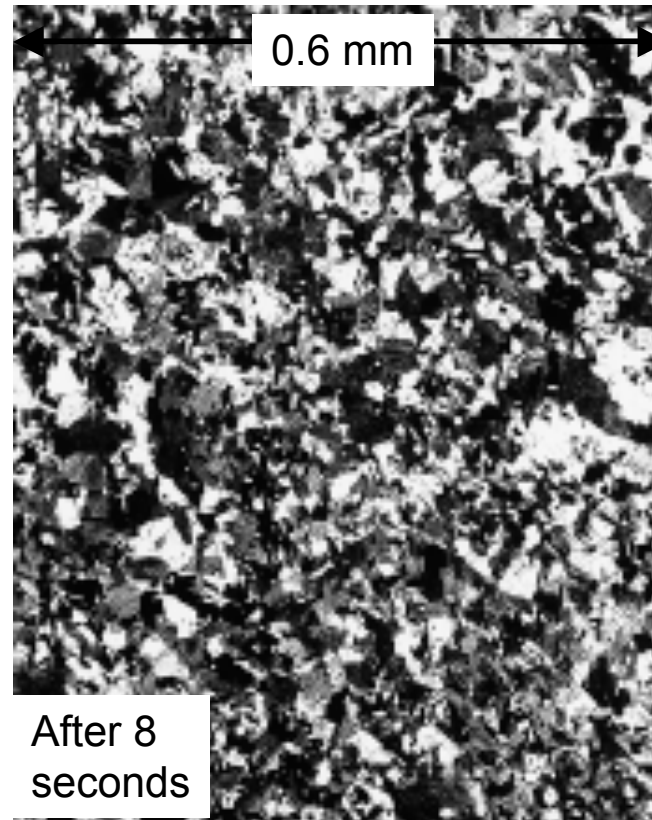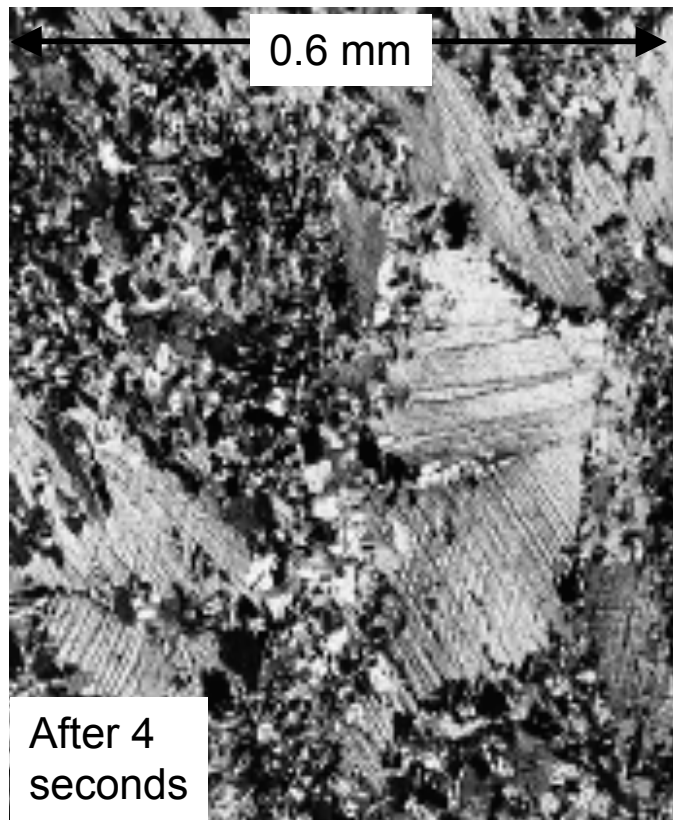
Adapted from Fig. 7.21 (c),(d), *Callister 7e.* (Fig. 7.21 (c),(d) are courtesy of J.E. Burke, General Electric Company.)

Grain growth

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

0.6 mm

0.6 mm

After 8 s, 580ºC

After 15 min, 580ºC
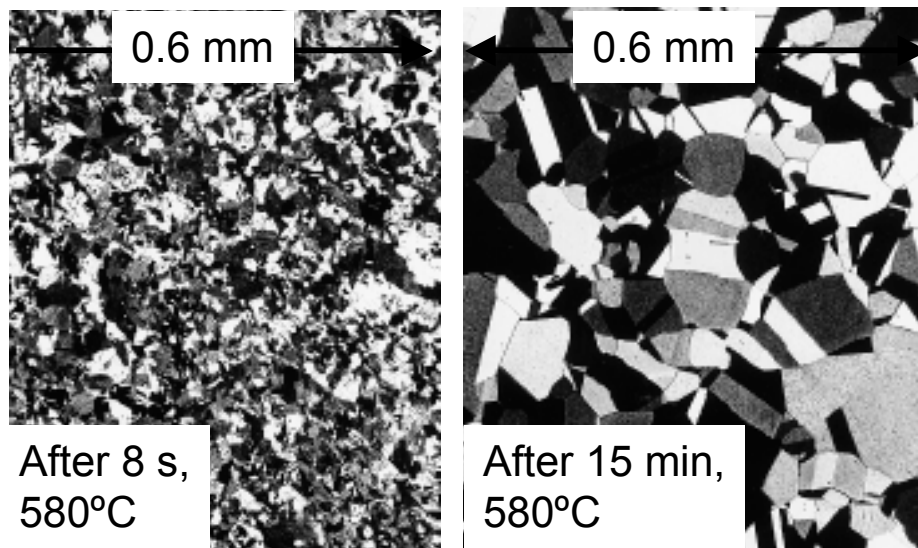
Adapted from Fig. 7.21 (d),(e), *Callister 7e.* (Fig. 7.21 (d),(e) are courtesy of J.E. Burke, General Electric Company.)

- Empirical Relation:

grain diam. at time t.

exponent typ. ~ 2
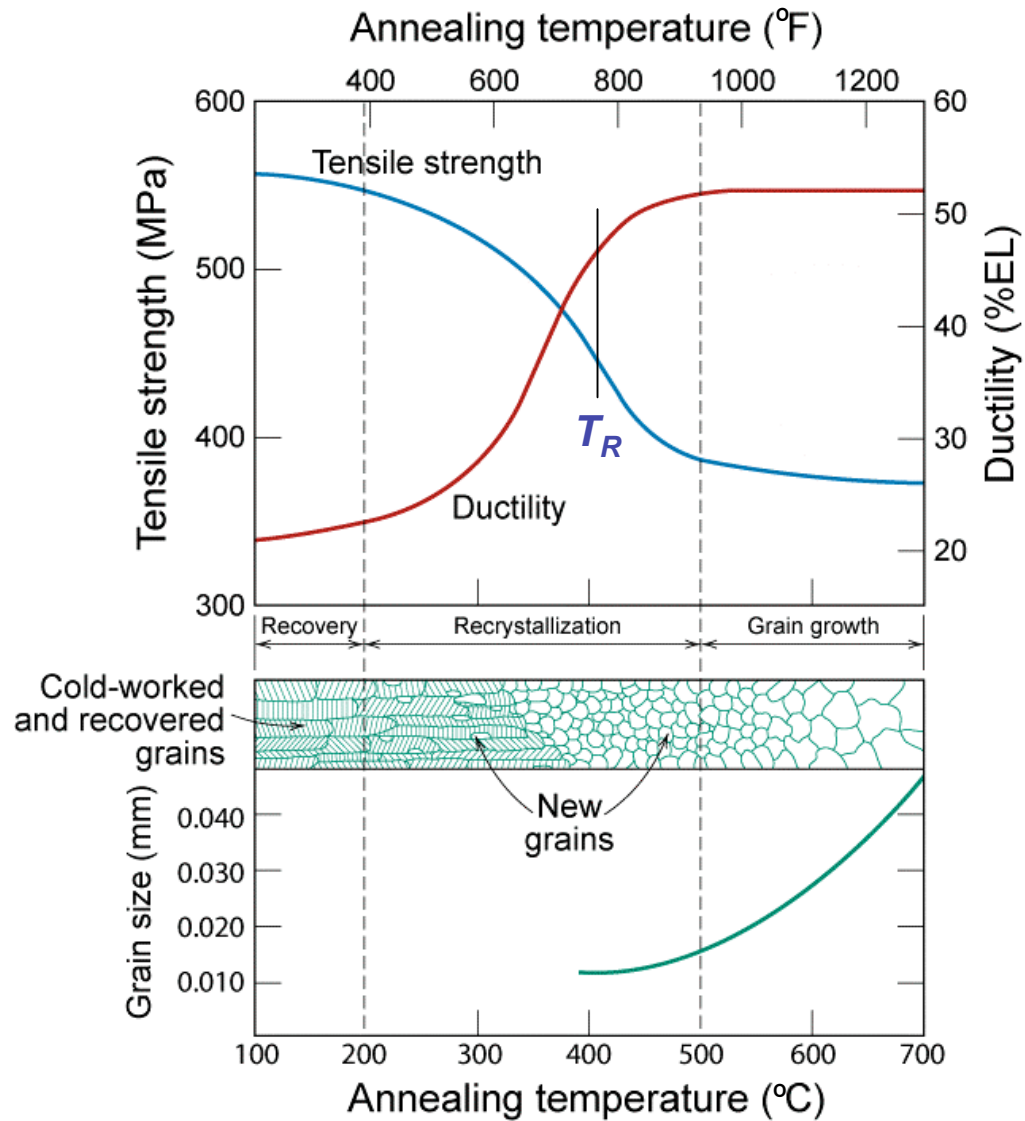
coefficient dependent on material and *T*.

elapsed time

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

Ostwald Ripening

4

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 => $T_R \approx$ 0.3-0.6 T_m (K)

  - Due to diffusion $\rightarrow$ annealing time$\rightarrow$ 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*.)
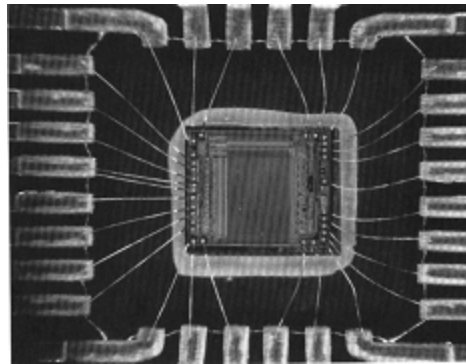
Computer chip-cyclic thermal loading.

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

Hip implant-cyclic loading from walking.

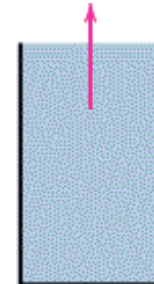Adapted from Fig. 22.26(b), *Callister 7e.*
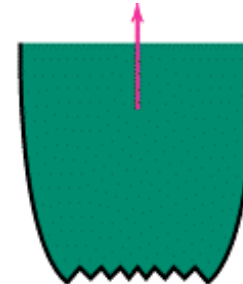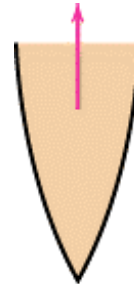
Ductile vs. brittle failure

- Classification:

Fracture behavior:

	Very Ductile	Moderately Ductile	Brittle

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

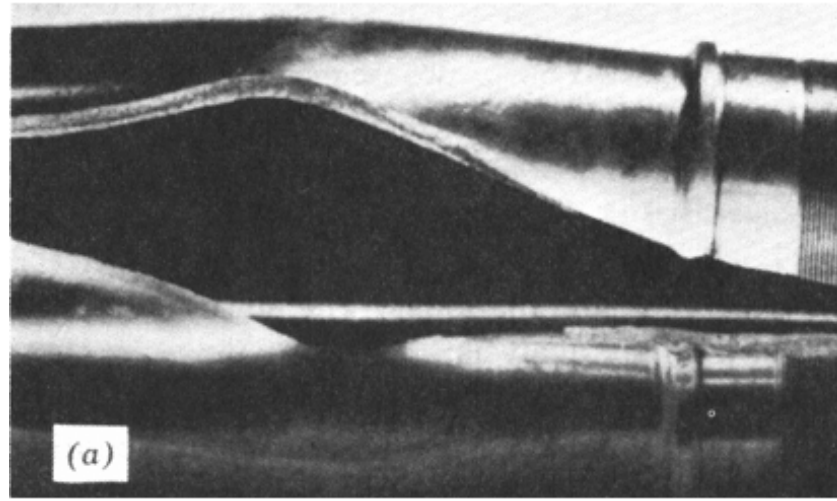%AR or %EL   Large   Moderate   Small

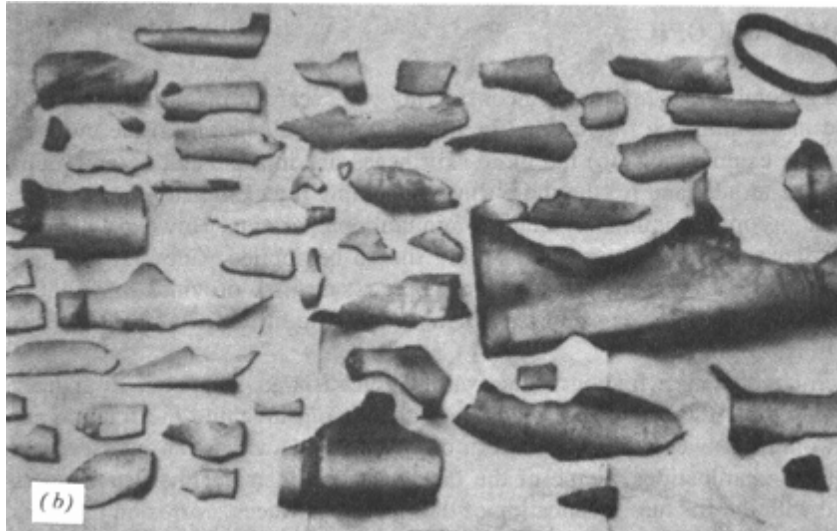- Ductile fracture is usually desirable!

Ductile: warning before fracture

Brittle: No warning

Example: failure of a pipe

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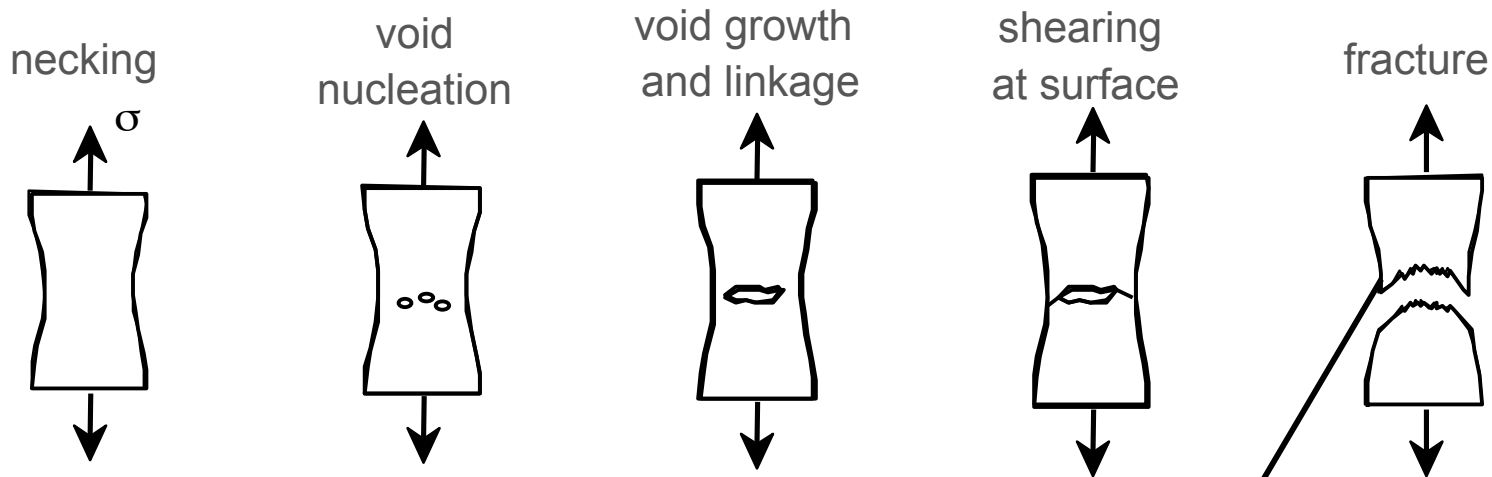 --one piece
  --large deformation

- **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.
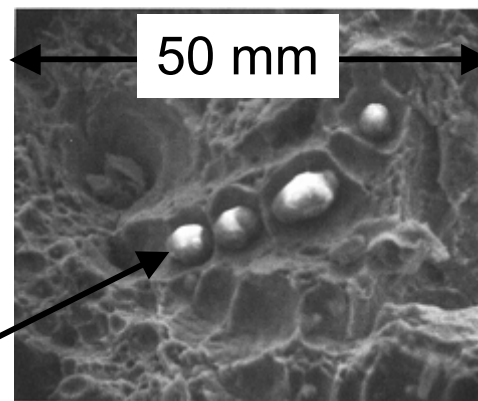
Moderately ductile failure
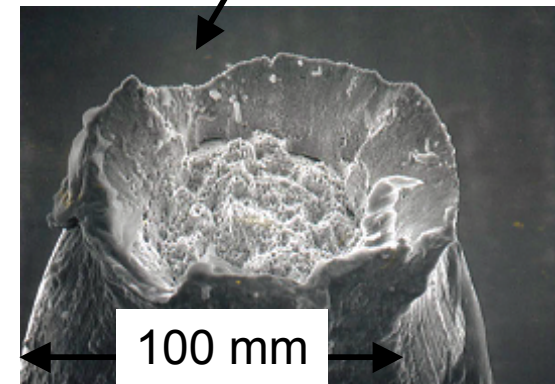
• Evolution to failure:

| necking | void nucleation | void growth and linkage | shearing at surface | fracture |

σ

• Resulting fracture surfaces (steel)

50 mm

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.)

100 mm

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

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Ductile vs. brittle failure
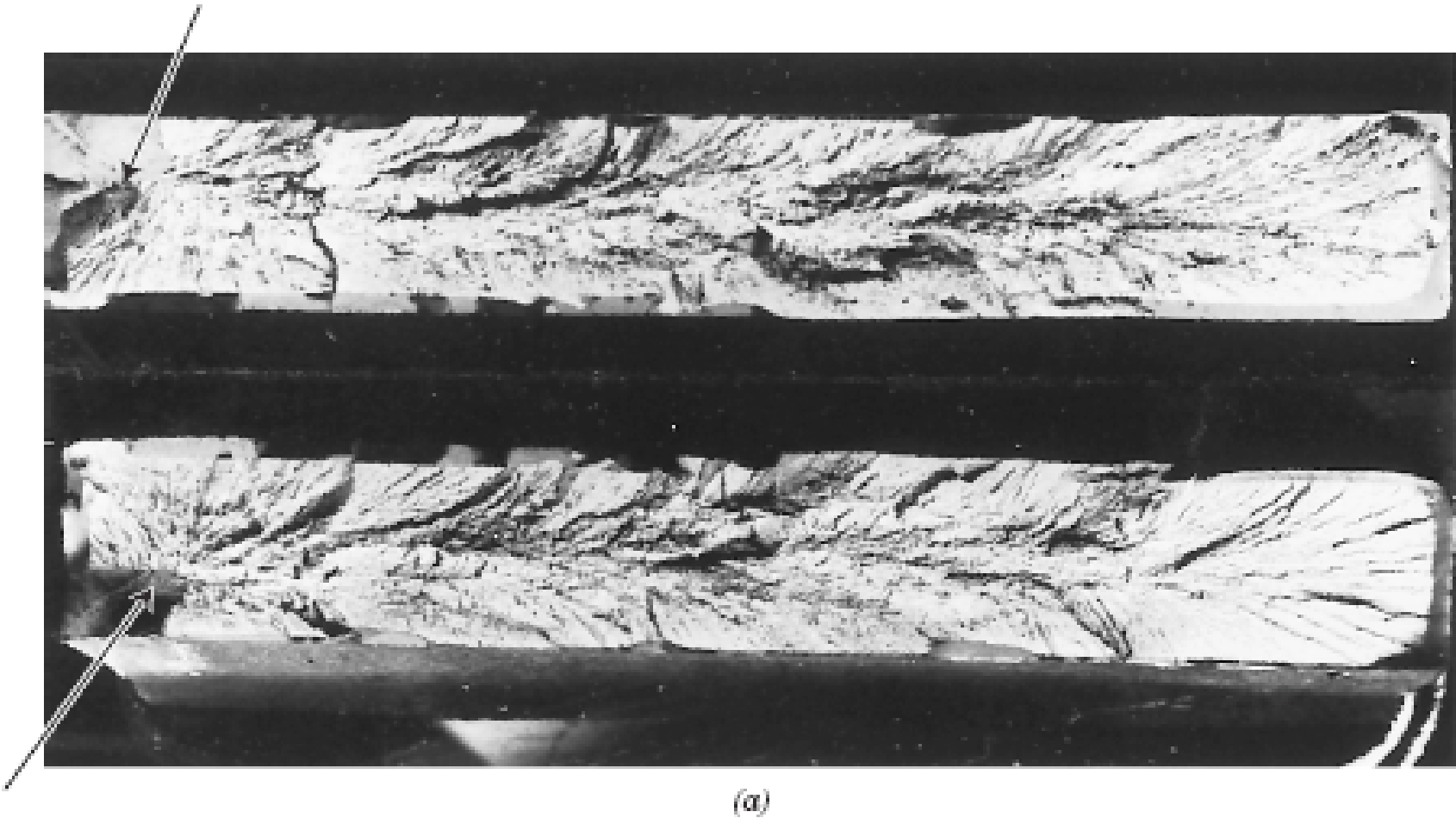

cup-and-cone fracture

brittle fracture

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

Brittle failure

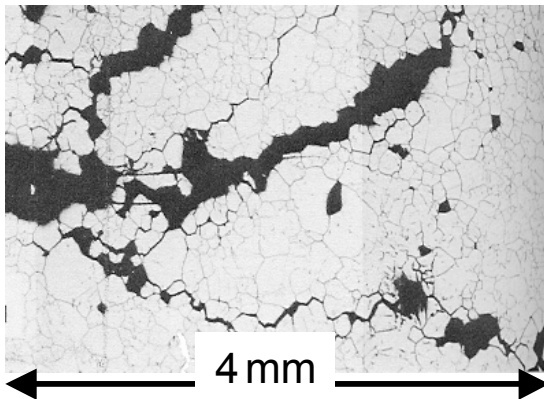Arrows indicate point at which failure originated

(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.)

4 mm

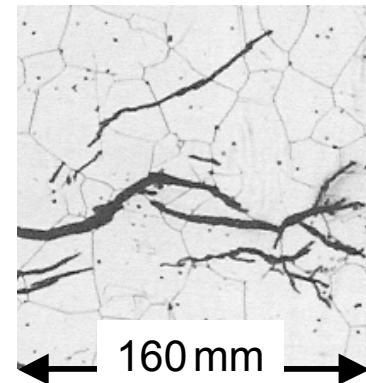- Intragranular
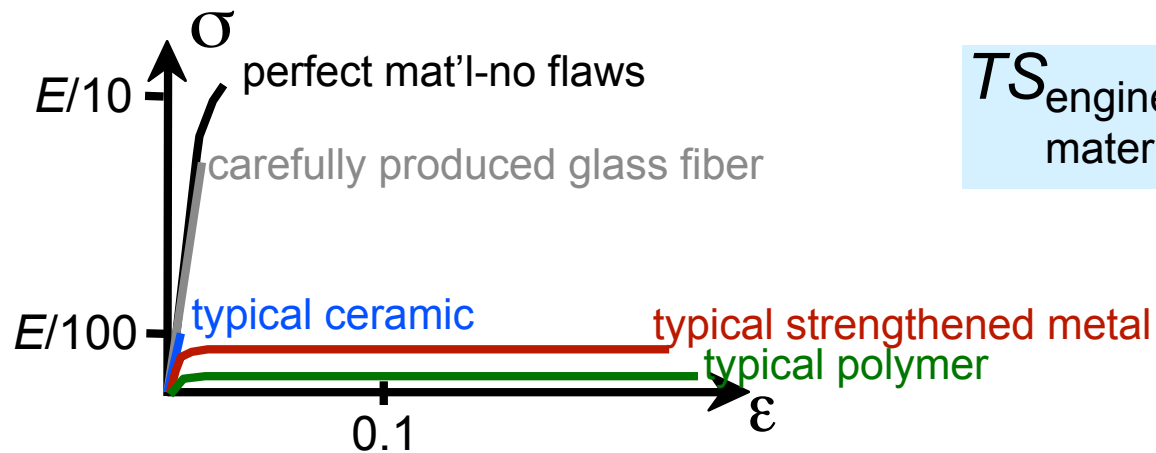(within grains)

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.)

160 mm

Ideal vs. real materials

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

$$TS_{engineering \atop materials} \ll TS_{perfect \atop materials}$$

Flaws are Stress Concentrators!

Ideal vs. real materials

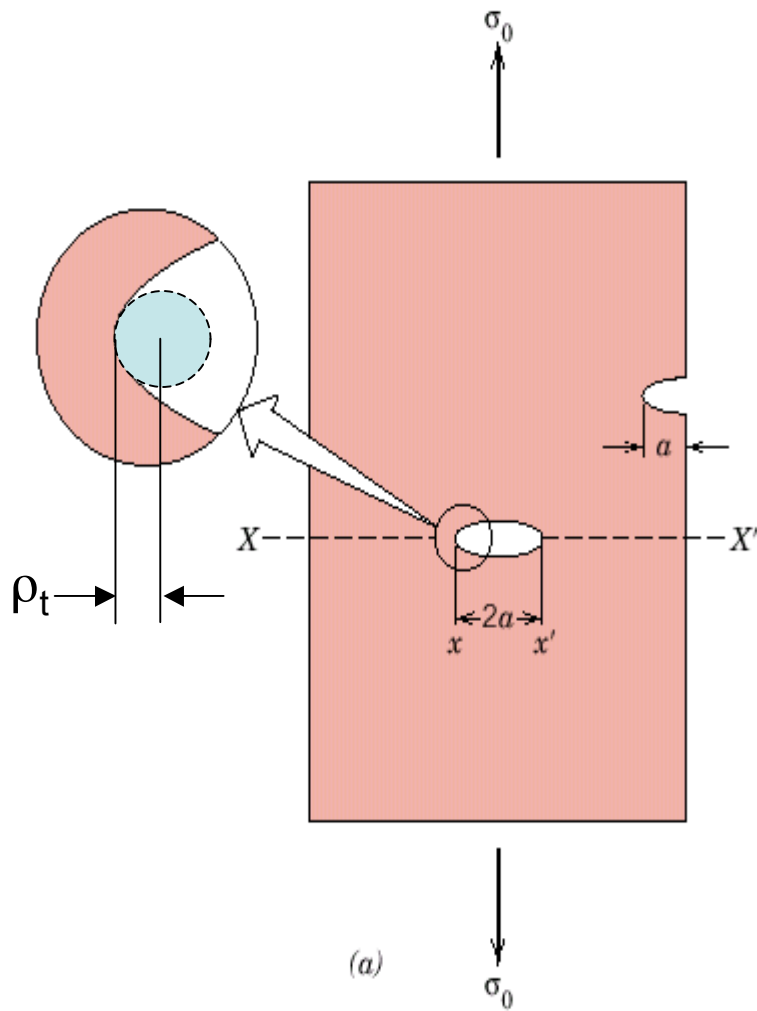Adapted from Fig. 8.8(a), *Callister 7e.*

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

$$\text{i.e.,} \quad \sigma_m > \sigma_c$$

$$\text{or} \quad K_t > K_c$$

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

where

E = modulus of elasticity

γ_s = specific surface energy

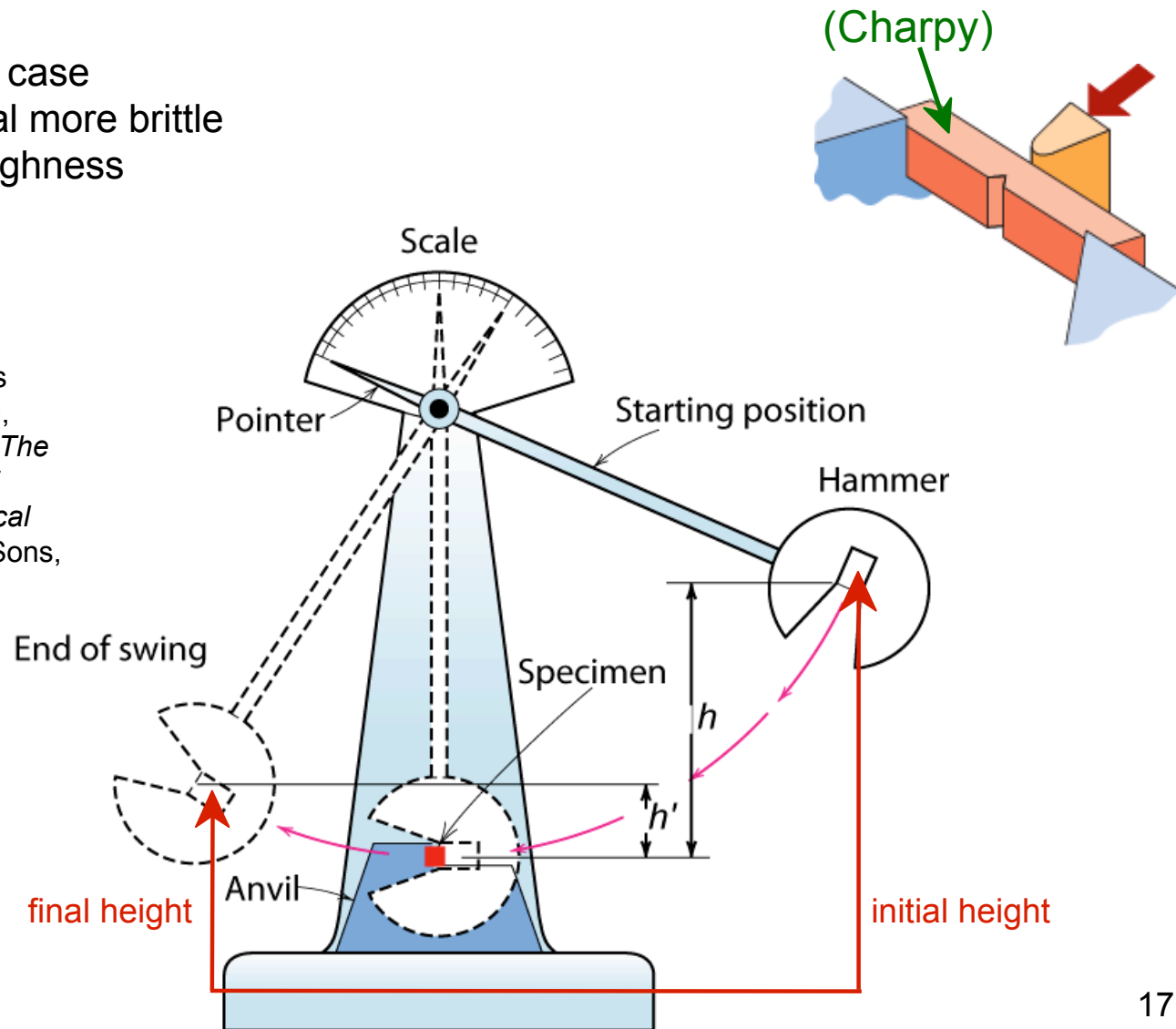a = one half length of internal crack

$K_c = \sigma_c/\sigma_0$

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

(Charpy)

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.)

Scale

Pointer

Starting position

Hammer

End of swing

Specimen

h

h'

Anvil

final height

initial height

Temperature effects

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

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

FCC metals (e.g., Cu, Ni)

BCC metals (e.g., iron at $T < 914°C$)
polymers

Brittle ⟵——⟶ More Ductile

High strength materials ($\sigma_y > E/150$)

Impact Energy

Temperature

Ductile-to-brittle
transition temperature
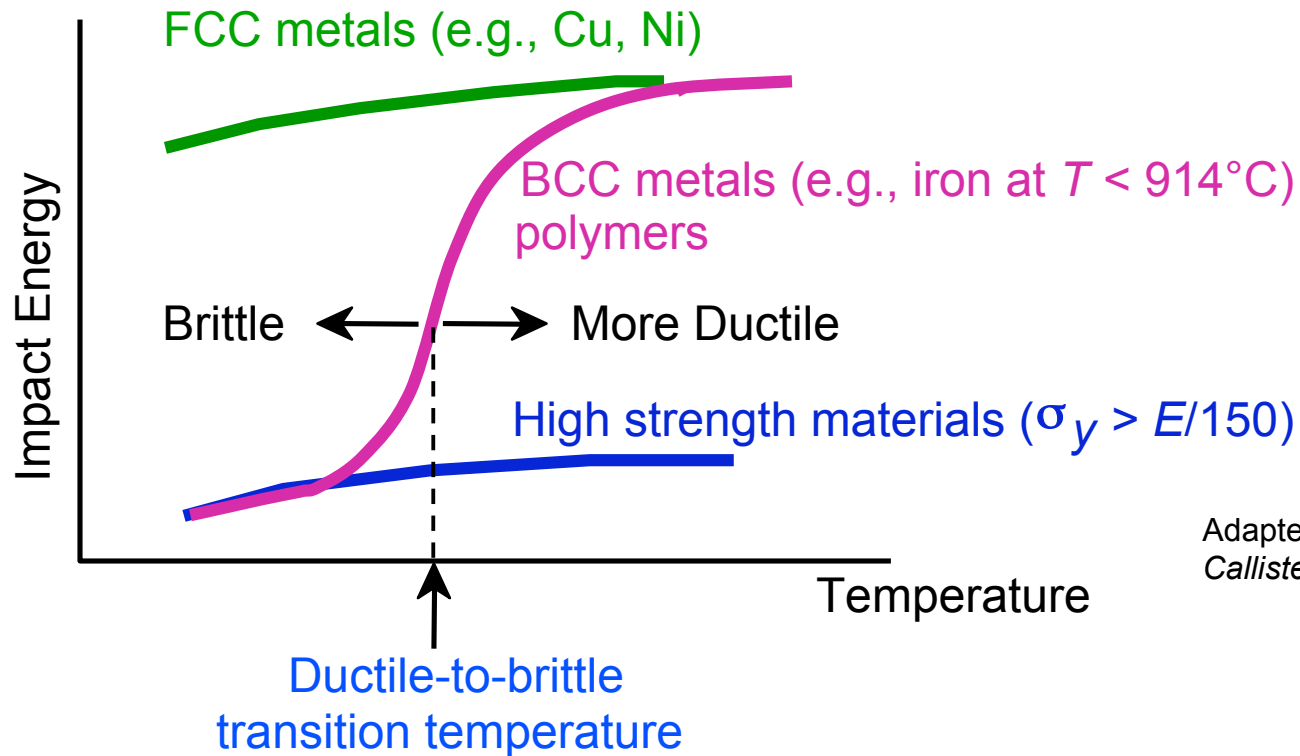
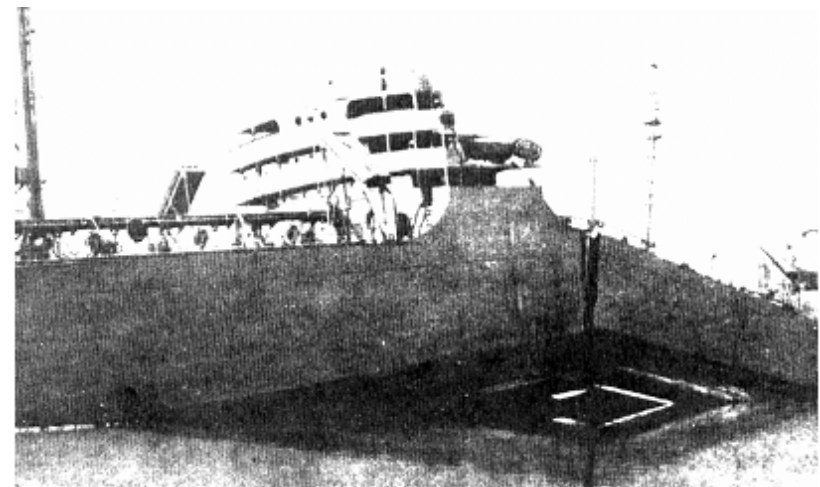Adapted from Fig. 8.15,
Callister 7e.

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*.)
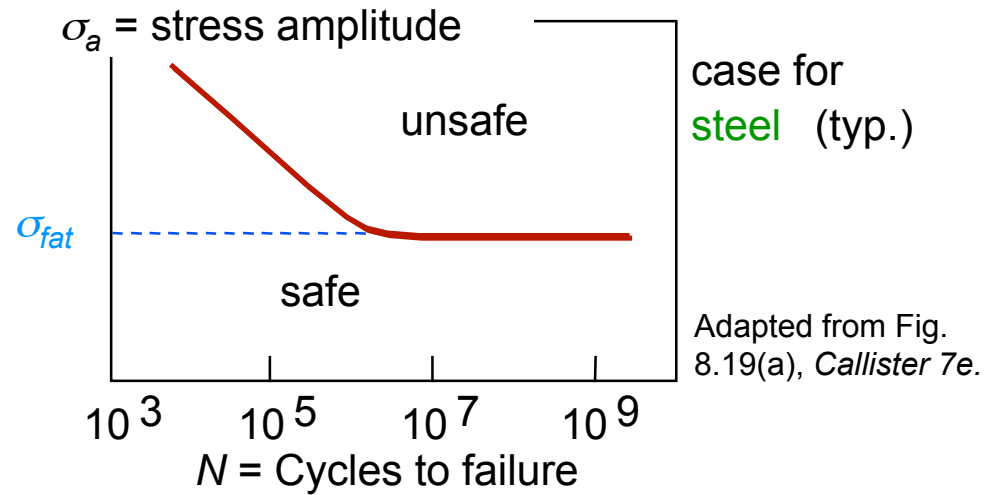
- **WWII: Liberty ships**

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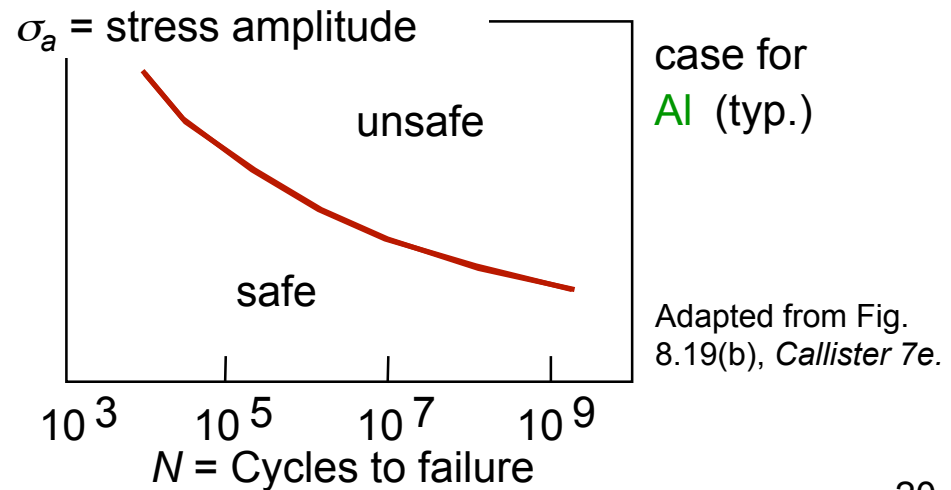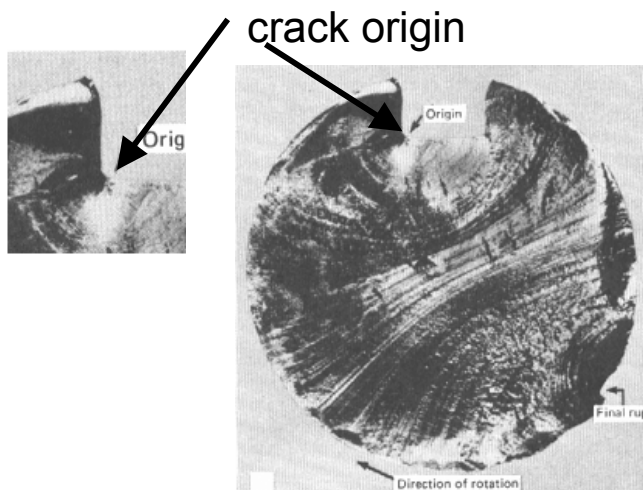
- Problem: Used a type of steel with a DBTT ~ Room temp.

Fatigue

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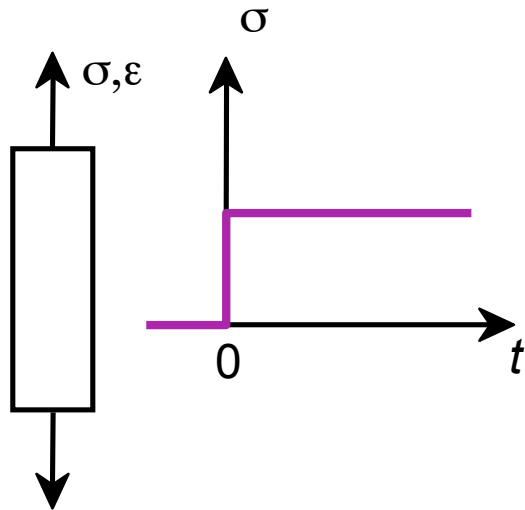 --no fatigue if $\sigma < \sigma_{fat}$

σ_a = stress amplitude

unsafe

σ_{fat}

safe

10^3 10^5 10^7 10^9

N = Cycles to failure

case for
steel (typ.)

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

• Sometimes, the
  fatigue limit is zero!

crack origin

σ_a = stress amplitude

unsafe

safe

10^3 10^5 10^7 10^9

N = Cycles to failure

case for
Al (typ.)

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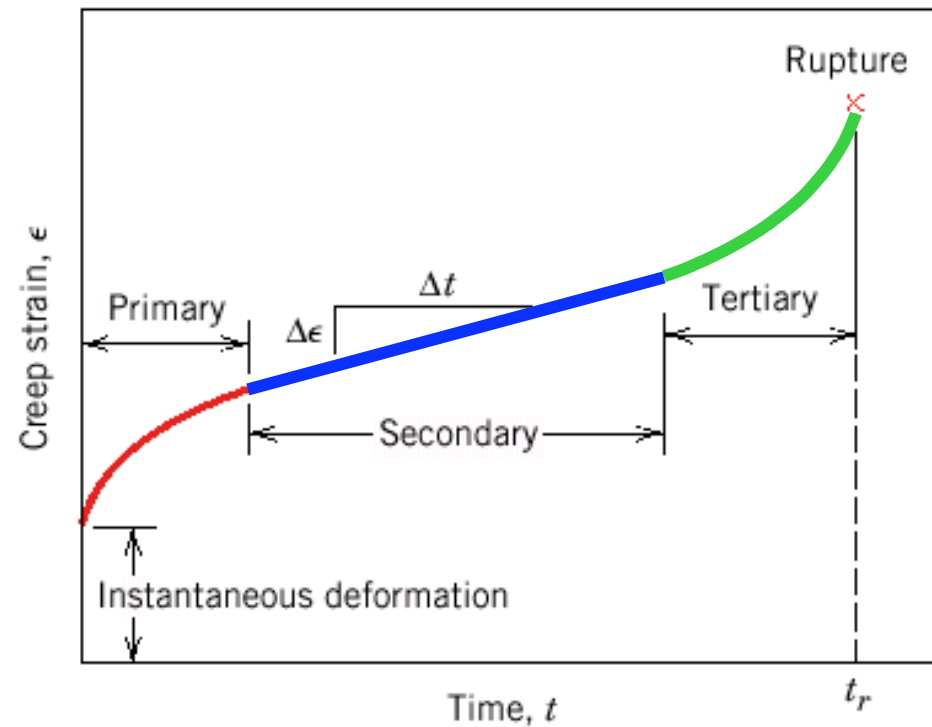8.19(b), *Callister 7e.*

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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.

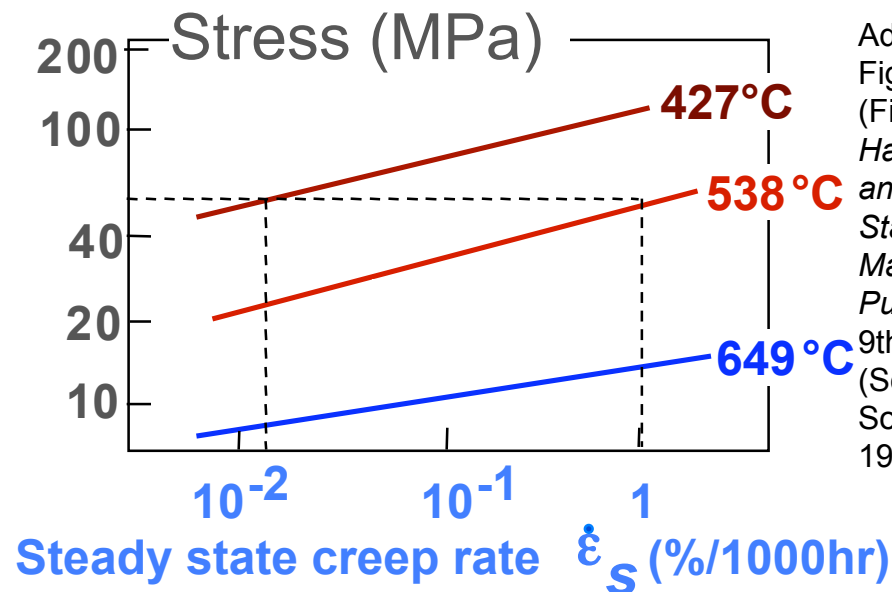Adapted from
Fig. 8.28, *Callister 7e.*

Secondary creep

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

stress exponent (material parameter)

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

strain rate

material const.

applied stress

activation energy for creep
(material parameter)

- Strain rate
  increases
  for higher T, σ

Stress (MPa)

200

100

427°C

538°C

40

20

649°C

10

10^{-2} 10^{-1} 1

Steady state creep rate $\dot{\varepsilon}_s$ (%/1000hr)

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.)

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