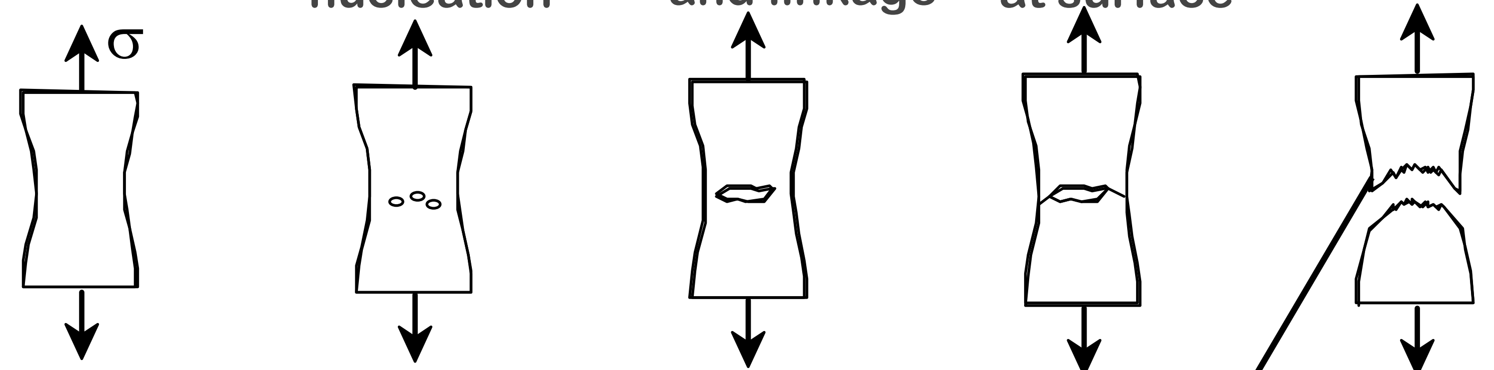
Chapter 9 : Failure

MODERATELY DUCTILE FAILURE

- **Evolution to failure:**



necking

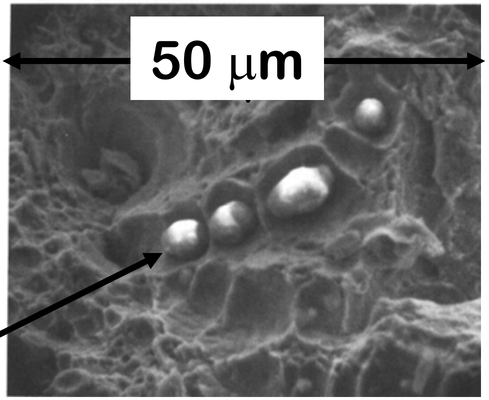
void nucleation

void growth and linkage

shearing at surface

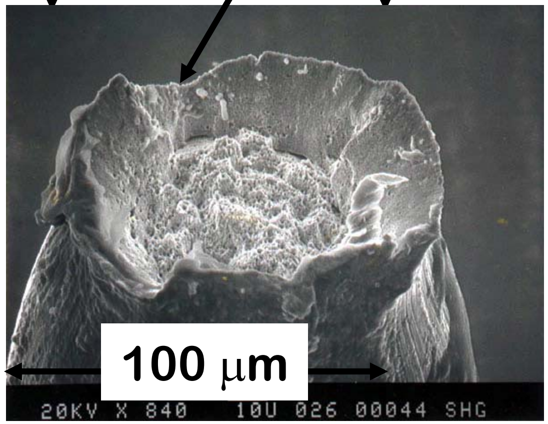
fracture

- **Resulting fracture surfaces (steel)**



particles serve as void nucleation sites.

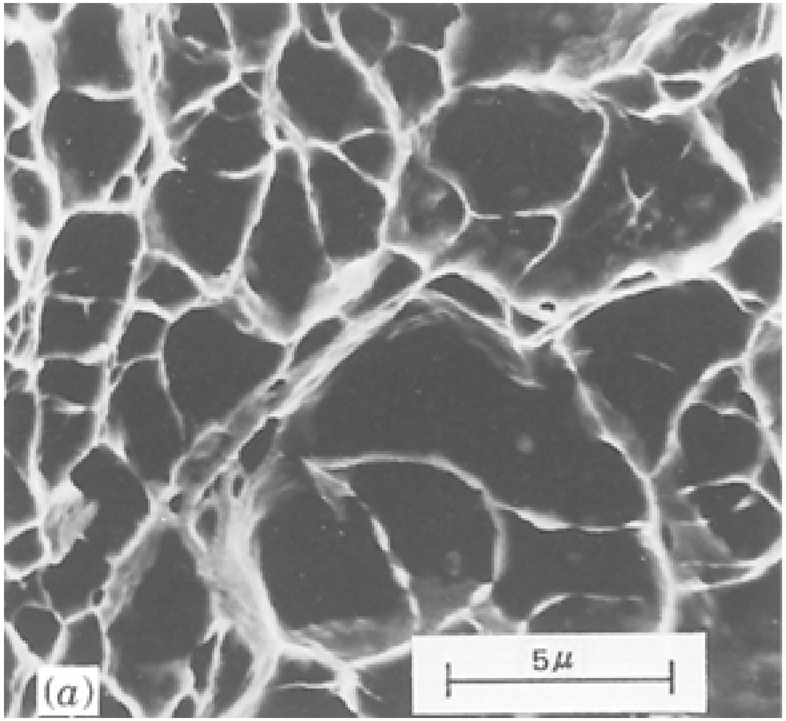
From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 11.28, p. 294, John Wiley and Sons, Inc., 1987. (Orig. source: P. Thornton, *J. Mater. Sci.*, Vol. 6, 1971, pp. 347-56.)



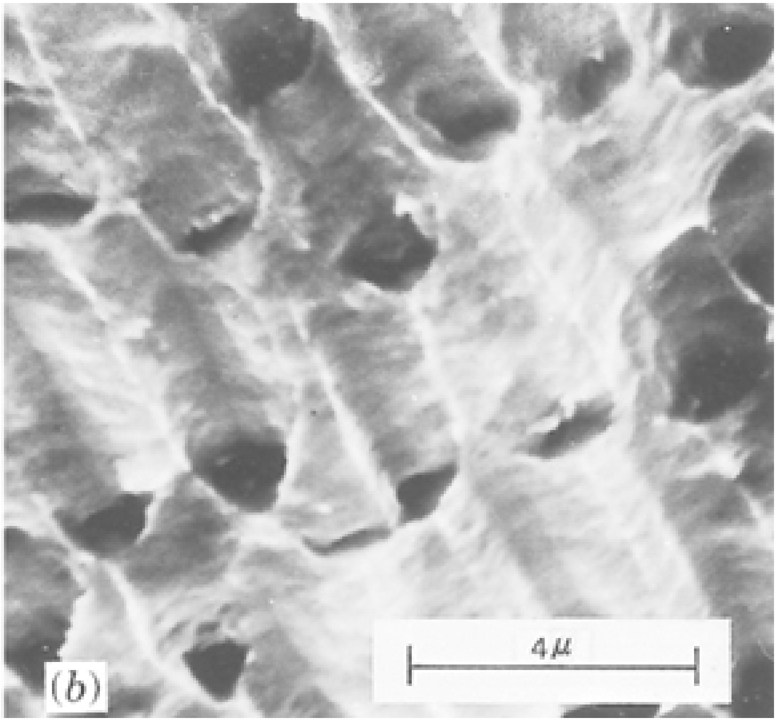
Fracture surface of tire cord wire loaded in tension. Courtesy of F. Roehrig, CC Technologies, Dublin, OH. Used with permission.

"Cup and cone" ductile fracture

Ductile Fracture surface



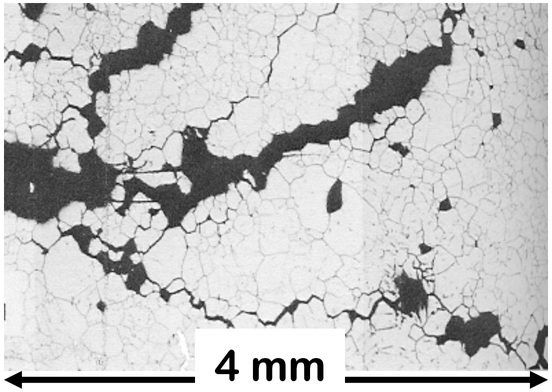
From center of specimen



From shear edge of specimen

BRITTLE FRACTURE

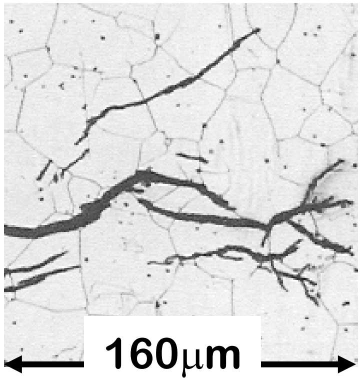
- Intergranular (between grains)

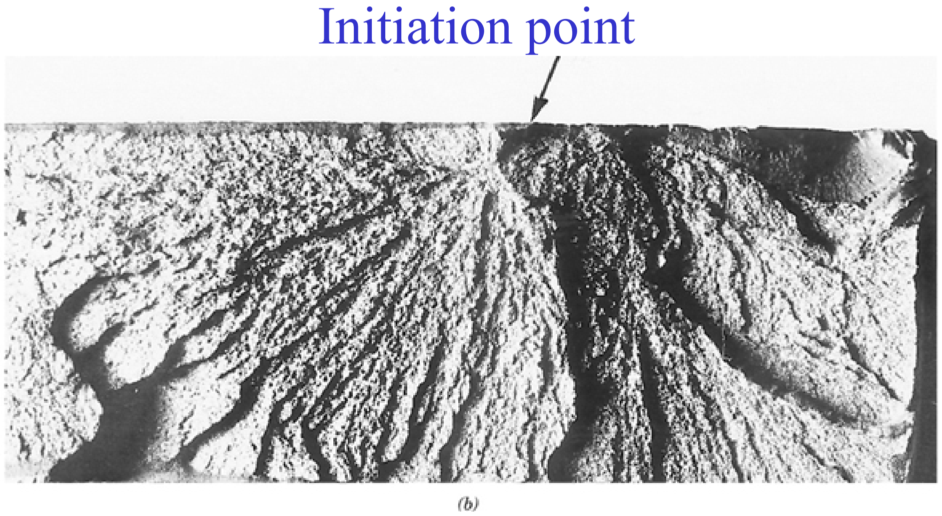


304 S. Steel (metal)
Reprinted w/permission from "Metals Handbook", 9th ed, Fig. 633, p. 650. Copyright 1985, ASM International, Materials Park, OH. (Micrograph by J.R. Keiser and A.R. Olsen, Oak Ridge National Lab.)

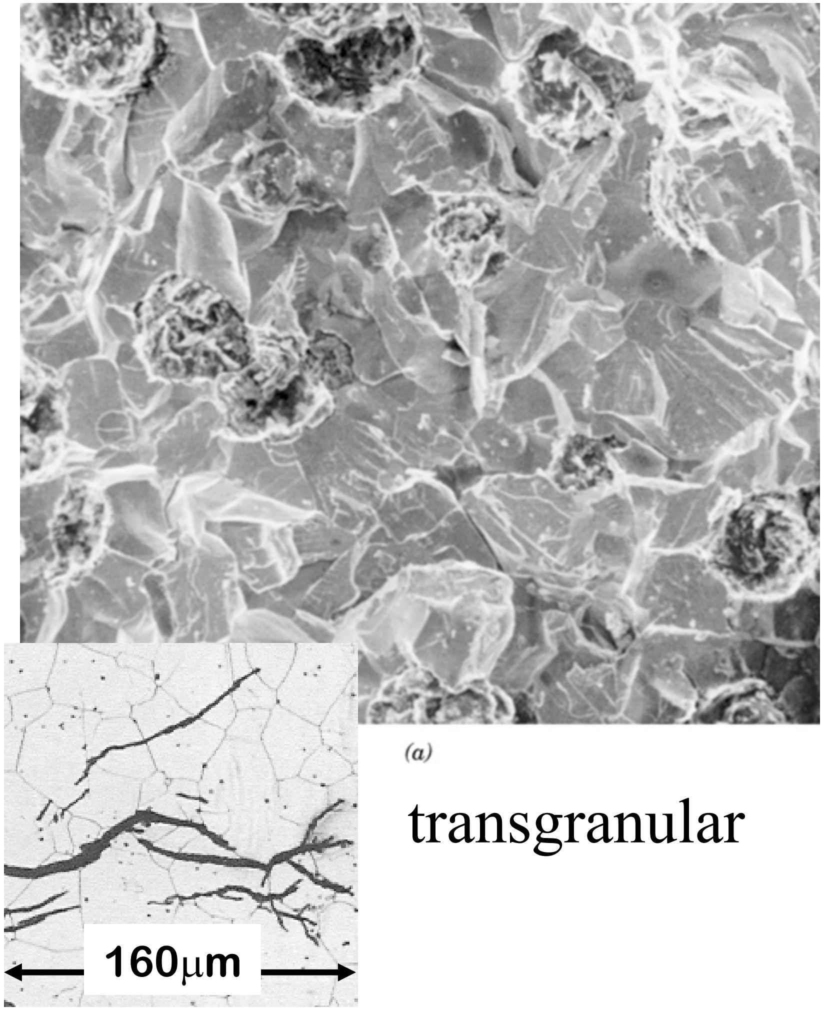
- Intragranular (within grains)

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.)



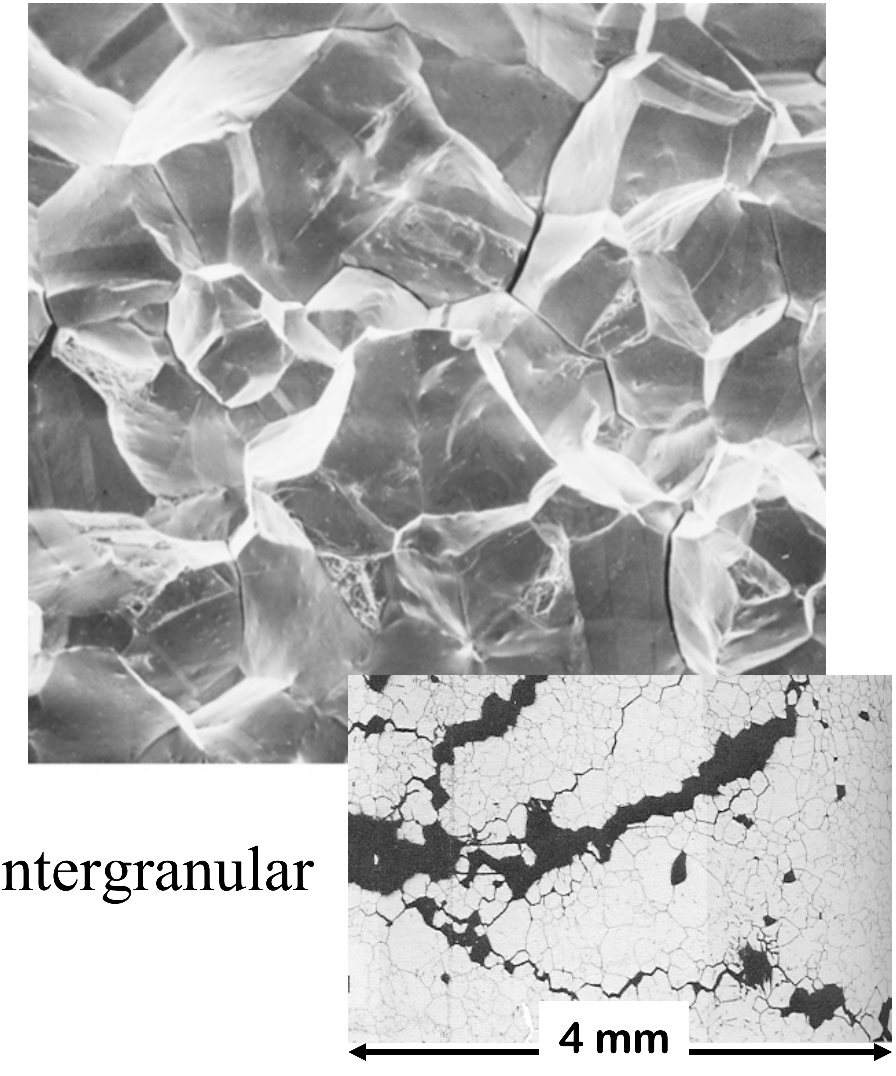


Brittle fracture surface



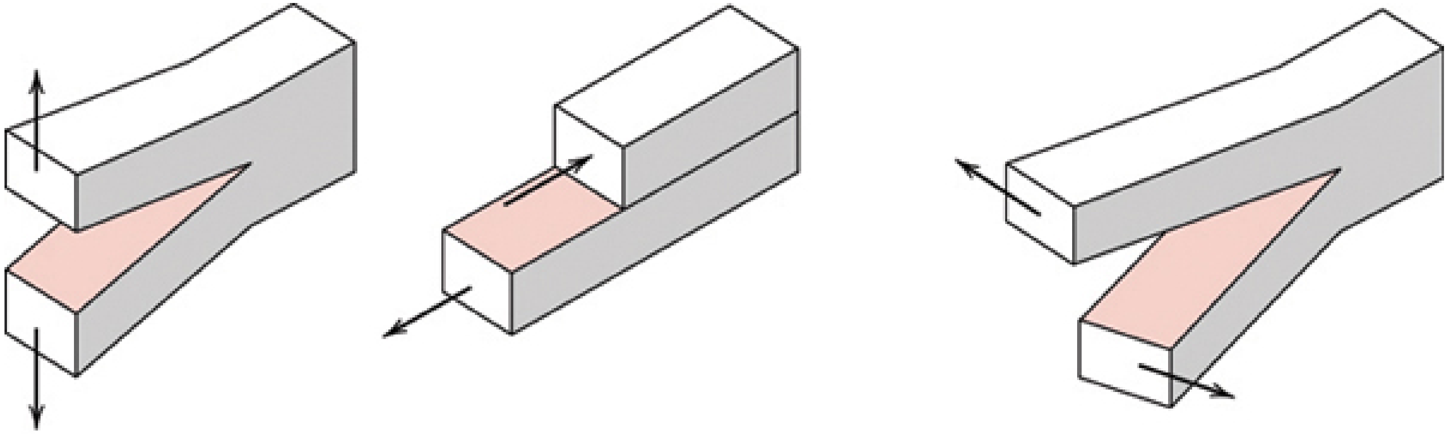
(a)

transgranular



intergranular

Failure MODE



(a) (b) (c)

Mode I
tension

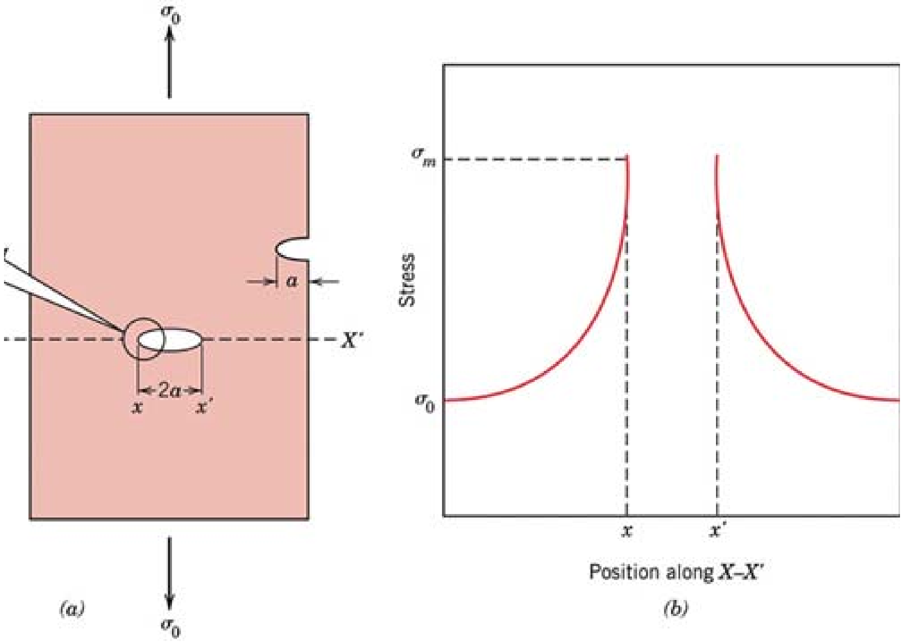
Mode II
sliding

Mode III
Tearing

FLAWS ARE STRESS CONCENTRATORS

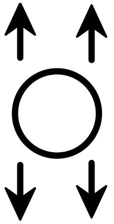
- **Stress distribution in front of a hole:**

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

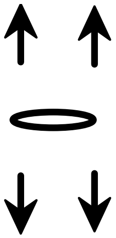


- **Stress conc. factor:** $K_t = \sigma_{max} / \sigma_o$ OR $K_t = 2(a/\rho_t)^{1/2}$

- **Large K_t promotes failure:**



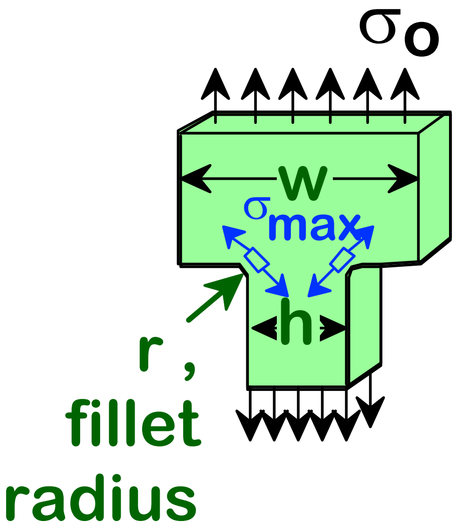
NOT SO BAD **K_t=3**

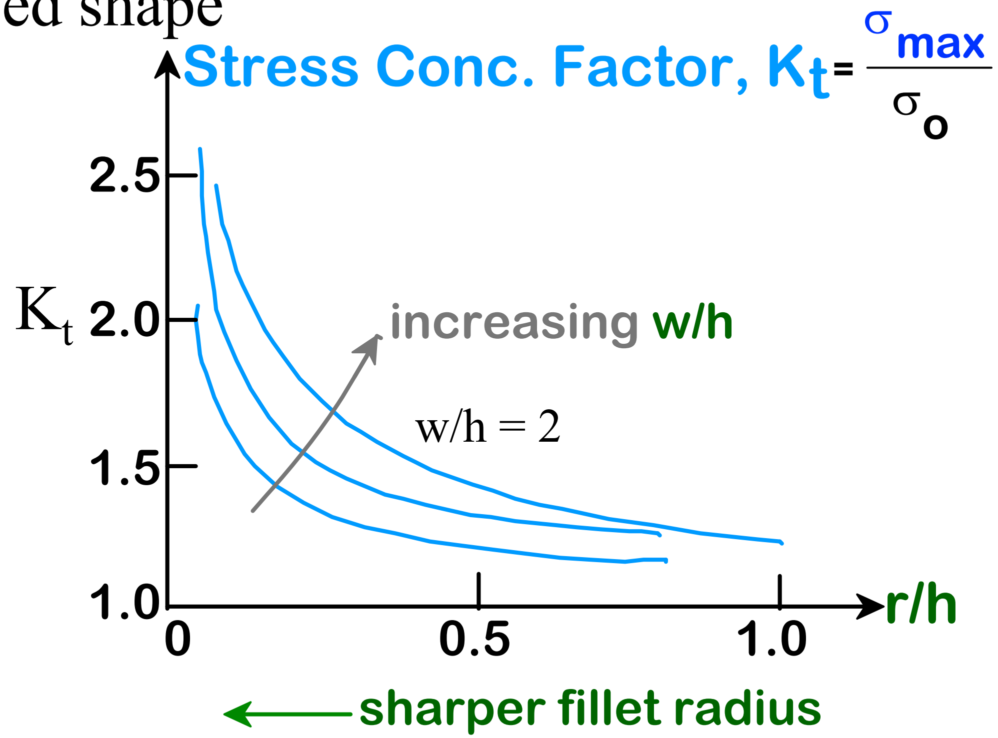


BAD! **K_t>>3**

ENGINEERING FRACTURE DESIGN

Example of commonly used shape

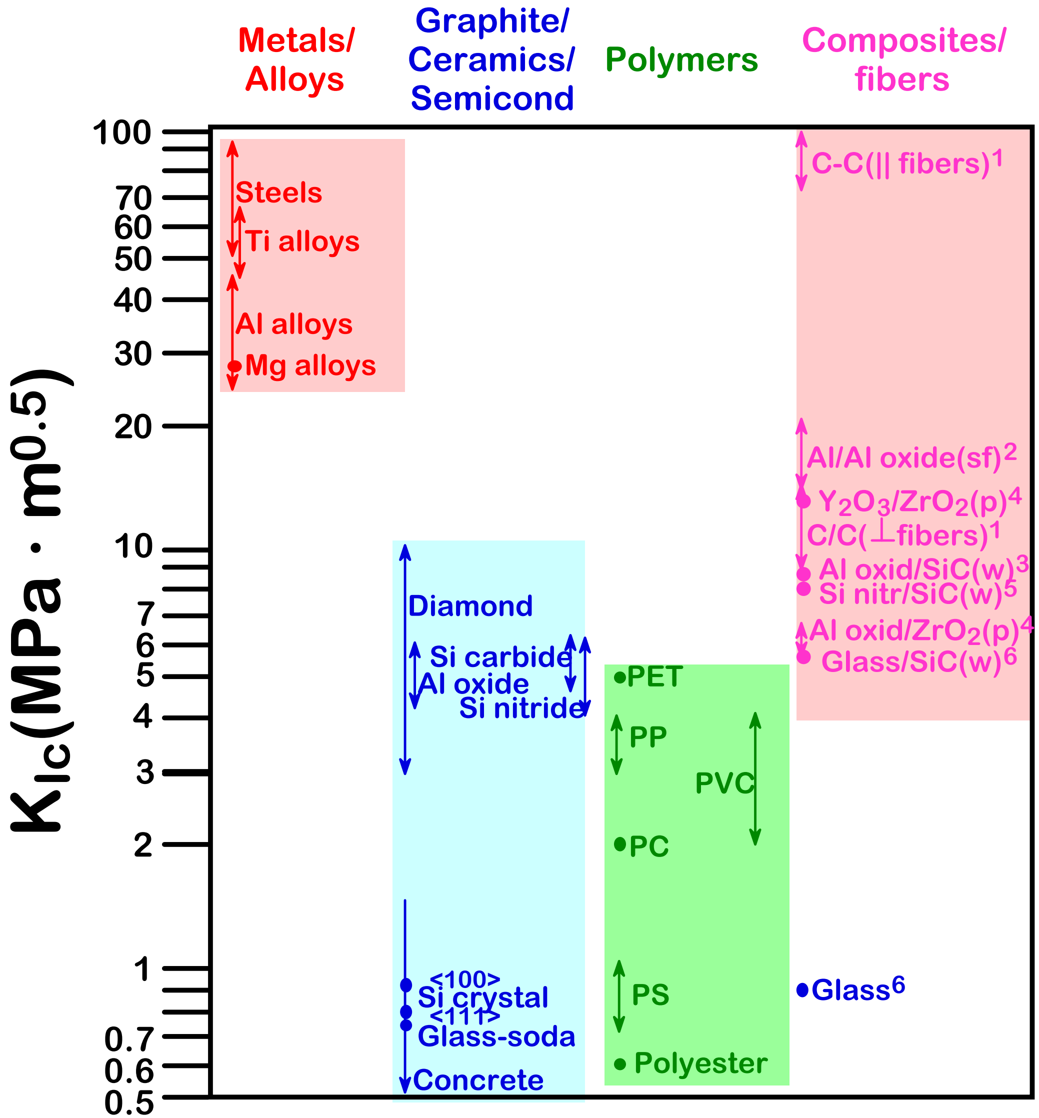


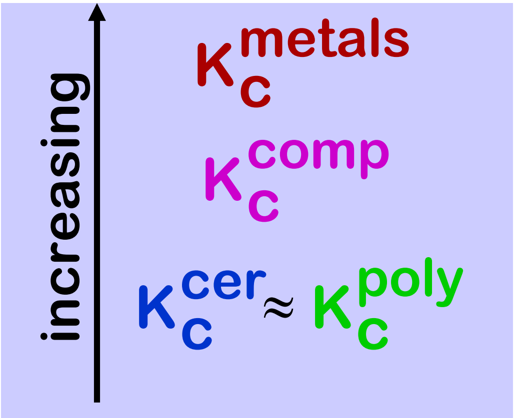


Adapted from Fig. 8.2W(c), *Callister 6e.*
(Fig. 8.2W(c) is from G.H. Neugebauer, *Prod. Eng.* (NY), Vol. 14, pp. 82-87 1943.)

- **Avoid sharp corners!**

FRACTURE TOUGHNESS





$$K_c^{metals}$$
$$K_c^{comp}$$
$$K_c^{cer} \approx K_c^{poly}$$

Based on data in Table B5, *Callister 6e*.

Composite reinforcement geometry is: f = fibers; sf = short fibers; w = whiskers; p = particles. Addition data as noted (vol. fraction of reinforcement):

1. (55vol%) *ASM Handbook*, Vol. 21, ASM Int., Materials Park, OH (2001) p. 606.
2. (55 vol%) Courtesy J. Cornie, MMC, Inc., Waltham, MA.
3. (30 vol%) P.F. Becher et al., *Fracture Mechanics of Ceramics*, Vol. 7, Plenum Press (1986). pp. 61-73.
4. Courtesy CoorsTek, Golden, CO.
5. (30 vol%) S.T. Buljan et al., "Development of Ceramic Matrix Composites for Application in Technology for Advanced Engines Program", ORNL/Sub/85-22011/2, ORNL, 1992.
6. (20vol%) F.D. Gace et al., *Ceram. Eng. Sci. Proc.*, Vol. 7 (1986) pp. 978-82.

DESIGN AGAINST CRACK GROWTH

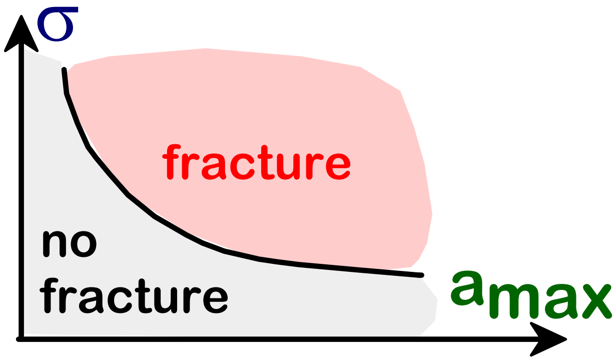
- Crack growth condition: $K \geq K_c$

$$\underbrace{Y\sigma\sqrt{\pi a}}\xrightarrow{} K$$

- Largest, most stressed cracks grow first!

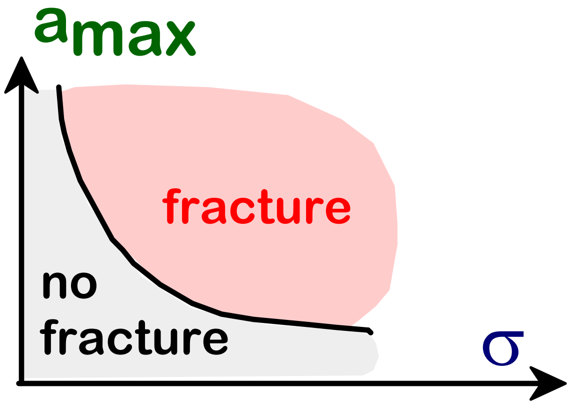
--Result 1: Max flaw size dictates design stress.

$$\sigma_{design} < \frac{K_c}{Y\sqrt{\pi a_{max}}}$$



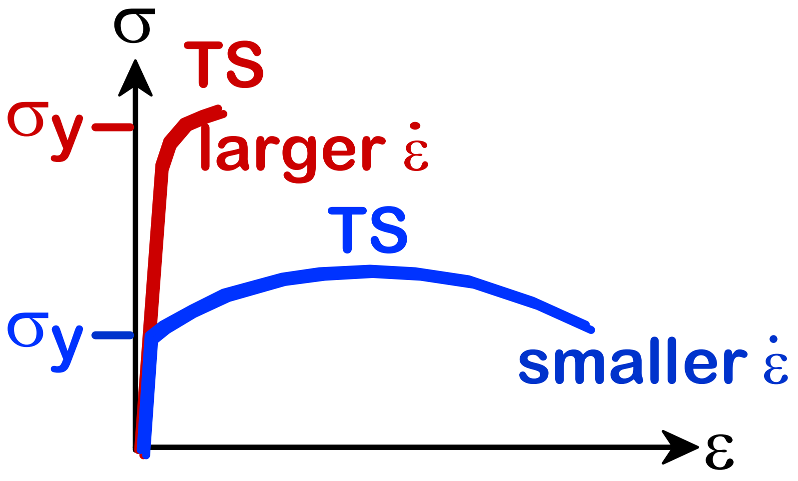
--Result 2: Design stress dictates max. flaw size.

$$a_{max} < \frac{1}{\pi}\left(\frac{K_c}{Y\sigma_{design}}\right)^2$$

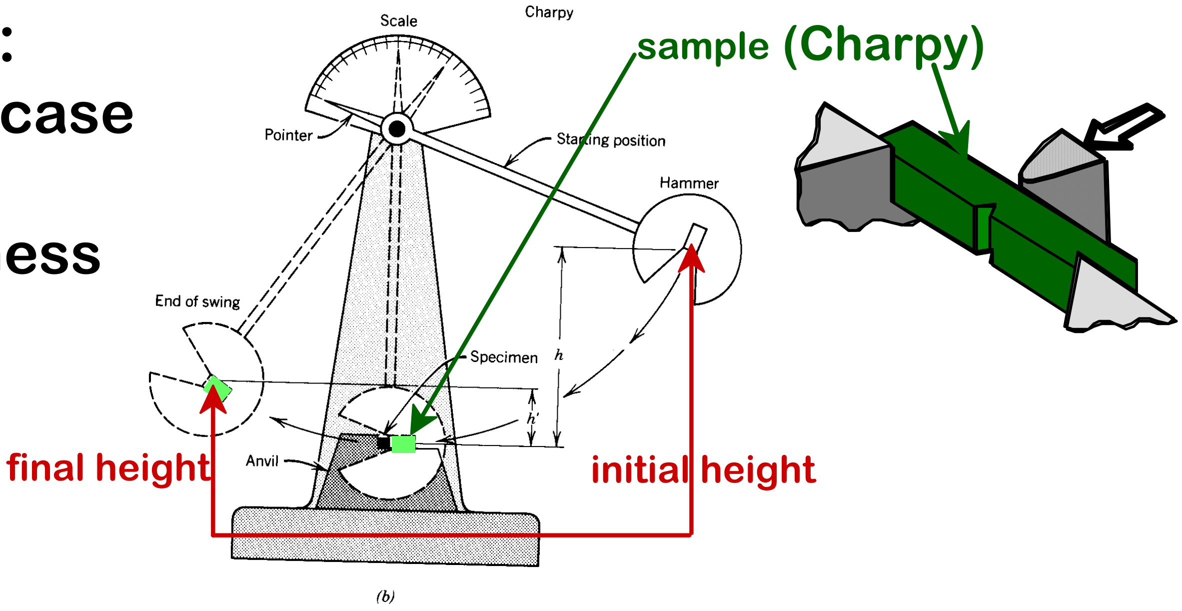


LOADING RATE

- Increased loading rate...
  --increases σ_y and TS
  --decreases %EL
- Why? An increased rate gives less time for disl. to move past obstacles.



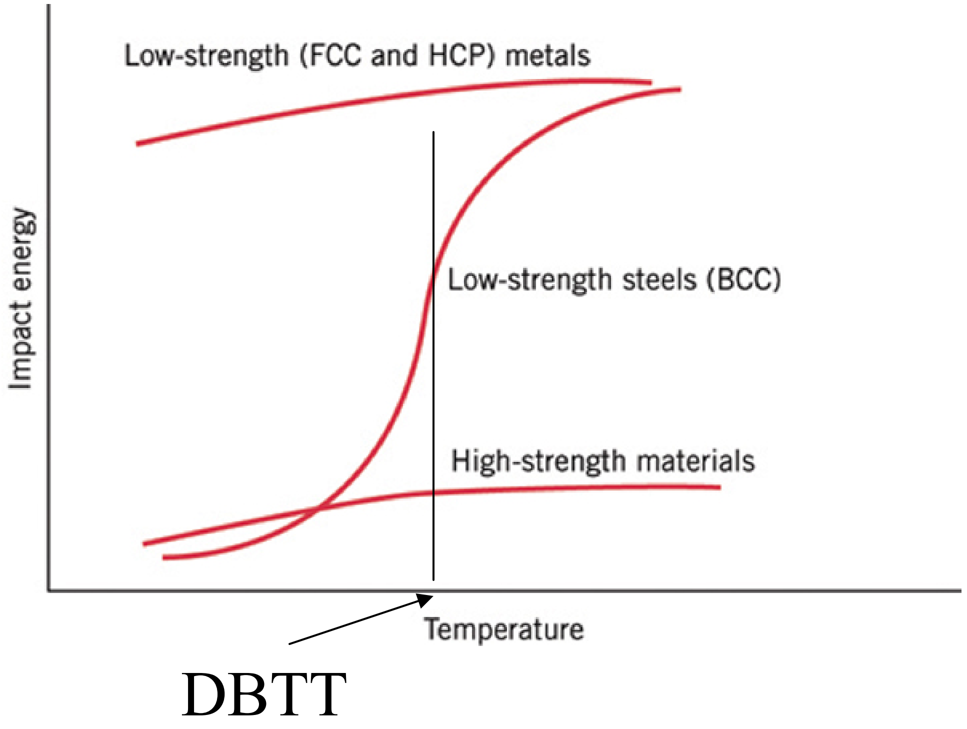
- Impact loading:
  --severe testing case
  --more brittle
  --smaller toughness



Adapted from Fig. 8.11(a) and (b), *Callister 6e.* (Fig. 8.11(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.)

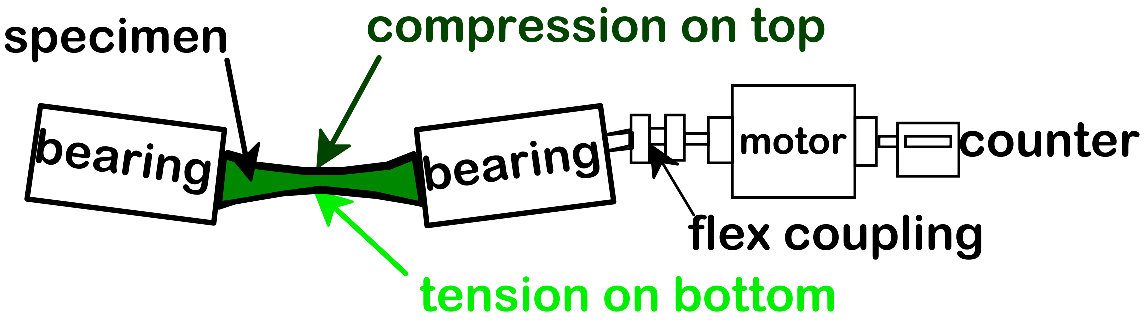
TEMPERATURE

- **Increasing temperature...**
  --increases %EL and K_c
- **Ductile-to-brittle transition temperature (DBTT)...**



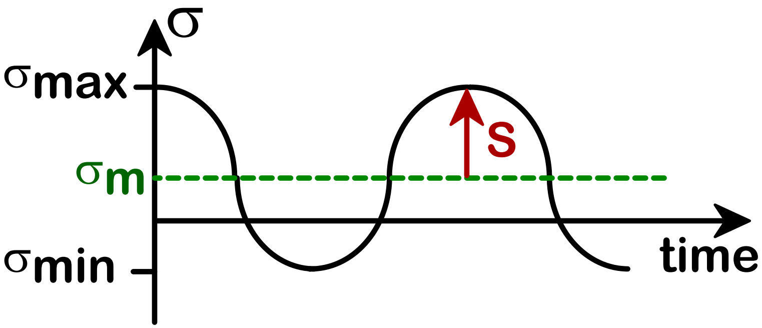
FATIGUE

- **Fatigue** = failure under cyclic stress.



Adapted from Fig. 8.16, *Callister 6e.* (Fig. 8.16 is from *Materials Science in Engineering*, 4/E by Carl. A. Keyser, Pearson Education, Inc., Upper Saddle River, NJ.)

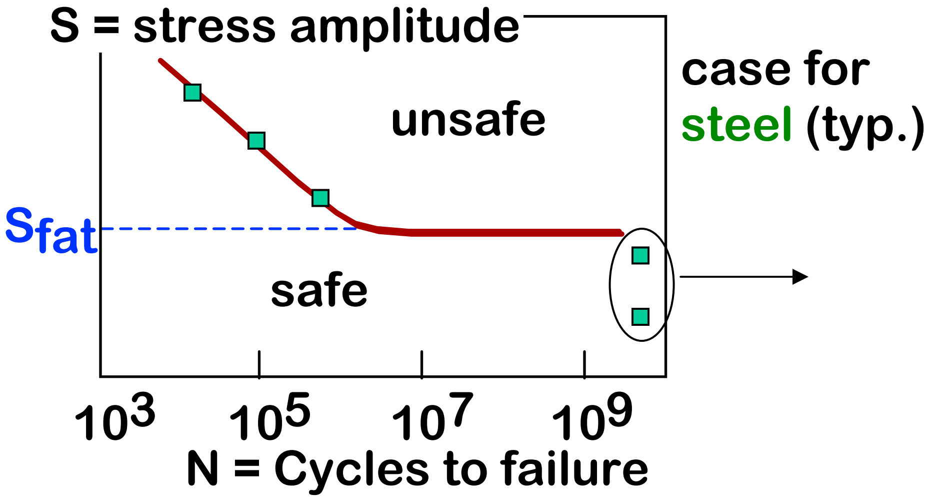
- Stress varies with time.
  --key parameters are S and σ_m



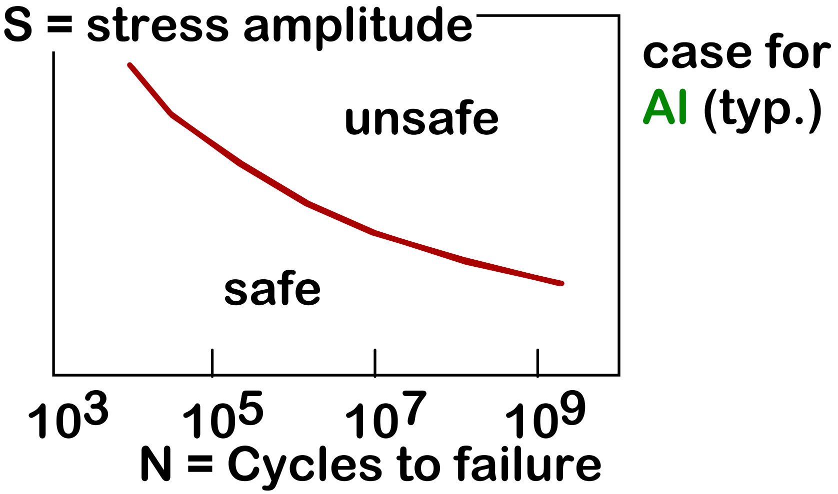
- Key points: Fatigue...
  --can cause part failure, even though $\sigma_{max} < \sigma_c$.
  --causes ~ 90% of mechanical engineering failures.

FATIGUE DESIGN PARAMETERS

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

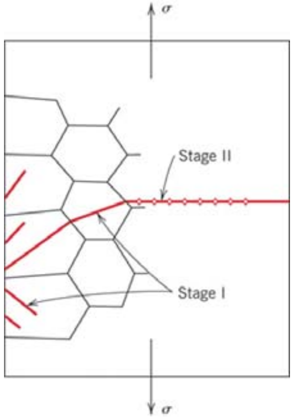


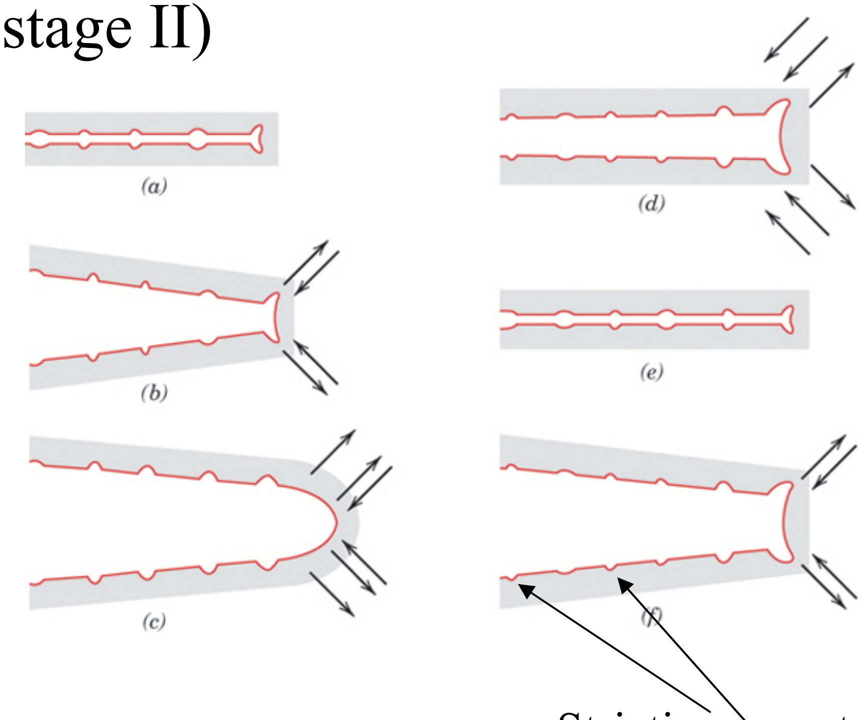
- Sometimes, the fatigue limit is zero!



Fatigue Mechanism

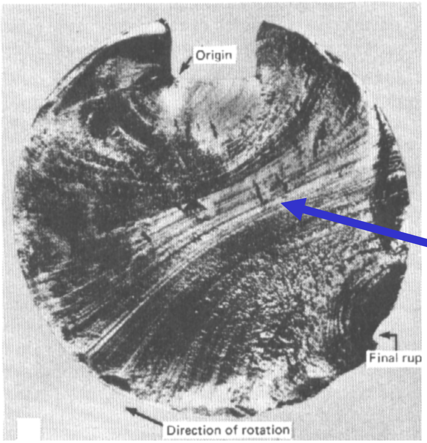
Stable crack growth (stage II)





Striations – not visible to eye

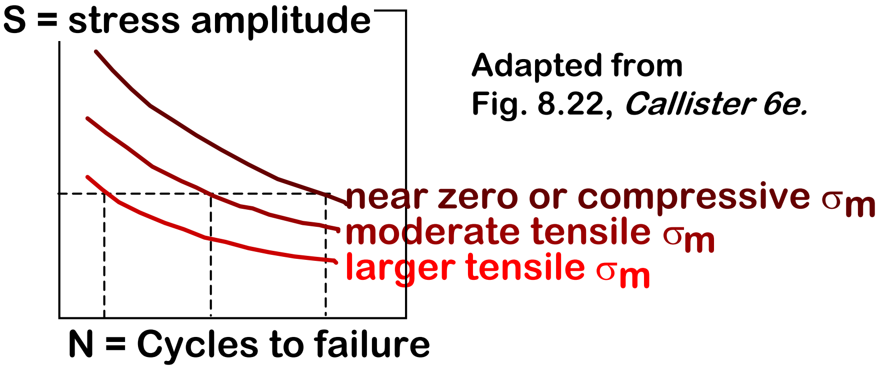
- **Failed rotating shaft**
  --crack grew even though
  $K_{max} < K_c$
  --crack grows faster if
  - **$\Delta\sigma$ increases**
  - **crack gets longer**
  - **loading freq. increases.**



Beachmarks – visible to eye

IMPROVING FATIGUE LIFE

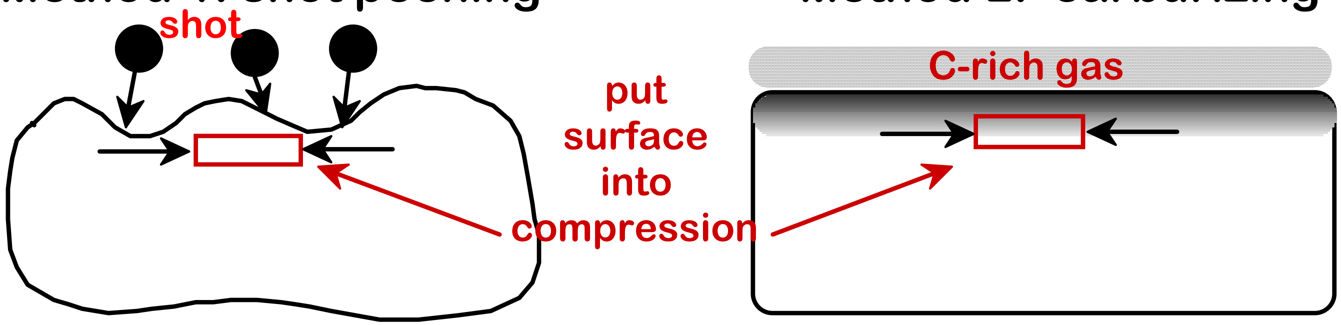
1. Impose a compressive surface stress (to suppress surface cracks from growing)



Adapted from Fig. 8.22, *Callister 6e.*

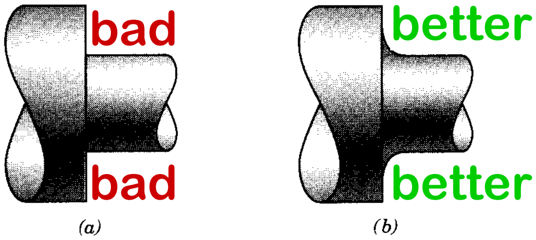
--Method 1: shot peening

--Method 2: carburizing



put surface into compression

2. Remove stress concentrators.



Adapted from Fig. 8.23, *Callister 6e.*

PROCESSING USING DIFFUSION (1)

- Case Hardening:
  - --Diffuse carbon atoms into the host iron atoms at the surface.
  - --Example of interstitial diffusion is a case hardened gear.

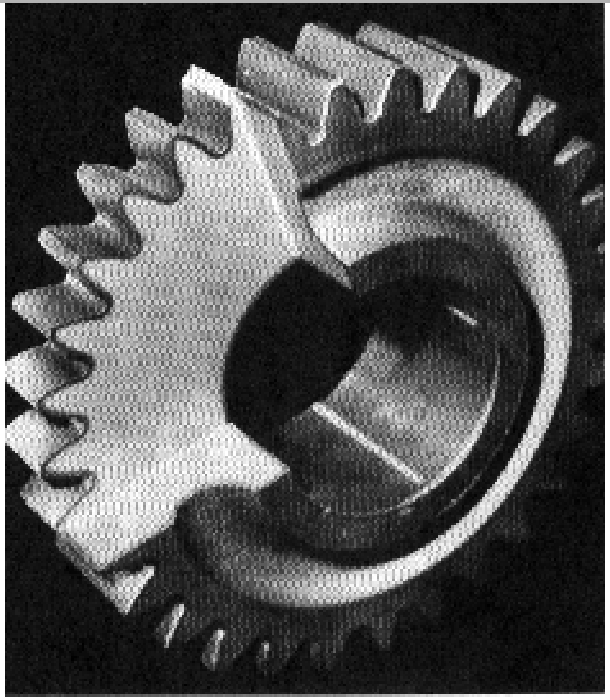
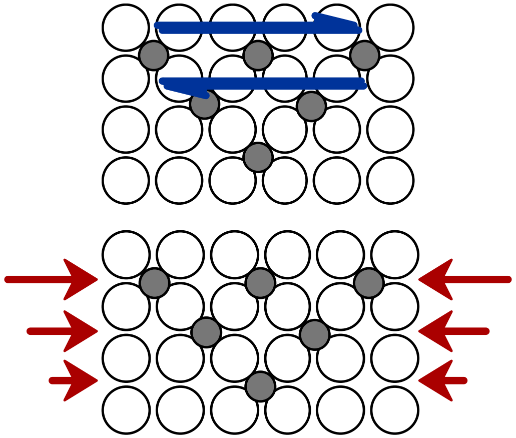


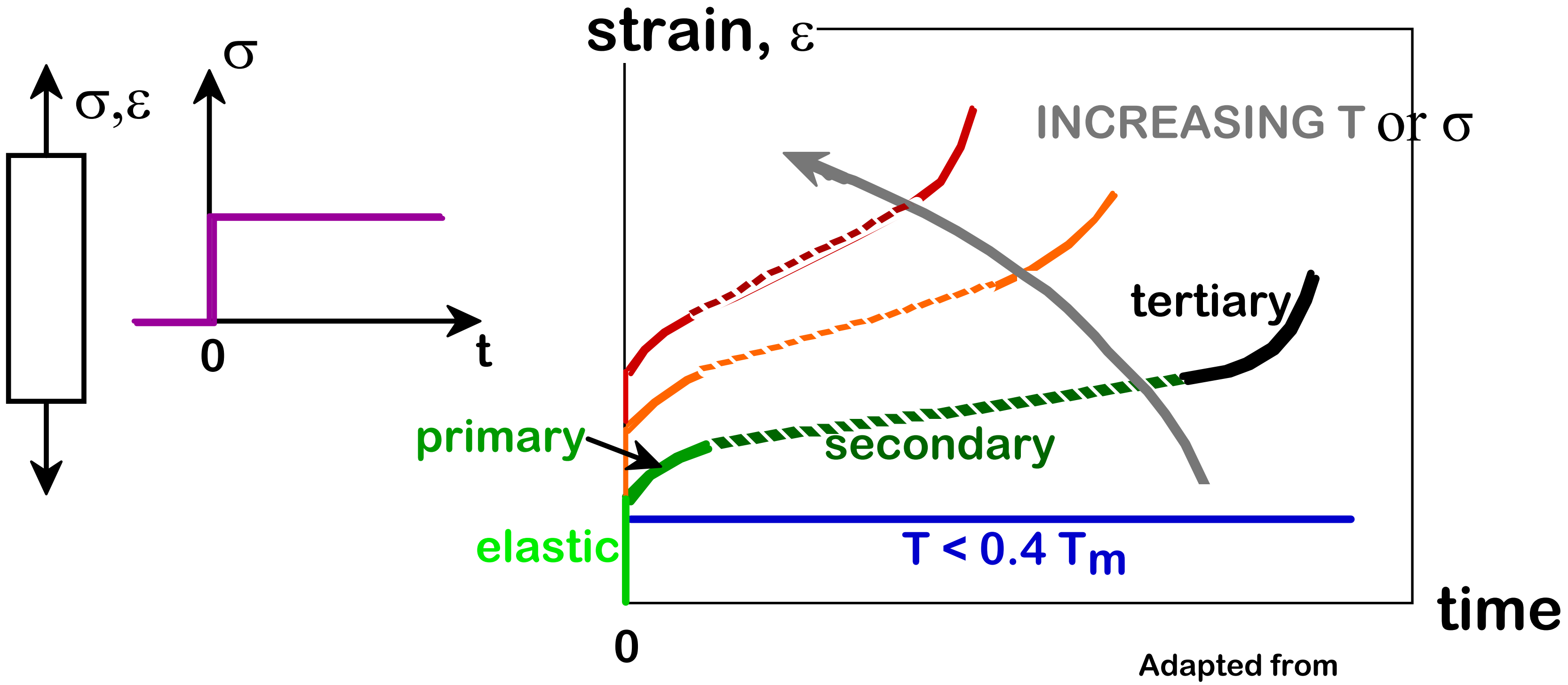
Fig. 5.0, *Callister 6e*. (Fig. 5.0 is courtesy of Surface Division, Midland-Ross.)

- Result: The "Case" is
  - --hard to deform: C atoms "lock" planes from shearing.
  - --hard to crack: C atoms put the surface in compression.



CREEP

- Occurs at elevated temperature, $T > 0.4\ T_{melt}$
- Deformation changes with time.

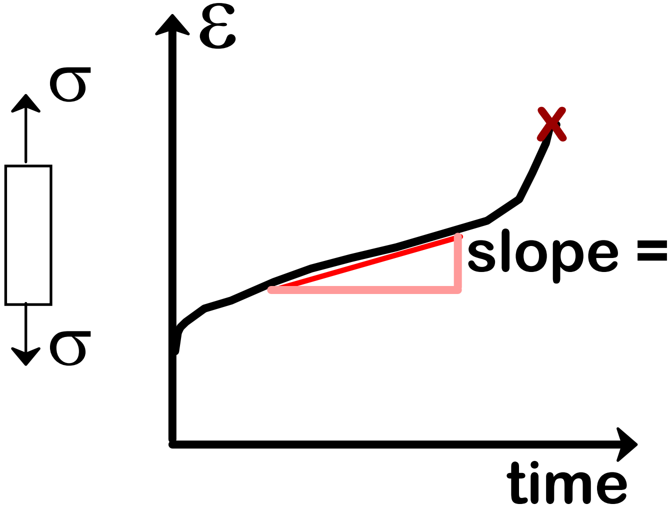


Adapted from
Figs. 8.26 and 8.27,
Callister 6e.

MEASURING ELEVATED T RESPONSE

- Elevated Temperature Tensile Test ($T > 0.4\ T_{melt}$).

  creep test



slope = $\dot{\varepsilon}_{ss}$ = steady-state creep rate

- Most of component life spent in secondary creep
- Strain rate is constant at a given T, σ

  --strain hardening is balanced by recovery

- **Generally,**

$$\dot{\varepsilon}_{ss}^{\text{ceramics}} < \dot{\varepsilon}_{ss}^{\text{metals}} \ll \dot{\varepsilon}_{ss}^{\text{polymers}}$$