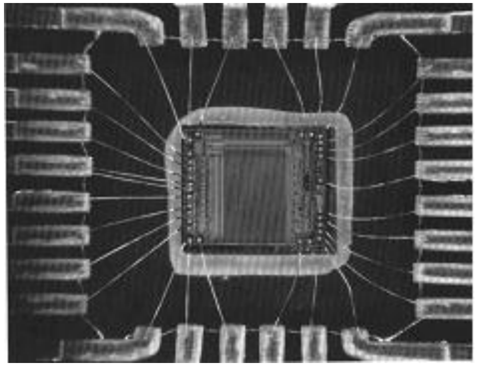
Chapter 8: Mechanical Failure

ISSUES TO ADDRESS...

- How do cracks that lead to failure form?
- How is fracture resistance quantified? How do the fracture resistances of the different material classes compare?
- How do we estimate the stress to fracture?
- How do loading rate, loading history, and temperature affect the failure behavior of materials?

Ship-cyclic loading from waves.

Adapted from chapter-opening photograph, Chapter 8, *Callister & Rethwisch 8e.* (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.*

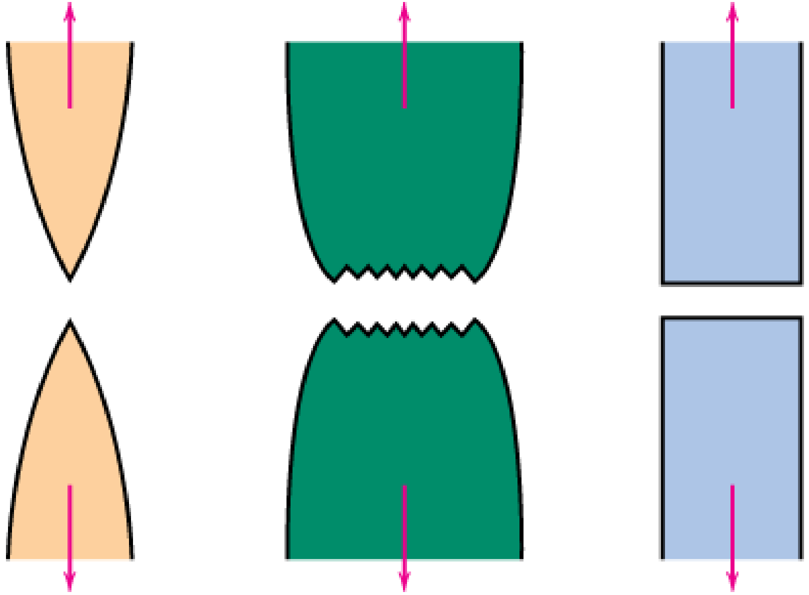
Fracture mechanisms

- Ductile fracture
  - Accompanied by significant plastic deformation
- Brittle fracture
  - Little or no plastic deformation
  - Catastrophic

Ductile vs Brittle Failure

- Classification:

Fracture behavior:	Very Ductile	Moderately Ductile	Brittle
$\%AR$ or $\%EL$	Large	Moderate	Small



Adapted from Fig. 8.1, *Callister & Rethwisch 8e.*

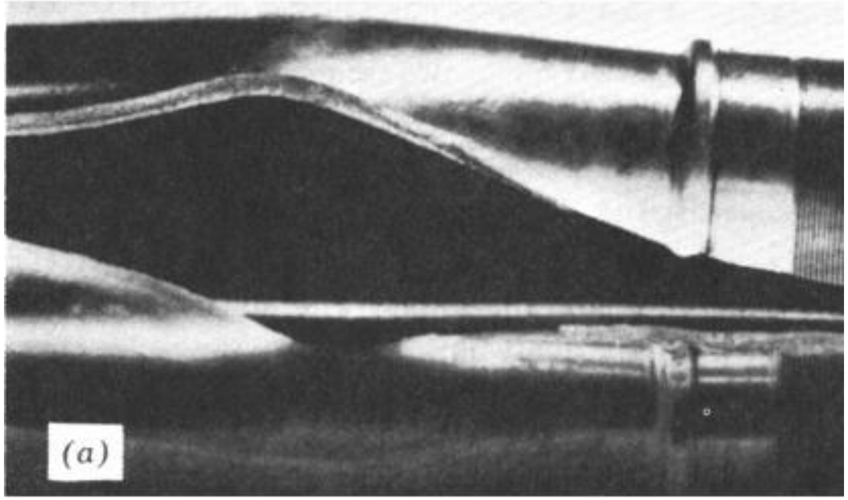
- Ductile fracture is usually more desirable than brittle fracture!

Ductile: Warning before fracture

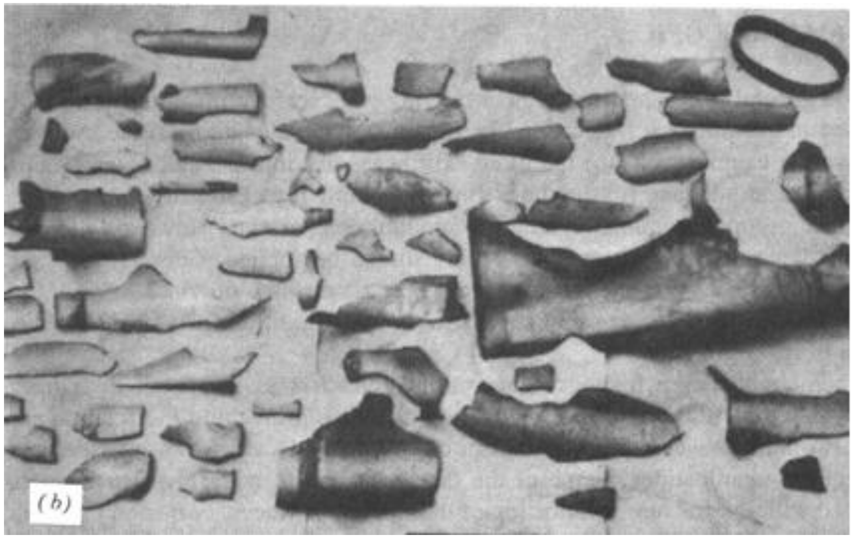
Brittle: No warning

Example: Pipe Failures

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



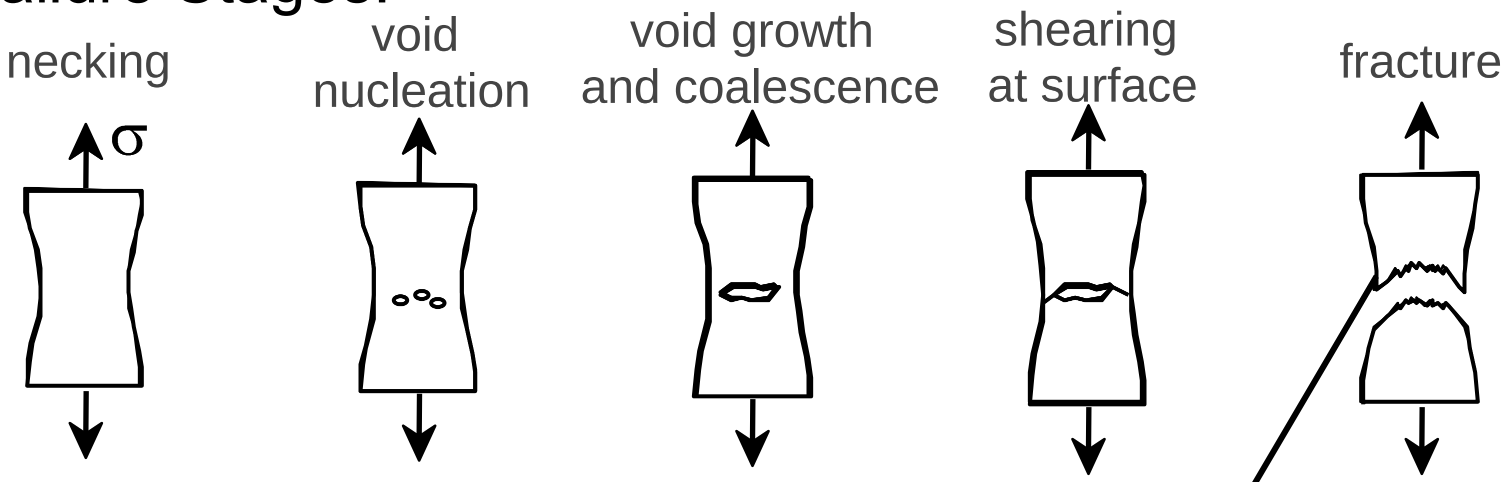
- **Brittle failure:**
  - -- many pieces
  - -- small deformations



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.

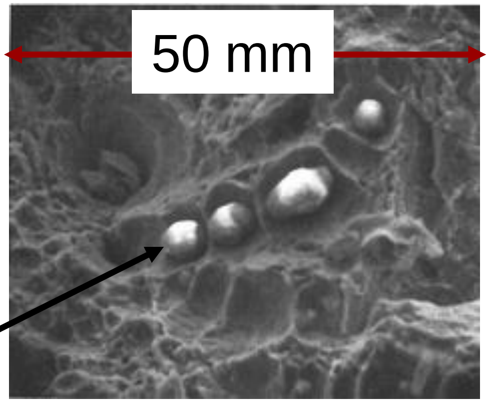
Moderately Ductile Failure

- Failure Stages:

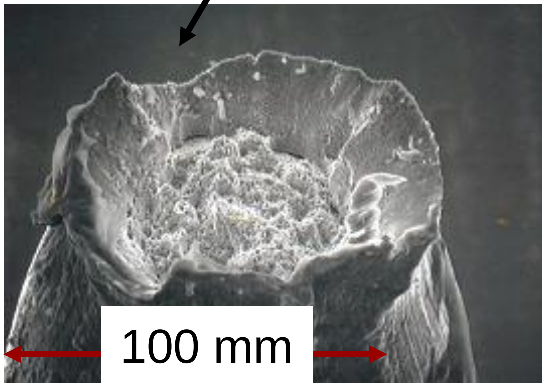


- Resulting fracture surfaces (steel)

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.

Moderately Ductile vs. Brittle Failure

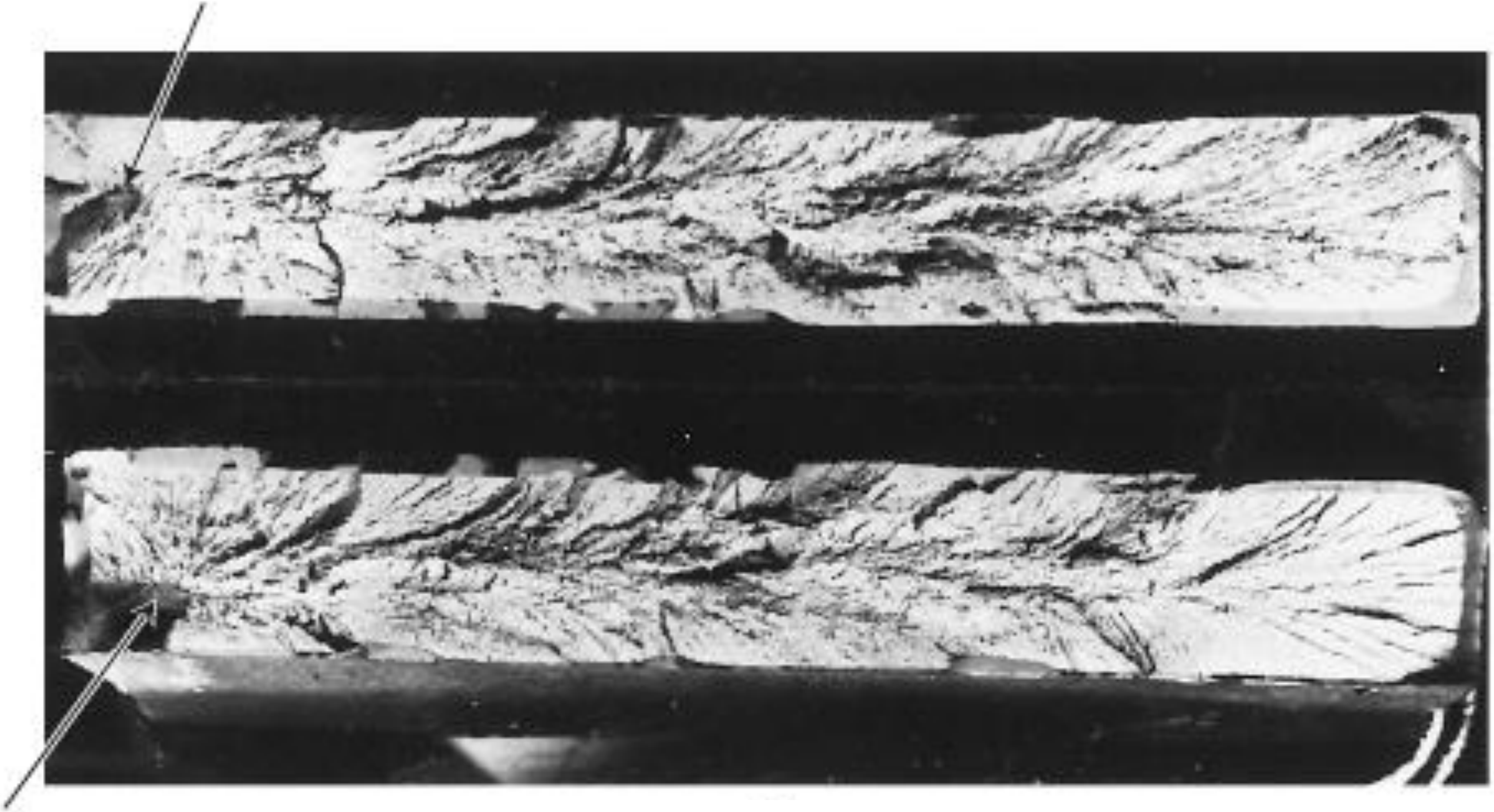
cup-and-cone fracture

brittle fracture

Adapted from Fig. 8.3, *Callister & Rethwisch 8e.*

Brittle Failure

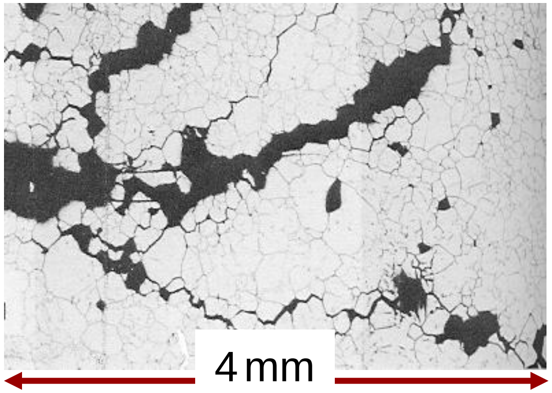
Arrows indicate point at which failure originated



Adapted from Fig. 8.5(a), *Callister & Rethwisch 8e.*

Brittle Fracture Surfaces

- Intergranular (between grains)
- Transgranular (through grains)



304 S. Steel (metal)

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316 S. Steel (metal)

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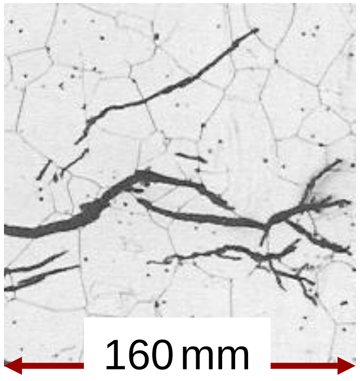

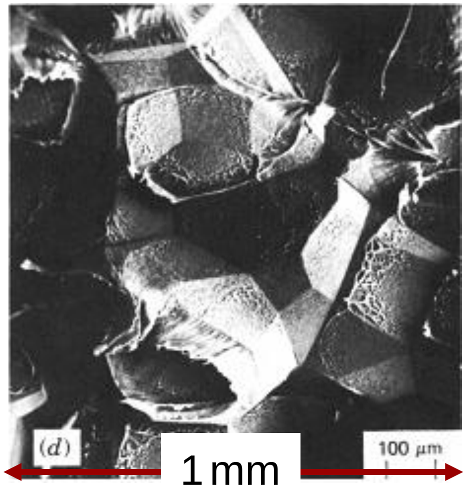

Polypropylene (polymer)

Reprinted w/ permission from R.W. Hertzberg, "Defor-mation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.35(d), p. 303, John Wiley and Sons, Inc., 1996.

(Orig. source: K. Friedrick, *Fracture 1977*, Vol. 3, ICF4, Waterloo, CA, 1977, p. 1119.)

Al Oxide (ceramic)

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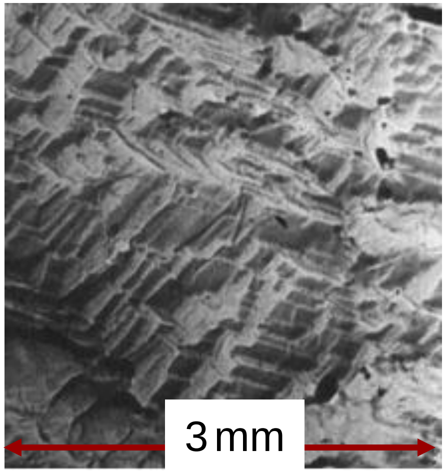
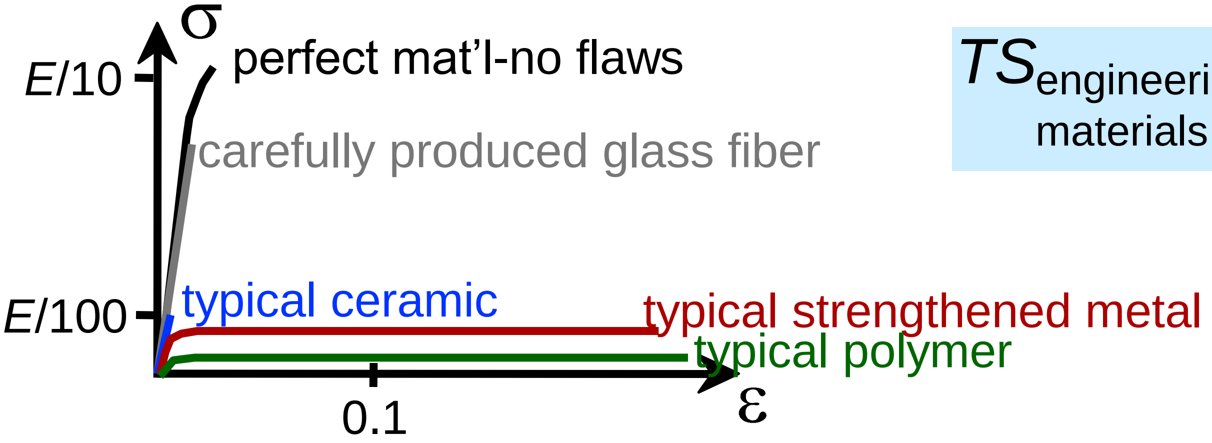


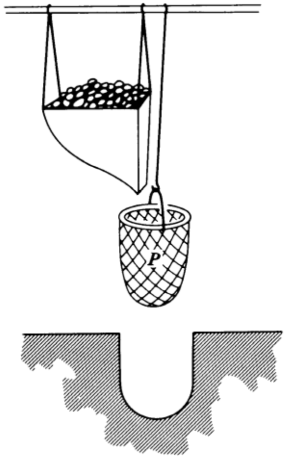
Ideal vs Real Materials

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



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

- DaVinci (500 yrs ago!) observed...
  -- the longer the wire, the smaller the load for failure.
- Reasons:
  -- flaws cause premature failure.
  -- larger samples contain longer flaws!



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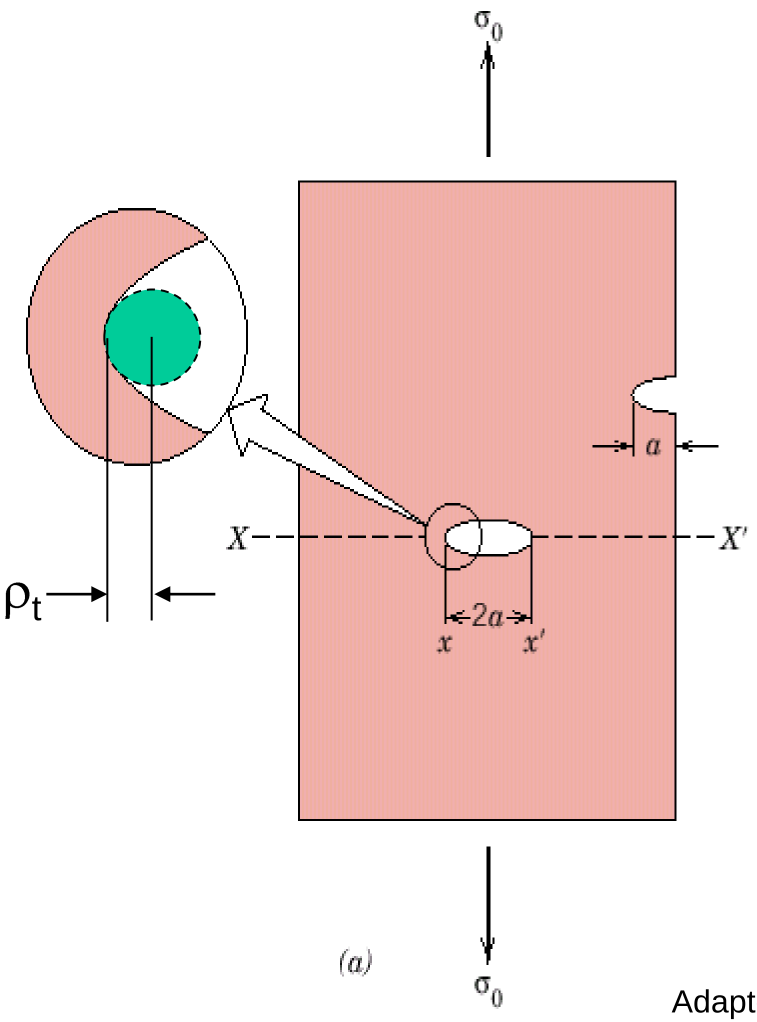
Flaws are Stress Concentrators!



- Griffith Crack

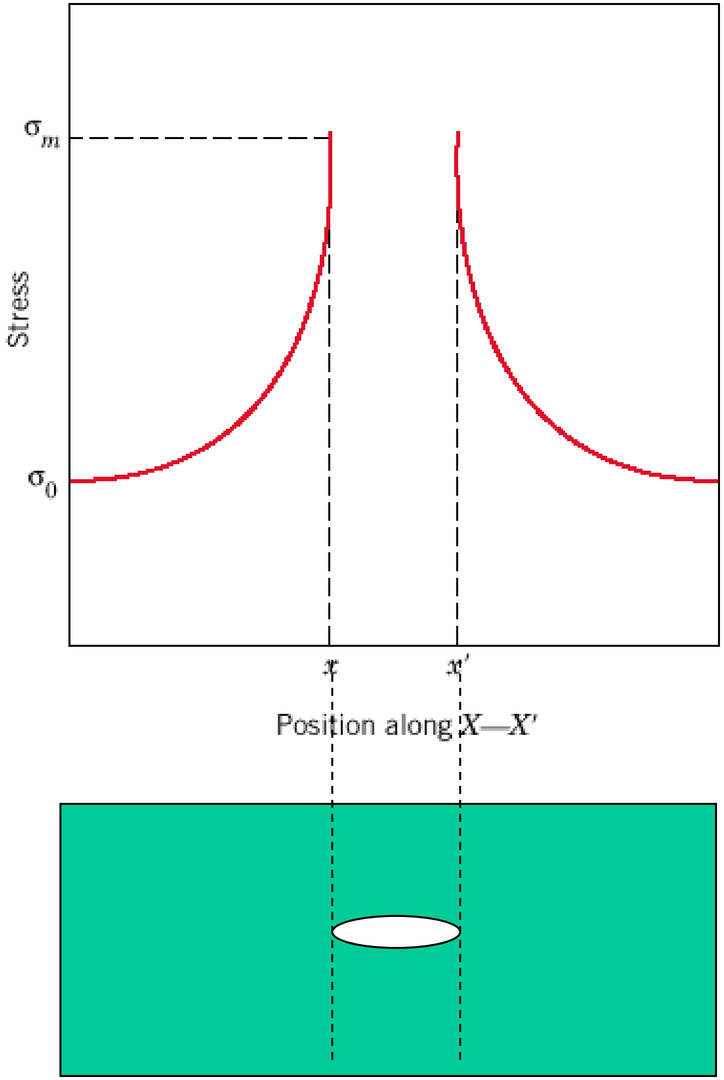
$$\sigma_m = 2\sigma_o\left(\frac{a}{\rho_t}\right)^{1/2} = K_t\sigma_o$$

where

ρ_t = radius of curvature
σ_o = applied stress
σ_m = stress at crack tip
a = lenght of crack
K_t = Stress concentration factor
(σ_m / σ_o)

Adapted from Fig. 8.8(a), *Callister & Rethwisch 8e.*

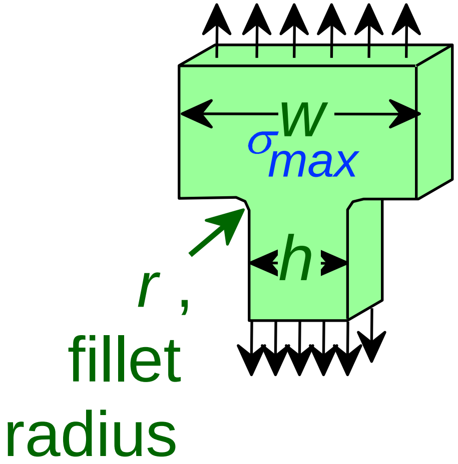
Concentration of Stress at Crack Tip



Adapted from Fig. 8.8(b),
Callister & Rethwisch 8e.

Crack Creation & Propagation

- **Avoid sharp corners!**



Cracks having sharp tips propagate easier than cracks having blunt tips

Energy balance on the crack

- Elastic strain energy-
  - energy stored in material as it is elastically deformed
  - this energy is released when the crack propagates
  - creation of new surfaces requires energy

Criterion for Crack Propagation

Crack propagates if crack-tip stress (σ_m) exceeds a critical stress (σ_c)

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

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

where

- E = modulus of elasticity
- γ_s = specific surface energy
- a = one half length of internal crack

For ductile materials => replace γ_s with $\gamma_s + \gamma_p$
where γ_p is plastic deformation energy

Design Against Crack Growth

- Crack growth condition:

$$K_{Ic} = Y\sigma\sqrt{\pi a}$$

K_c = Fracture toughness

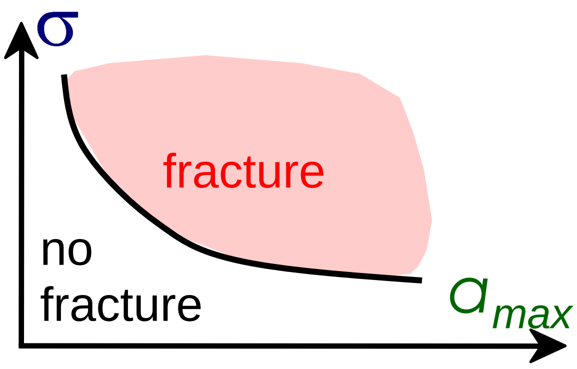
- Largest, most highly stressed cracks grow first!

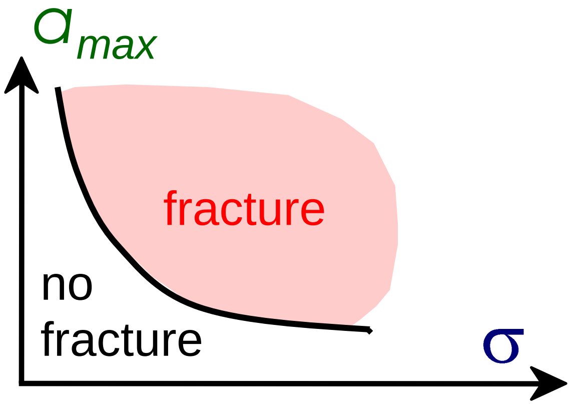
--Scenario 1: Max. flaw size dictates design stress.

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

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

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





Design Example: Aircraft Wing

- Material has K_{Ic} = 26 MPa-m$^{0.5}$
- Two designs to consider...

Design A
--largest flaw is 9 mm
--failure stress = 112 MPa

Design B
--use same material
--largest flaw is 4 mm
--failure stress = ?

- Use...

$$\sigma_c = \frac{K_{Ic}}{Y\sqrt{\pi a_{max}}}$$

- Key point: Y and K_{Ic} are the same for both designs.

$$\frac{K_{Ic}}{Y\sqrt{\pi}} = \sigma\sqrt{a} = \text{constant}$$

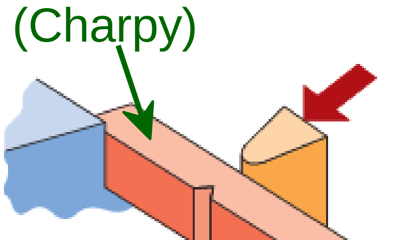
--Result:

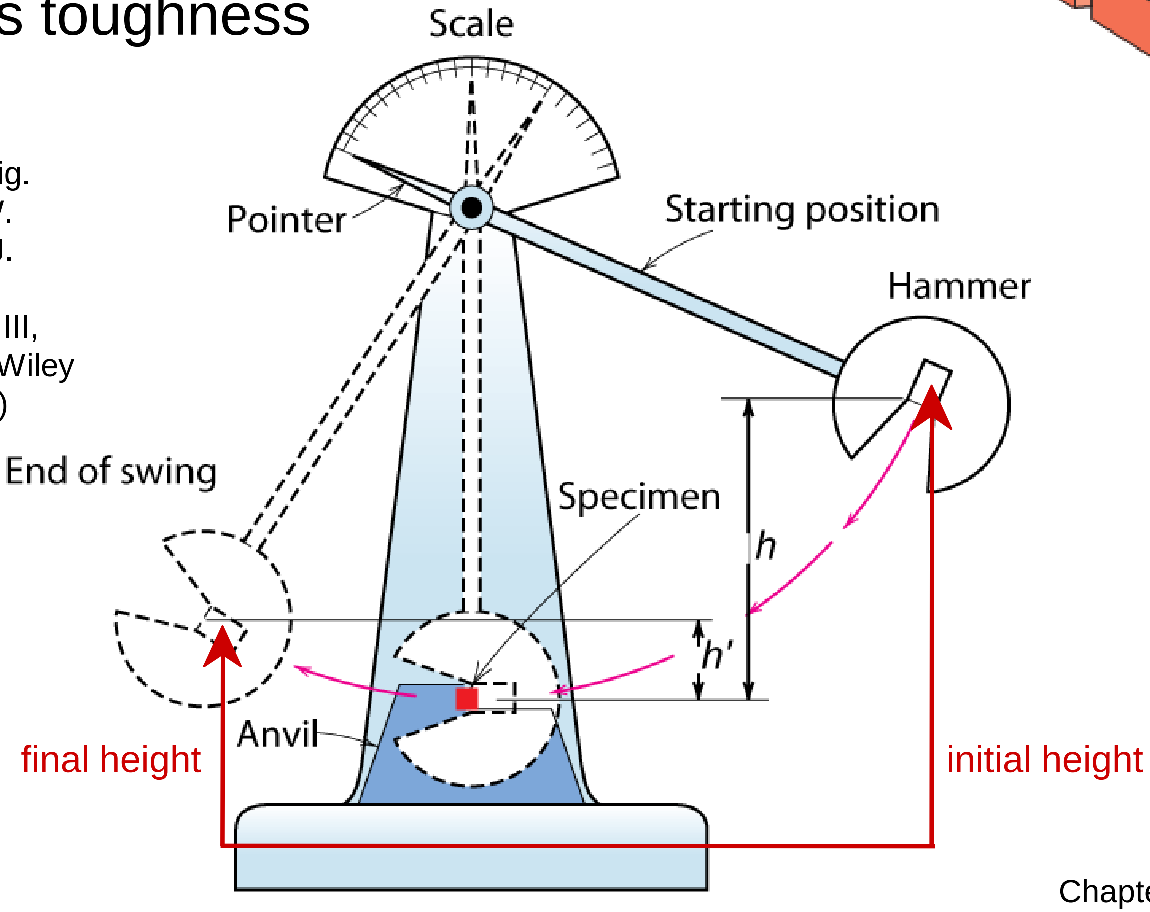
$$\left(\overset{112\text{ MPa}}{\sigma_c}\sqrt{\overset{9\text{ mm}}{a_{max}}}\right)_A = \left(\sigma_c\sqrt{\overset{4\text{ mm}}{a_{max}}}\right)_B$$

Answer: $(\sigma_c)_B = 168$ MPa

Impact Testing

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

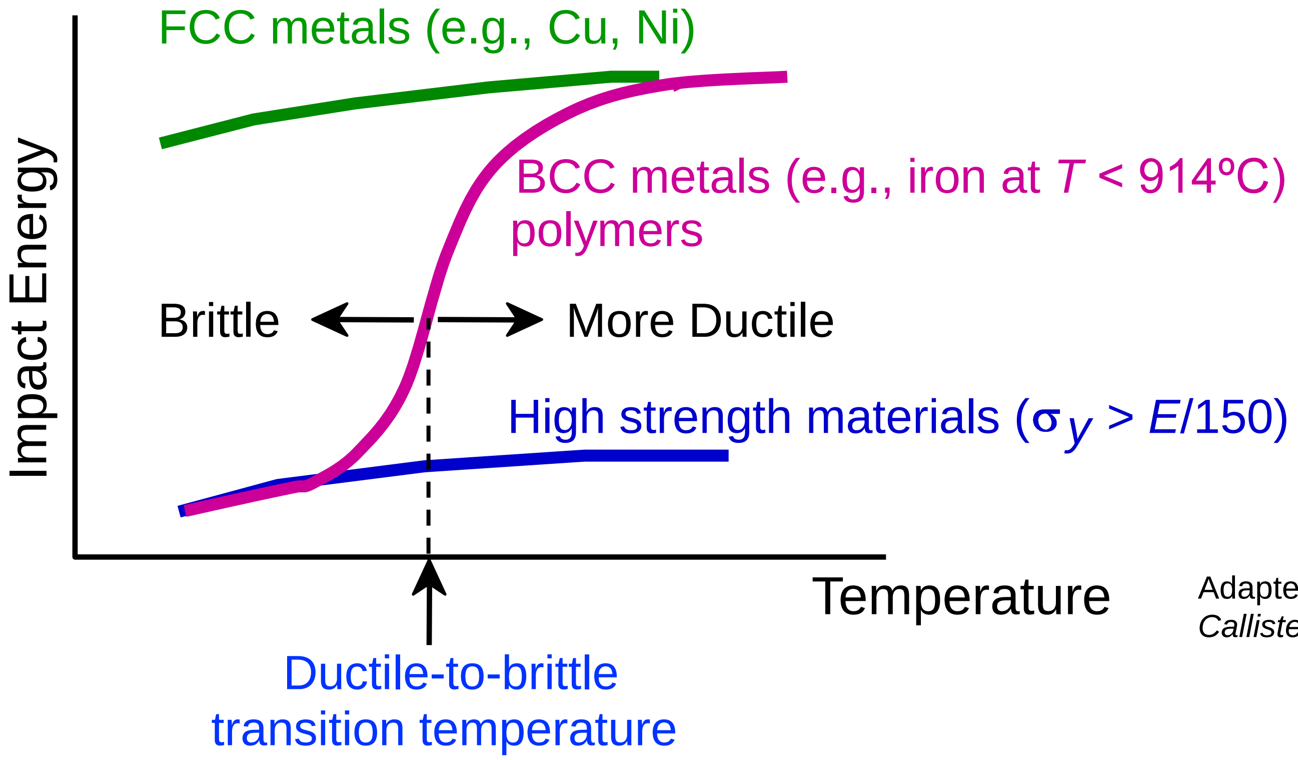




Adapted from Fig. 8.12(b), *Callister & Rethwisch 8e.* (Fig. 8.12(b) is adapted from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, John Wiley and Sons, Inc. (1965) p. 13.)

Influence of Temperature on Impact Energy

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



Adapted from Fig. 8.15, *Callister & Rethwisch 8e.*

Design Strategy:
Stay Above The DBTT!

- **Pre-WWII: The Titanic**

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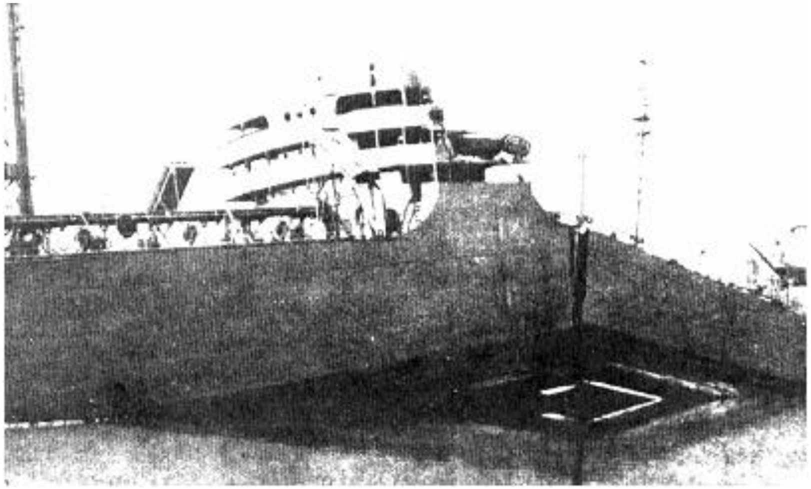
- **WWII: Liberty ships**

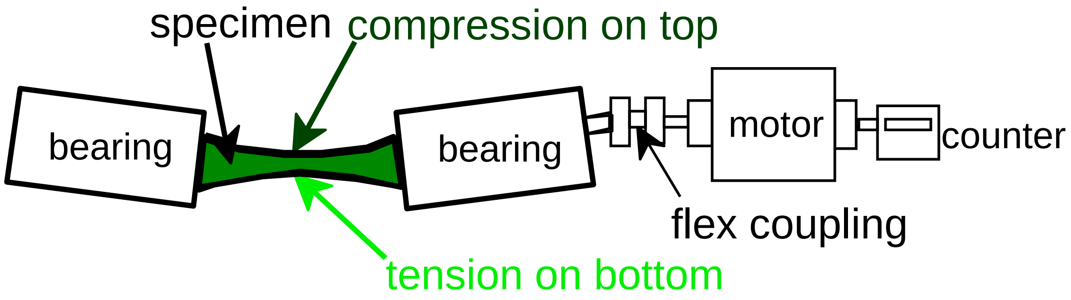


Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(b), p. 262, John Wiley and Sons, Inc., 1996. (Orig. source: Earl R. Parker, "Behavior of Engineering Structures", Nat. Acad. Sci., Nat. Res. Council, John Wiley and Sons, Inc.,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

- Problem: Steels were used having DBTT's just below room temperature.

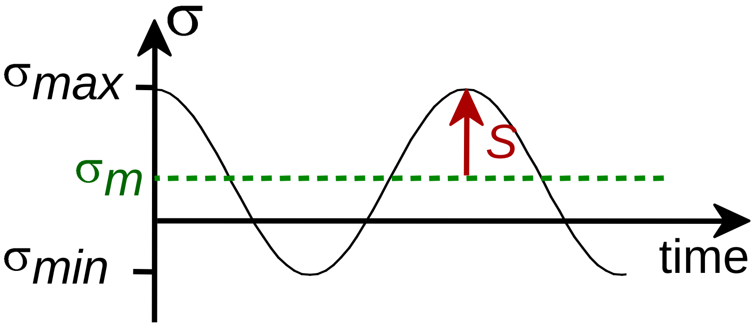
Fatigue

- Fatigue = failure under applied cyclic stress.



Adapted from Fig. 8.18, *Callister & Rethwisch 8e.* (Fig. 8.18 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, σ_m, and cycling frequency

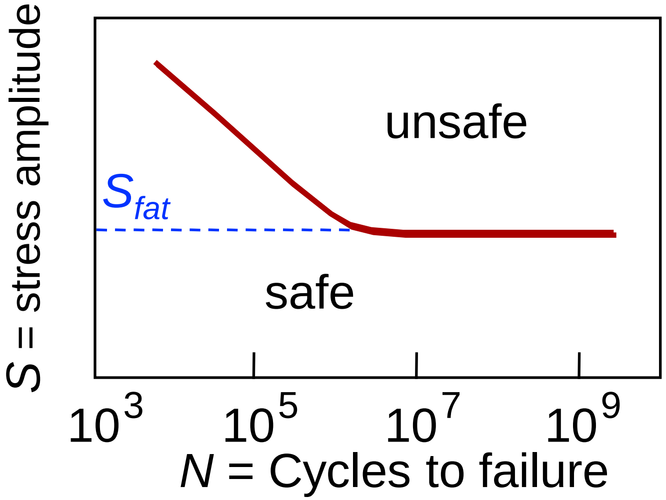


- Key points: Fatigue...
  --can cause part failure, even though $\sigma_{max} < \sigma_y$.
  --responsible for ~ 90% of mechanical engineering failures.

Types of Fatigue Behavior

- Fatigue limit, S_{fat}:

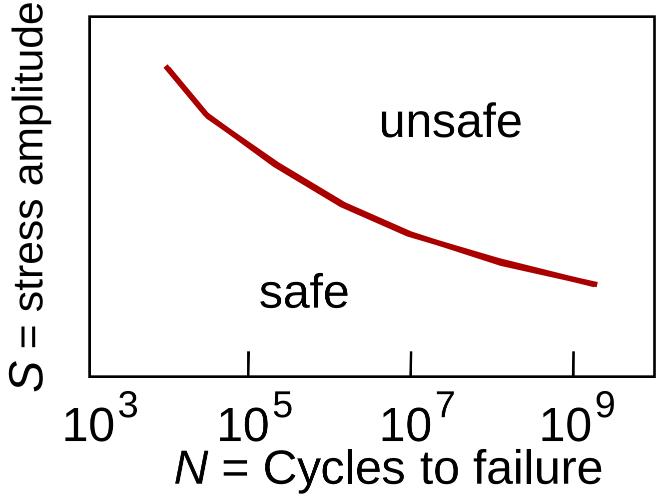
  --no fatigue if $S < S_{fat}$



case for
steel (typ.)

Adapted from Fig. 8.19(a), *Callister & Rethwisch 8e.*

- For some materials, there is no fatigue limit!



case for
Al (typ.)

Adapted from Fig. 8.19(b), *Callister & Rethwisch 8e.*

Rate of Fatigue Crack Growth

- Crack grows *incrementally*

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

typ. 1 to 6

$$\sim \left(\Delta\sigma\right)\sqrt{a}$$

increase in crack length per loading cycle

- Failed rotating shaft

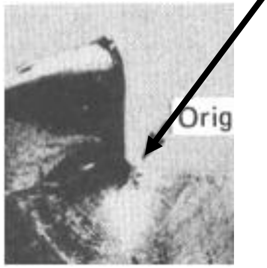
  -- crack grew even though

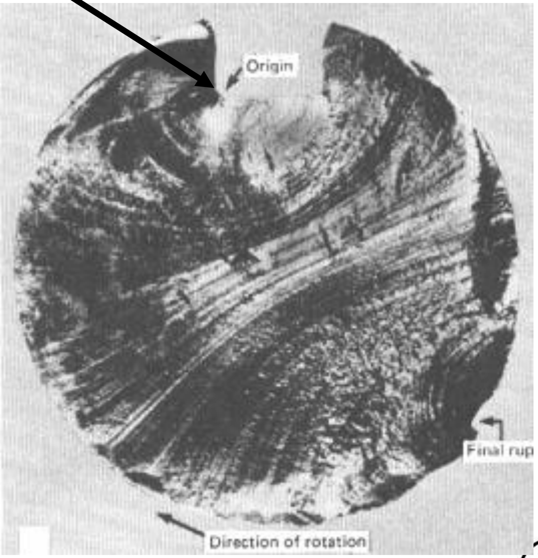
  $K_{max} < K_c$

  -- crack grows faster as

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

crack origin

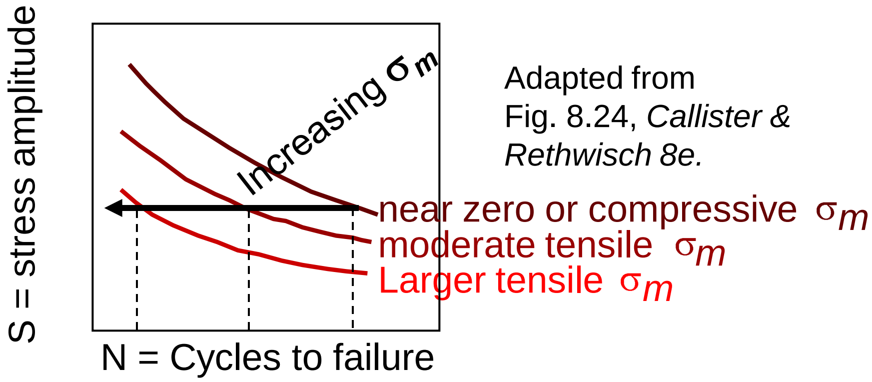




Adapted from Fig. 8.21, *Callister & Rethwisch 8e.* (Fig. 8.21 is from D.J. Wulpi, *Understanding How Components Fail*, American Society for Metals, Materials Park, OH, 1985.)

Improving Fatigue Life

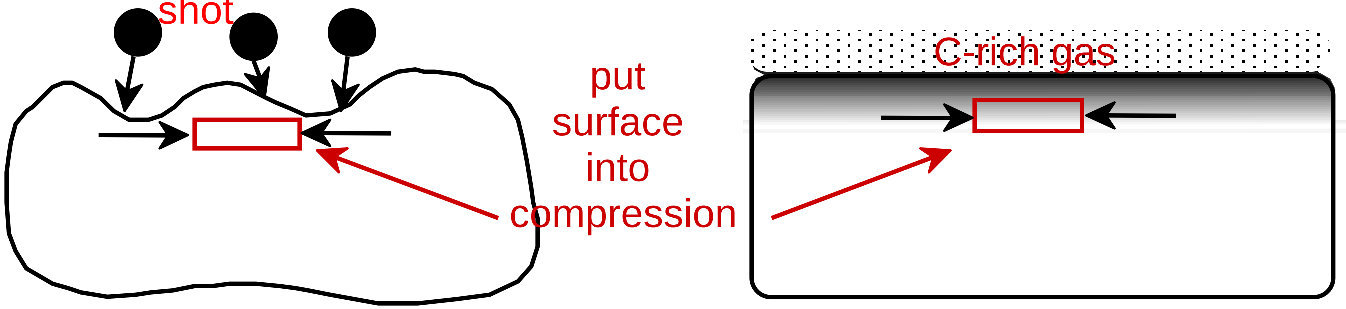
1. Impose compressive surface stresses (to suppress surface cracks from growing)



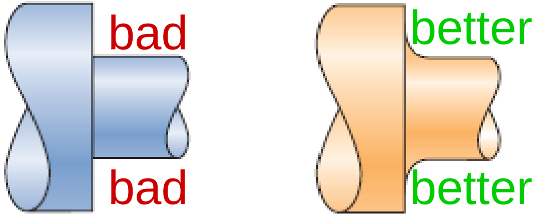
Adapted from Fig. 8.24, *Callister & Rethwisch 8e.*

--Method 1: shot peening

--Method 2: carburizing



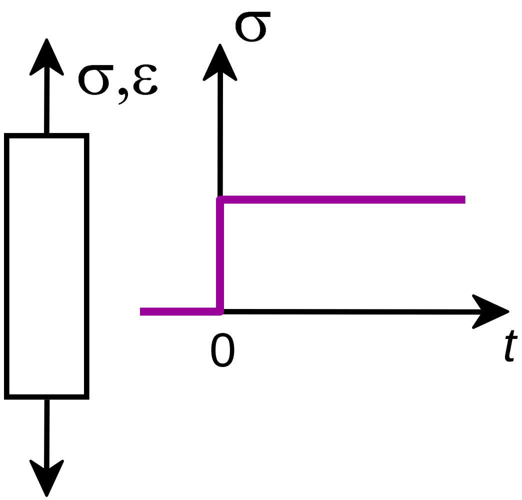
2. Remove stress concentrators.

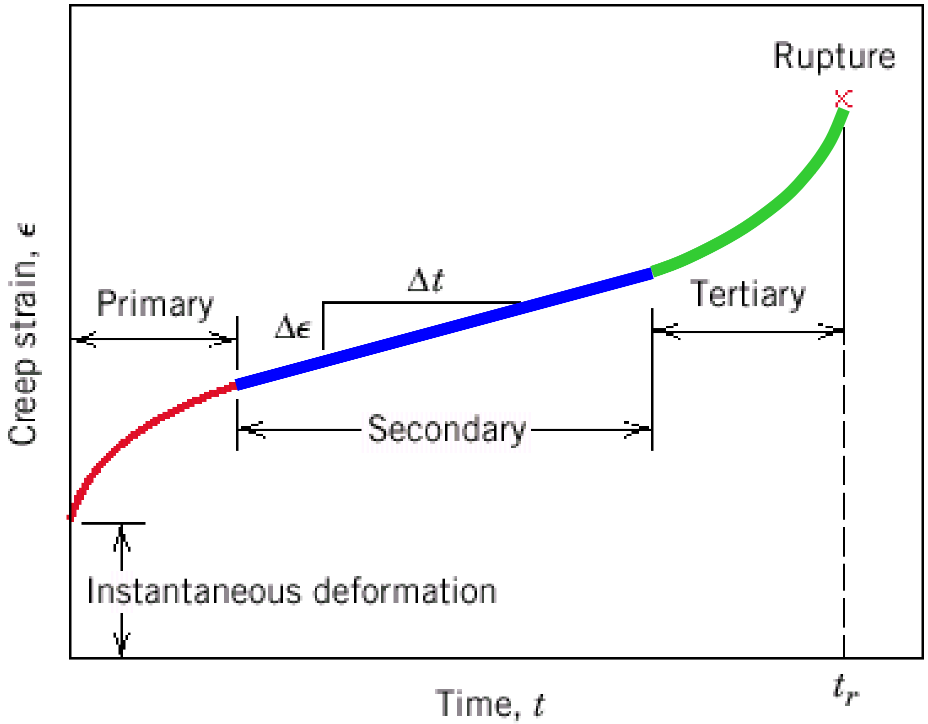


Adapted from Fig. 8.25, *Callister & Rethwisch 8e.*

Creep

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





Adapted from Fig. 8.28, *Callister & Rethwisch 8e.*

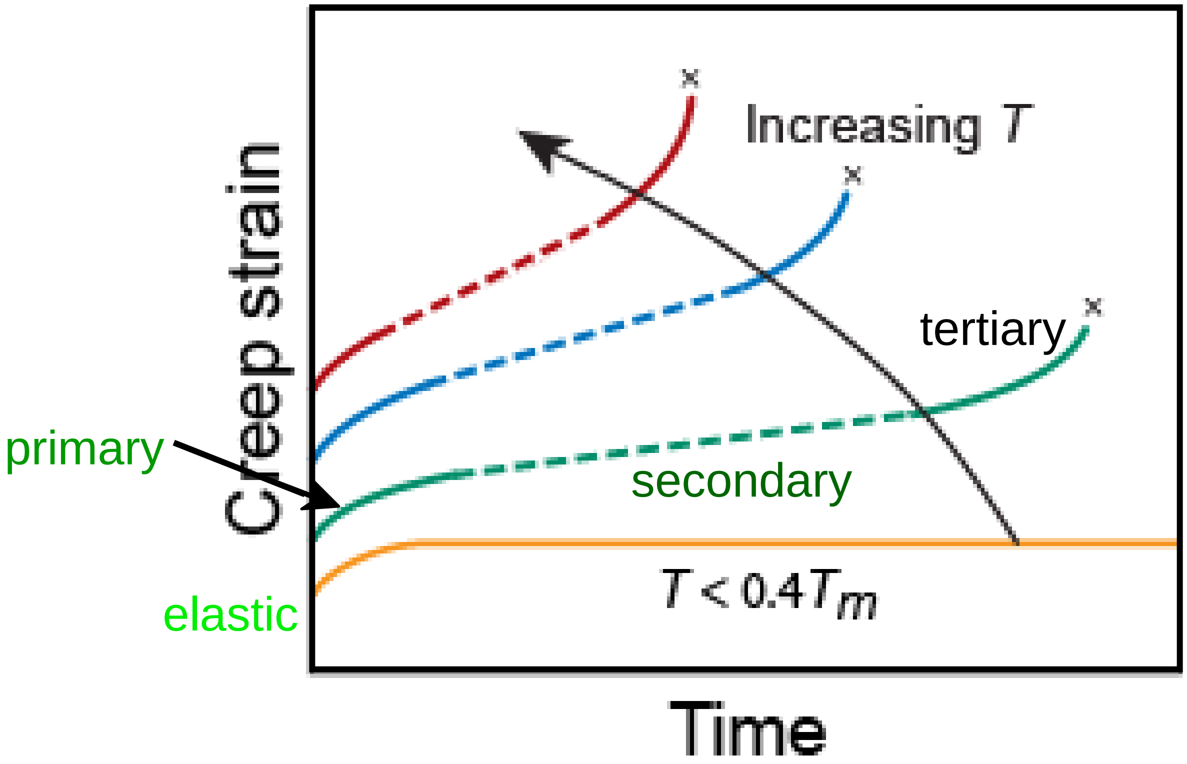
Primary Creep: slope (creep rate) decreases with time.

Secondary Creep: steady-state i.e., constant slope ($\Delta\varepsilon/\Delta t$).

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

Creep: Temperature Dependence

- Occurs at elevated temperature, $T > 0.4\ T_m$ (in K)



Adapted from Fig. 8.29,
Callister & Rethwisch 8e.

Secondary Creep

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

stress exponent (material parameter)

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

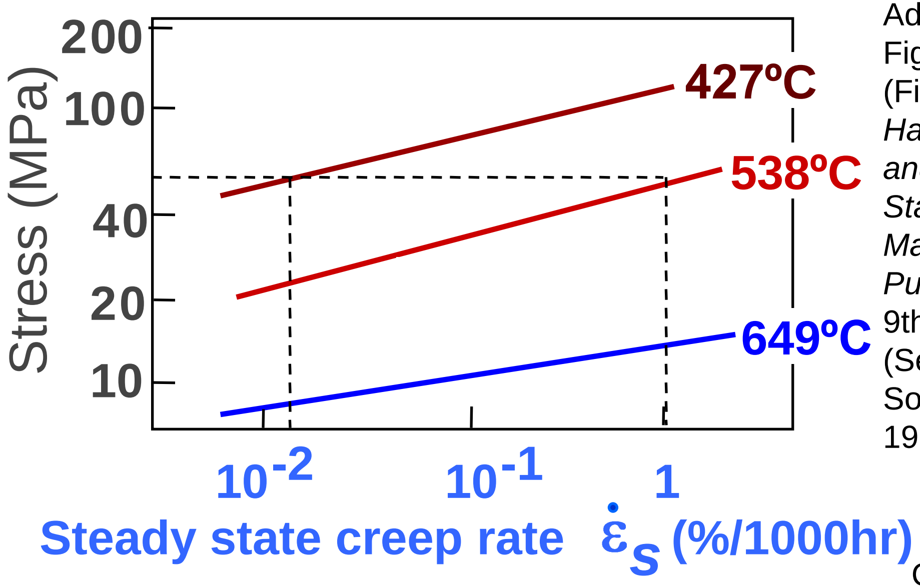
strain rate

material const.

applied stress

activation energy for creep (material parameter)

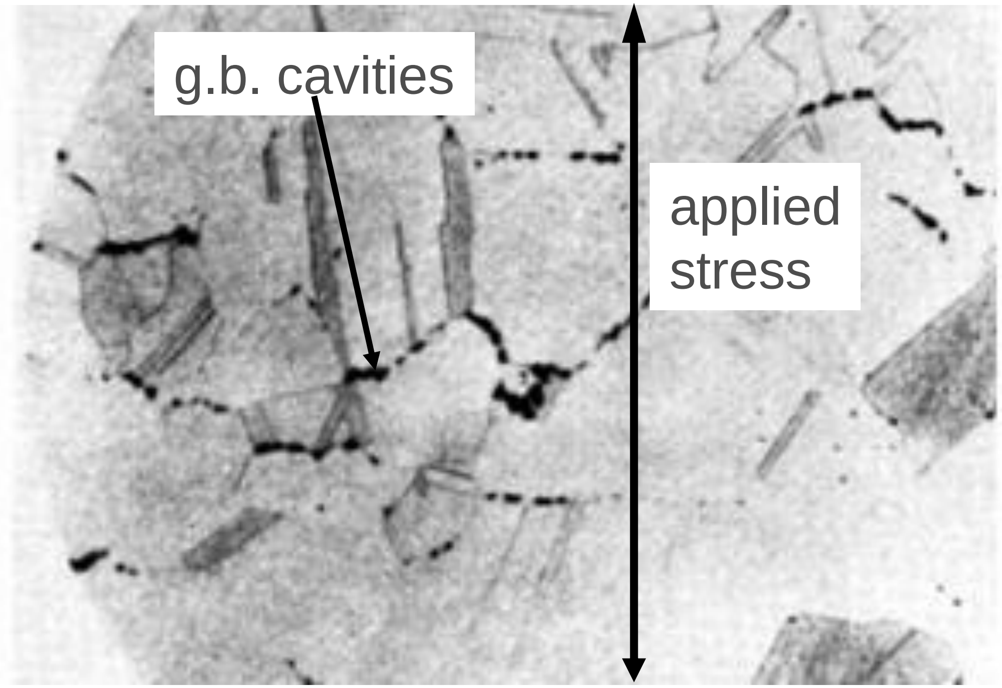
- Strain rate increases with increasing *T*, σ



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.)

Creep Failure

- Failure: along grain boundaries.



From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.32, p. 87, John Wiley and Sons, Inc., 1987. (Orig. source: Pergamon Press, Inc.)

SUMMARY

- Engineering materials not as strong as predicted by theory
- Flaws act as stress concentrators that cause failure at stresses lower than theoretical values.
- Sharp corners produce large stress concentrations and premature failure.
- Failure type depends on T and σ:

  -For simple fracture (noncyclic σ and $T < 0.4T_m$), failure stress decreases with:

    - increased maximum flaw size,
    - decreased T,
    - increased rate of loading.

  - For fatigue (cyclic σ):

    - cycles to fail decreases as $\Delta\sigma$ increases.

  - For creep ($T > 0.4T_m$):

    - time to rupture decreases as σ or T increases.