Chapter 8: Mechanical Failure

Topics...

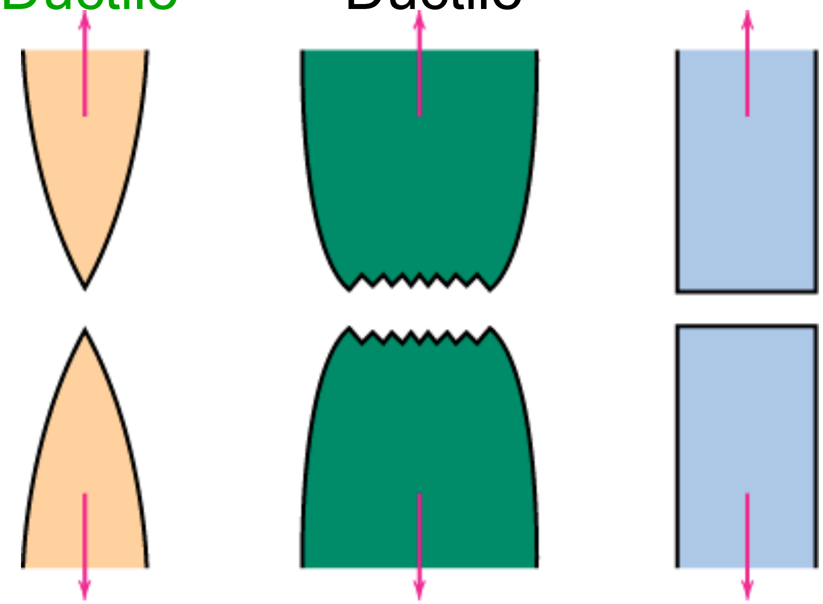
- How do loading rate, loading history, and temperature affect the failure stress?

Ship-cyclic loading from waves.

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!

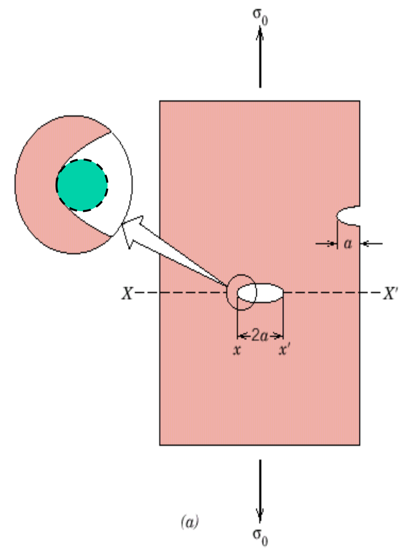
Ductile: warning before fracture

Brittle: No warning

Several K's Beware!

Stress Concentration factor:

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



$$K_t = \frac{\sigma max}{\sigma_o}$$ unitless

Stress Intensity factor:

$$K \geq K_c$$

Stress Intensity Factor:
--Depends on load & geometry.

Fracture Toughness:
--Depends on the material, temperature, environment, & rate of loading.

$$K \geq K_c = Y\sigma\sqrt{\pi a} \quad \text{MPa m}^{1/2}$$

When Does a Crack Propagate?

Crack propagates if above critical stress

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

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

where

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

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

where γ_p is plastic deformation energy

Design Against Crack Growth

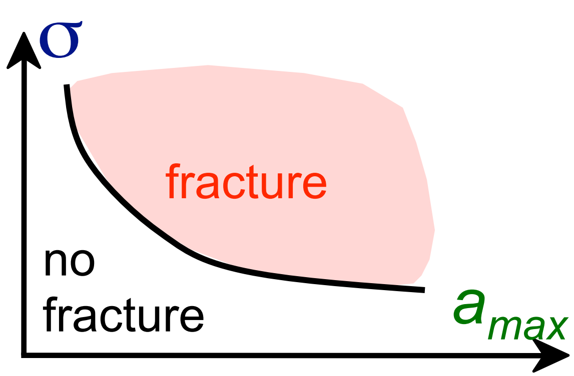
- Crack growth condition:

$$K \geq K_c = Y\sigma\sqrt{\pi a}$$

- Largest, most stressed cracks grow first!

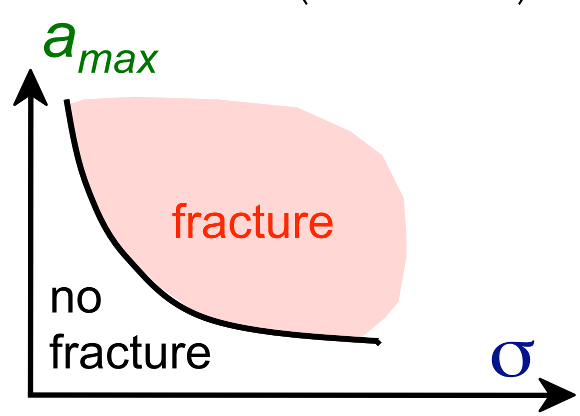
--Result 1: Max. flaw size dictates design stress.

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



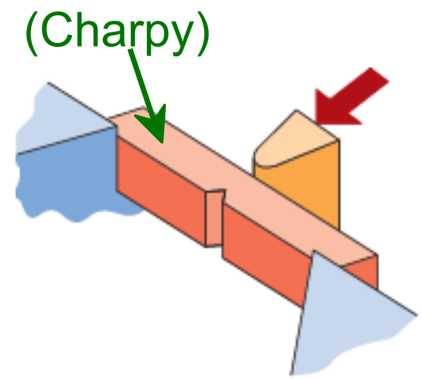
--Result 2: Design stress dictates max. flaw size.

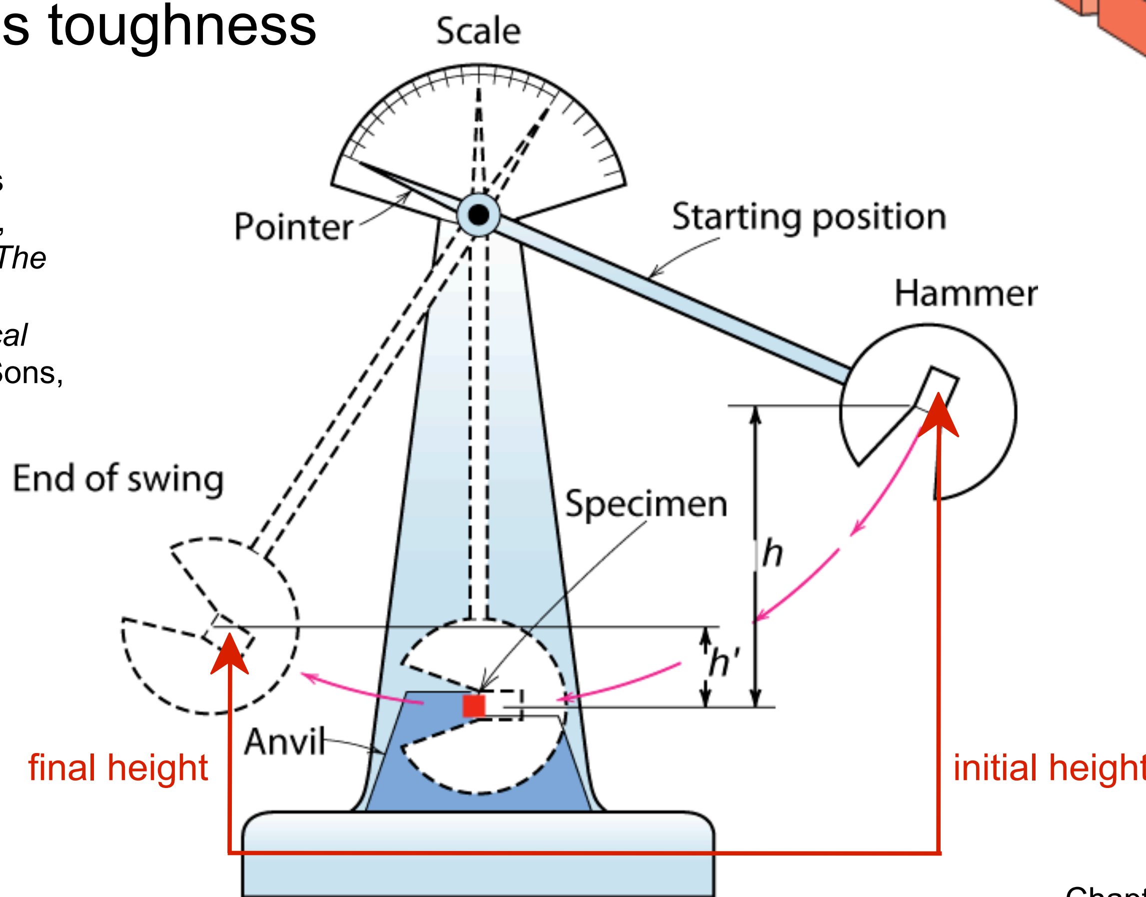
$$a_{max} < \frac{1}{\pi}\left(\frac{K_c}{Y\sigma_{design}}\right)^2$$



Impact Testing

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

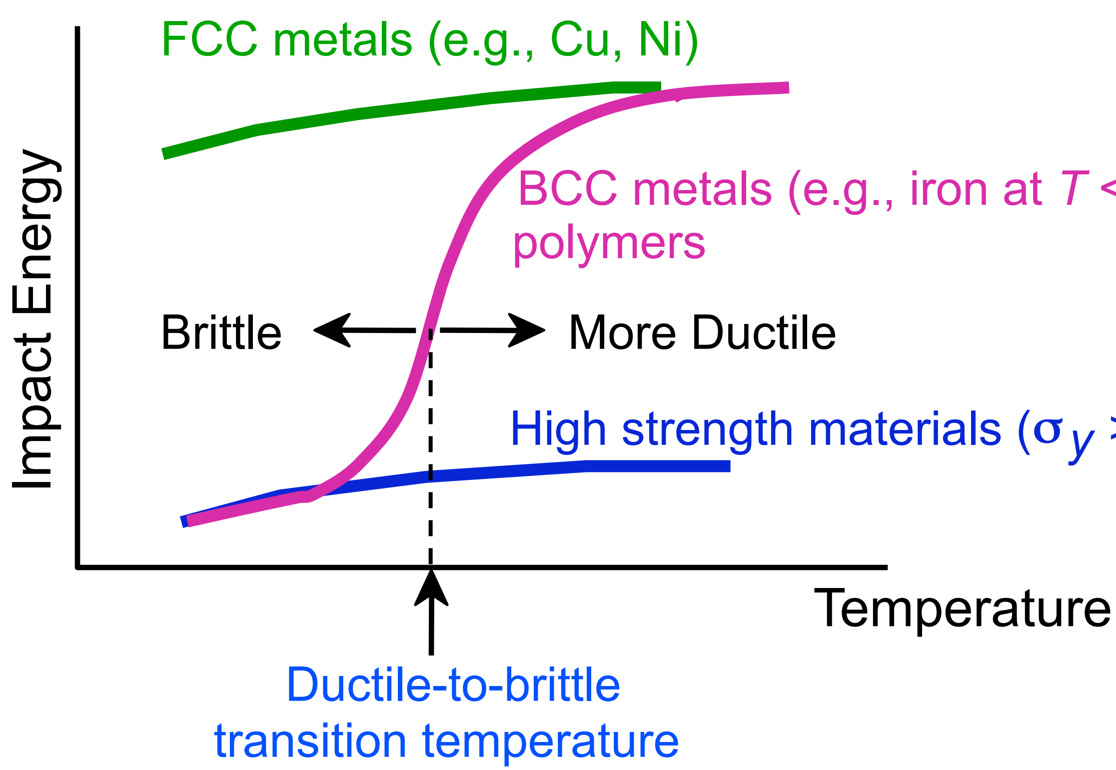




Adapted from Fig. 8.12(b), *Callister 7e.* (Fig. 8.12(b) is adapted from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, John Wiley and Sons, Inc. (1965) p. 13.)

Temperature

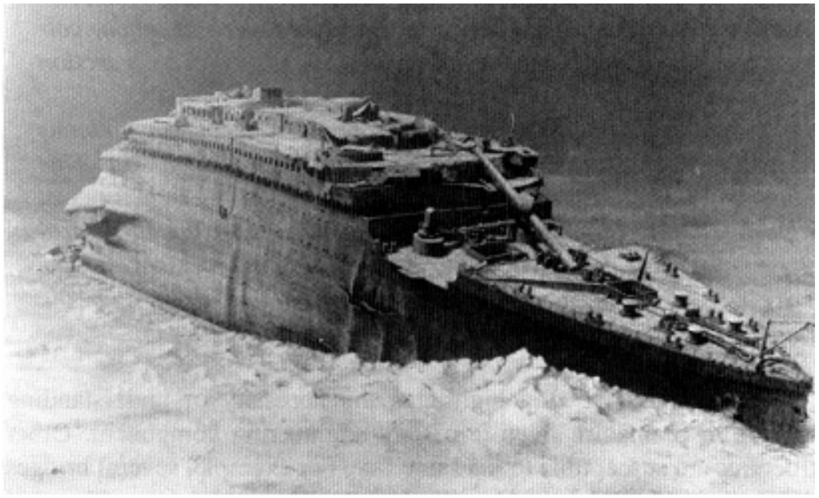
- **Increasing temperature...**
  --increases %*EL* and K_c
- **Ductile-to-Brittle Transition Temperature (DBTT)...**



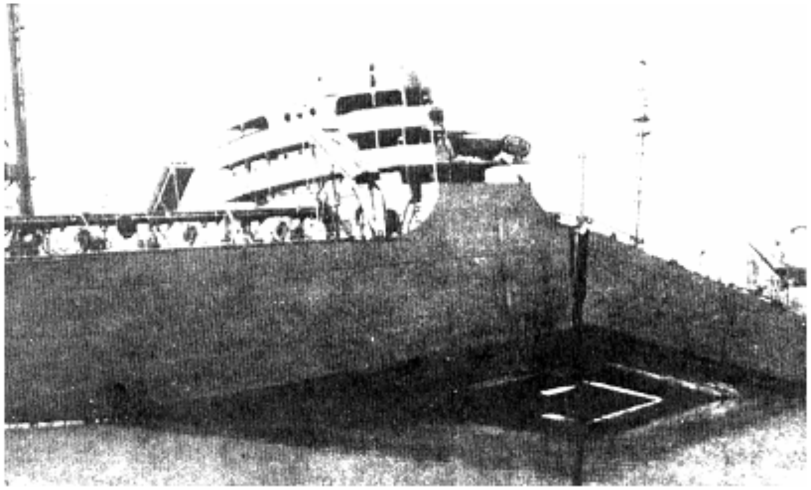
Adapted from Fig. 8.15, *Callister 7e.*

Design Strategy: Stay Above The DBTT!

- **Pre-WWII: The Titanic**



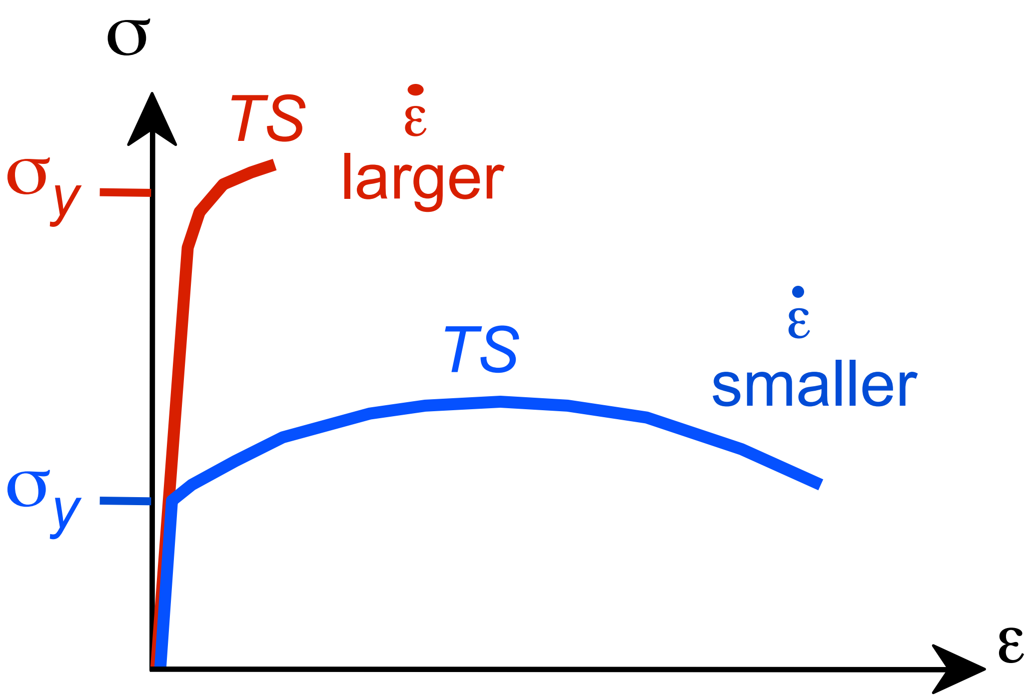
- **WWII: Liberty ships**



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

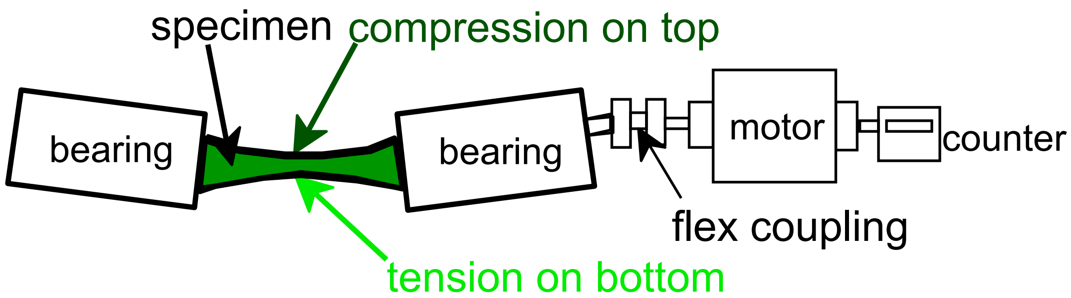
Loading Rate

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



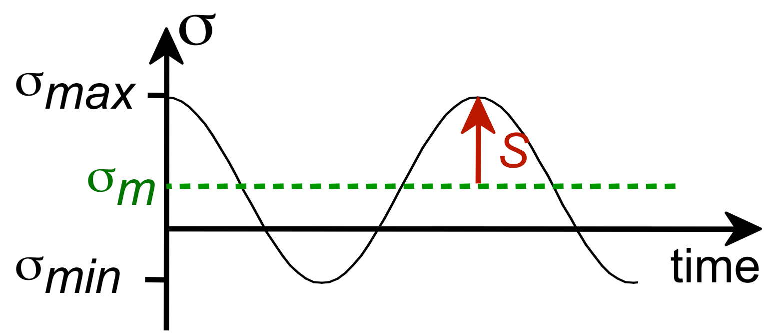
Fatigue

- Fatigue = failure under cyclic stress.



Adapted from Fig. 8.18, *Callister 7e.* (Fig. 8.18 is from *Materials Science in Engineering*, 4/E by Carl. A. Keyser, Pearson Education, Inc., Upper Saddle River, NJ.)

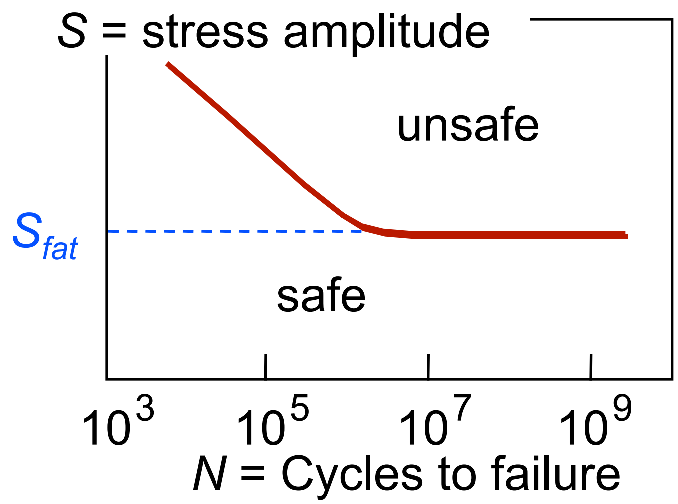
- Stress varies with time.
  -- key parameters are S, σ_m, and frequency



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

Fatigue Design Parameters

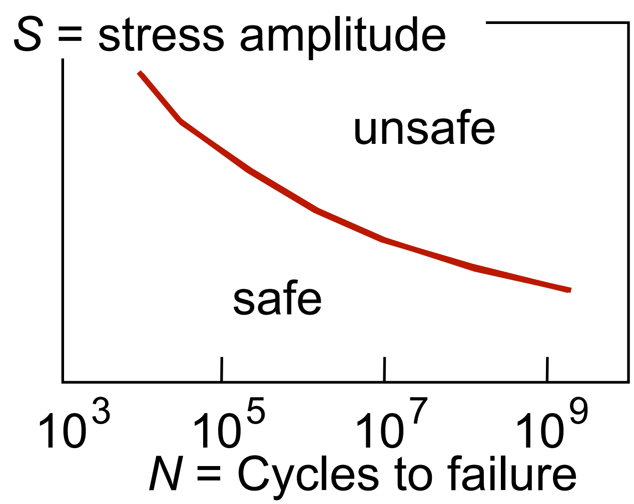
- Fatigue limit, S_{fat}:
  --no fatigue if $S < S_{fat}$



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.*

Fatigue Mechanism

- Crack grows *incrementally*

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

typ. 1 to 6

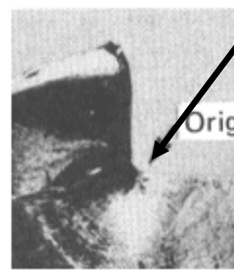
$$\Delta K \sim (\Delta\sigma)\sqrt{a}$$

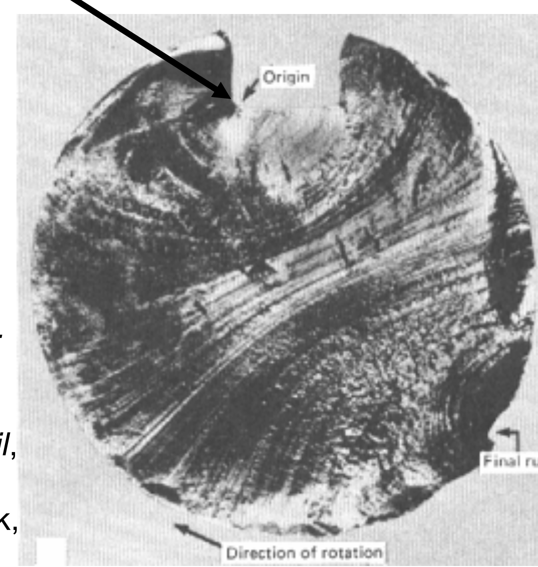
increase in crack length per loading cycle

- Failed rotating shaft

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

crack origin

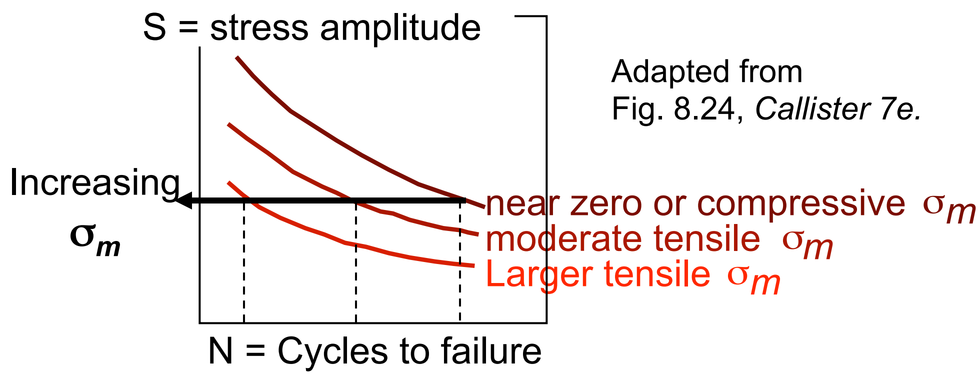




Adapted from Fig. 8.21, *Callister 7e.* (Fig. 8.21 is from D.J. Wulpi, *Understanding How Components Fail*, American Society for Metals, Materials Park, OH, 1985.)

Improving Fatigue Life

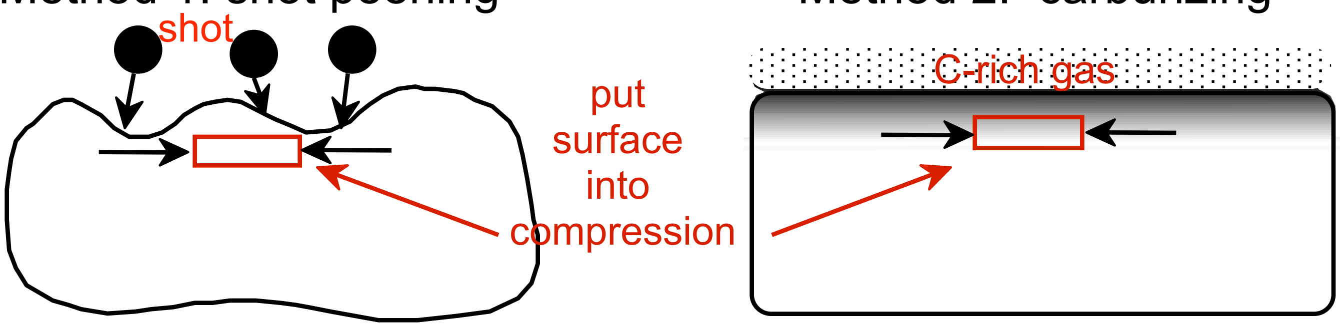
1. Impose a compressive surface stress (to suppress surface cracks from growing)



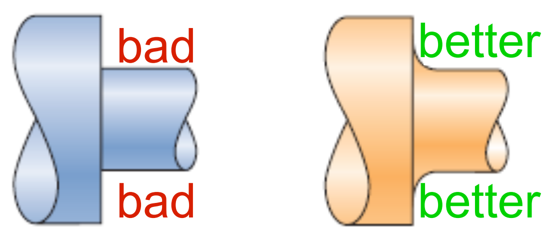
Adapted from Fig. 8.24, *Callister 7e.*

--Method 1: shot peening

--Method 2: carburizing



2. Remove stress concentrators.



Adapted from Fig. 8.25, *Callister 7e.*

Factors that affect fatigue life

- **Mean stress**
- **Surface effects**
  - Design factors
  - Surface treatments
  - Case hardening

Environmental effects

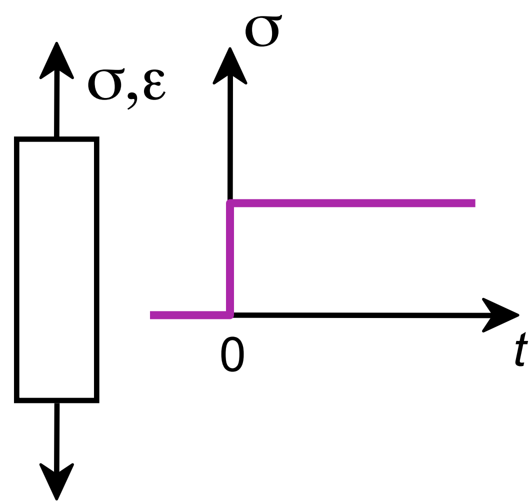
- **Thermal fatigue: induced at elevated temperatures by fluctuating thermal stresses.**

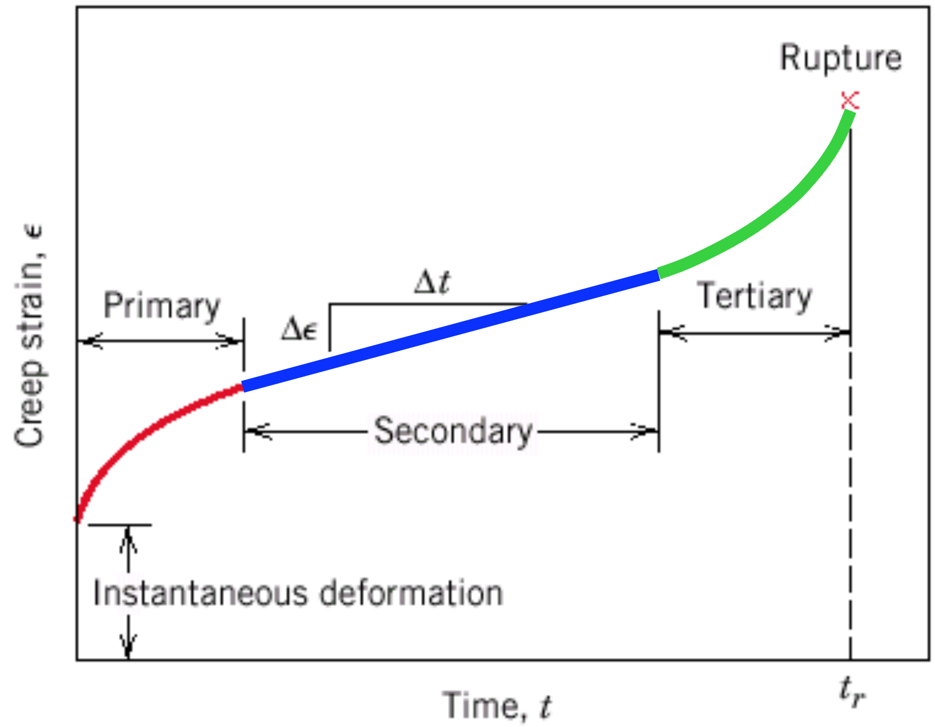
$$\sigma = \alpha_l E \Delta T$$

- **Corrosion fatigue: failure occurs by the simultaneous action of a cyclic stress and chemical attack**

Creep

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





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

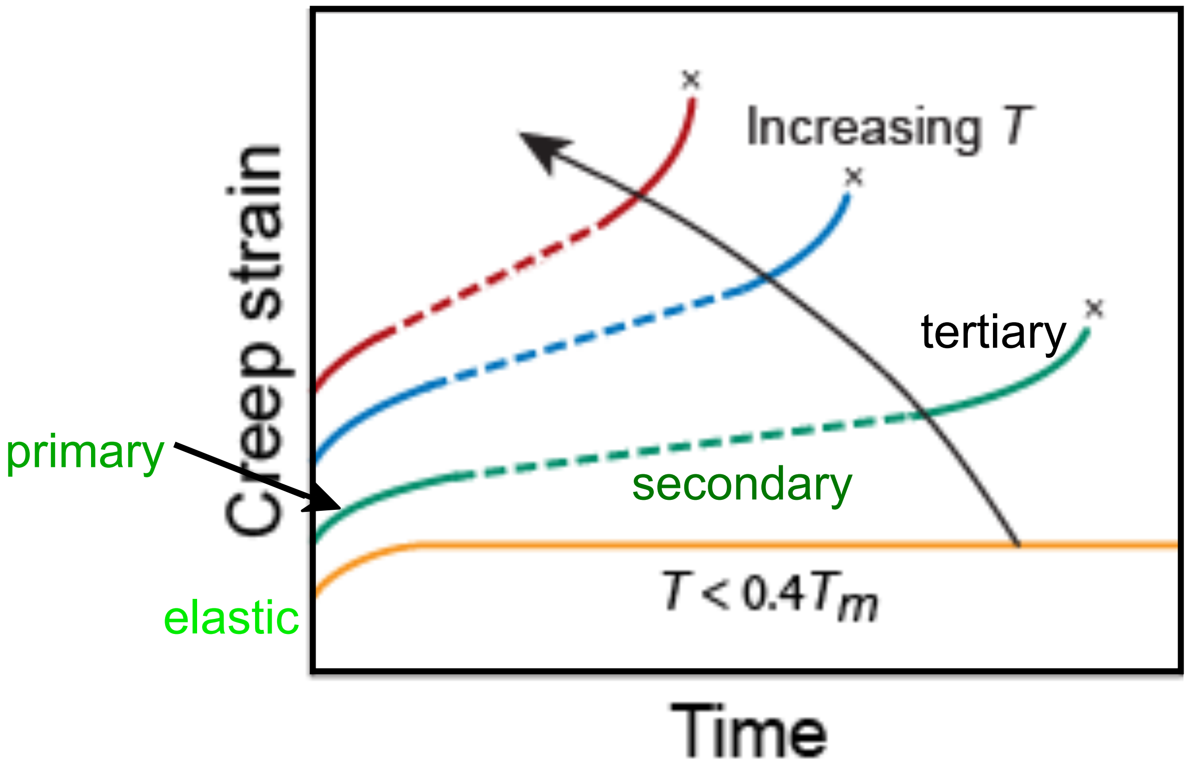
Secondary Creep: steady-state i.e., constant slope.

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

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

Creep

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



Adapted from Figs. 8.29,
Callister 7e.

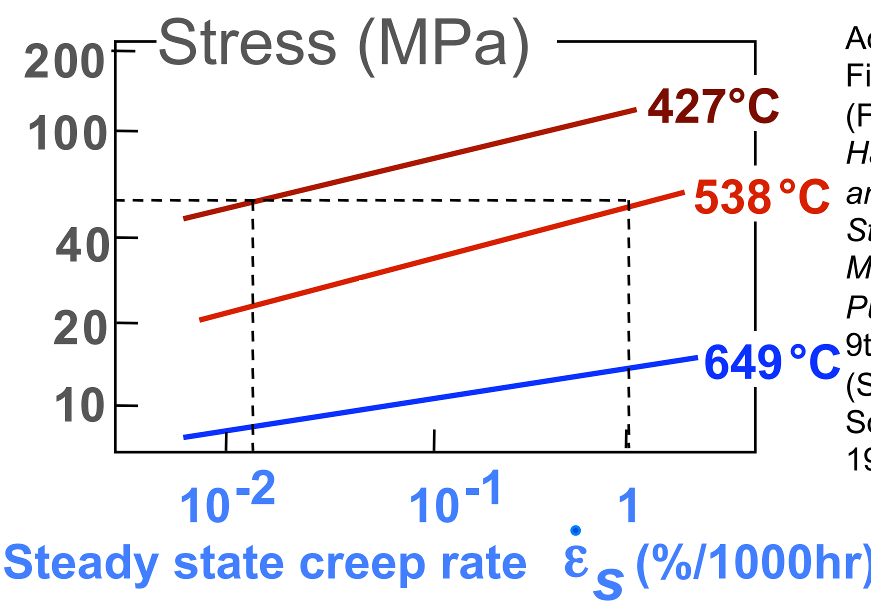
Secondary Creep

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

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

- strain rate: $\dot{\varepsilon}_s$
- material const.: K_2
- applied stress: σ
- stress exponent (material parameter): n
- activation energy for creep (material parameter): Q_c

- 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.)

Creep Failure

- Time to rupture, t_r

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

temperature

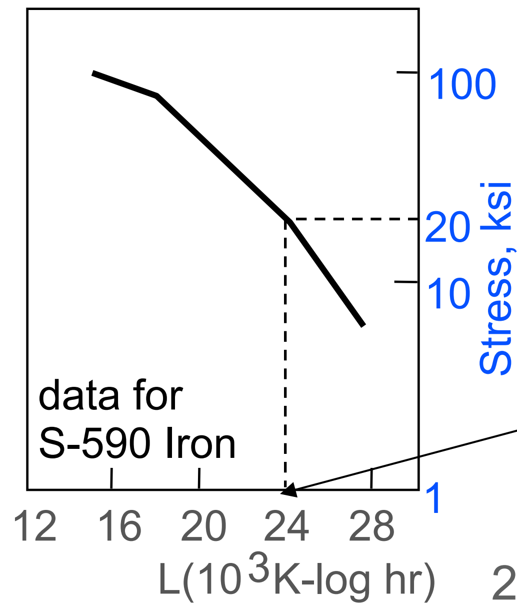
time to failure (rupture)

function of applied stress

Larson Miller Parameter

- Estimate rupture time

S-590 Iron, T = 800°C, σ = 20 ksi



Adapted from Fig. 8.32, *Callister 7e.* (Fig. 8.32 is from F.R. Larson and J. Miller, *Trans. ASME*, **74**, 765 (1952).)

24×10^3 K-log hr

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

1073K

Ans: t_r = 233 hr

SUMMARY

- Engineering materials don't reach theoretical strength.
- Flaws produce stress concentrations that cause premature failure.
- Sharp corners produce large stress concentrations and premature failure.
- Failure type depends on T and stress:
  - for noncyclic σ and $T < 0.4T_m$, failure stress decreases with:
    - increased maximum flaw size,
    - decreased T,

  - for cyclic σ:
    - cycles to fail decreases as $\Delta\sigma$ increases.
  - for higher T ($T > 0.4T_m$):
    - time to fail decreases as σ or T increases.