Chapter 8: Mechanical Failure

Topics...

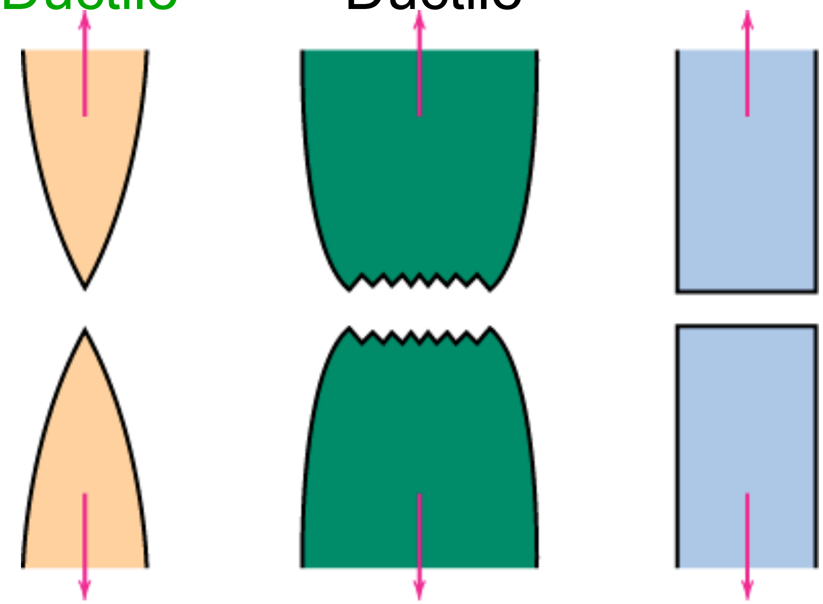
- How do loading rate, loading history, and temperature affect the failure stress?

Ship-cyclic loading from waves.

Failure

- Classification:

Fracture behavior:	Very Ductile	Moderately Ductile	Brittle



%*AR* or %*EL*	Large	Moderate	Small

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

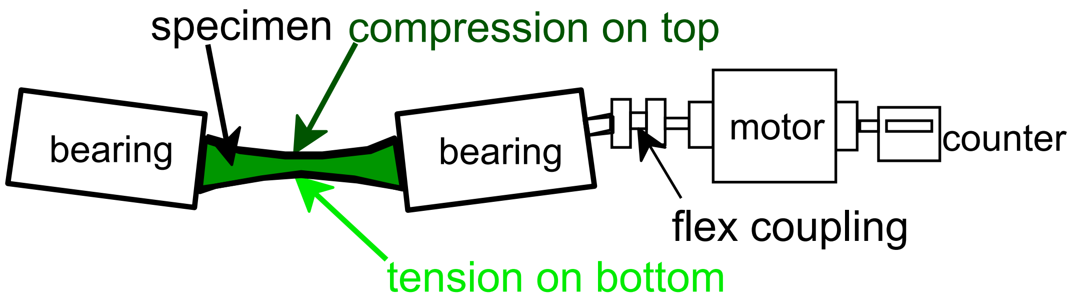
- Ductile fracture is usually desirable!

Ductile: warning before fracture

Brittle: No warning

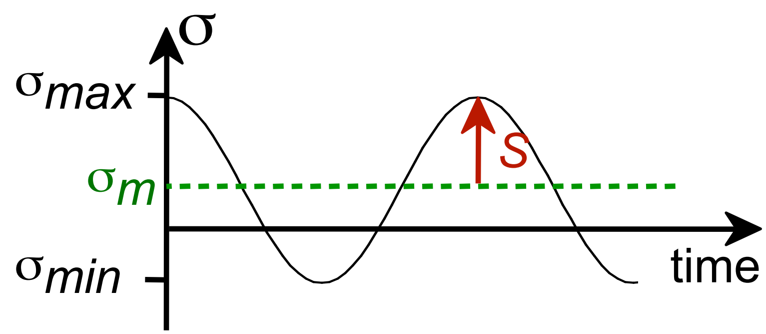
Fatigue

- 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.)

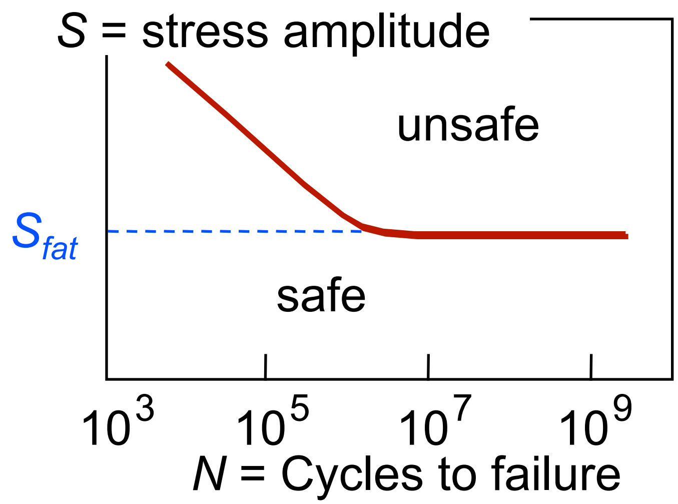
- Stress varies with time.
  -- key parameters are S, σ_m, and frequency



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

Fatigue Design Parameters

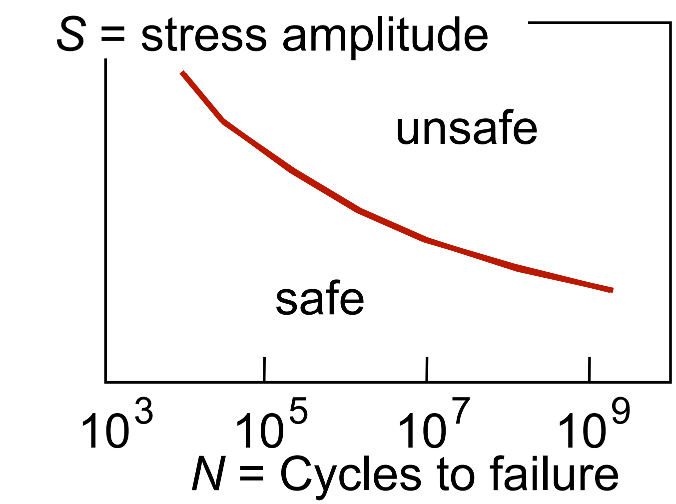
- Fatigue limit, S_{fat}:
  --no fatigue if $S < S_{fat}$



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*

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

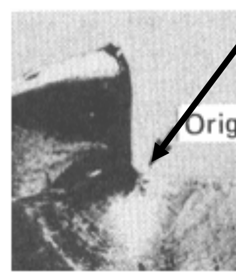
typ. 1 to 6

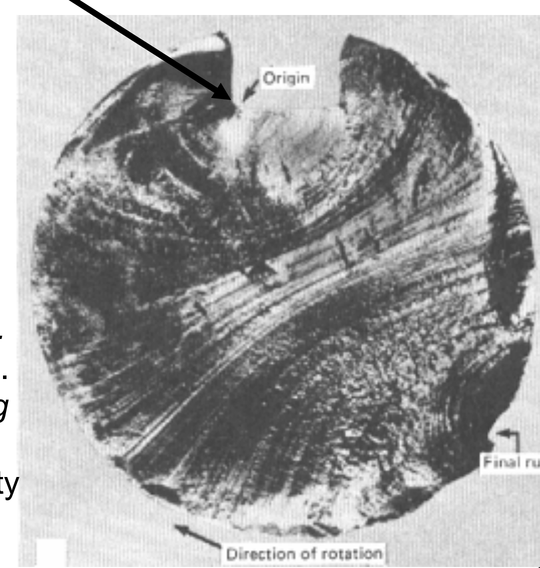
$\sim (\Delta\sigma)\sqrt{a}$

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

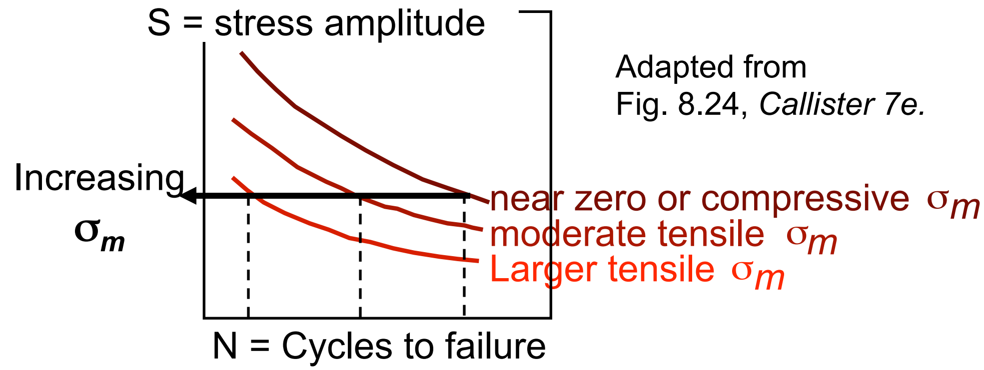




Adapted from Fig. 8.21, *Callister 7e.* (Fig. 8.21 is from D.J. Wulpi, *Understanding How Components Fail*, American Society for Metals, Materials Park, OH, 1985.)

Improving Fatigue Life

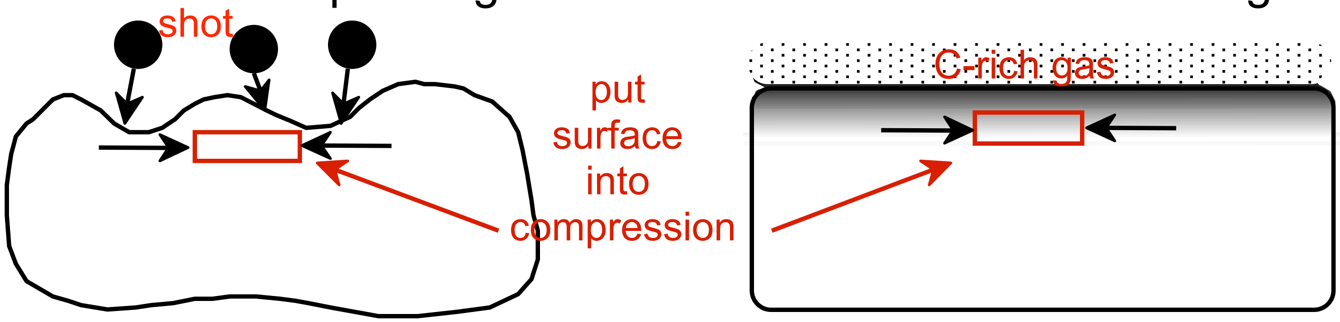
1. Impose a compressive surface stress
   (to suppress surface cracks from growing)



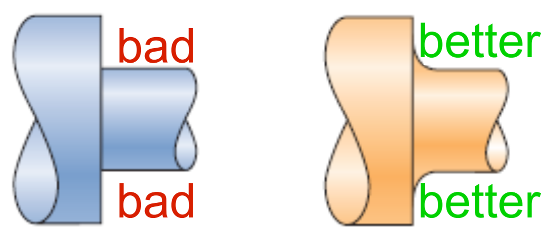
Adapted from Fig. 8.24, *Callister 7e.*

--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

Carburized steel

Core steel

Environmental effects

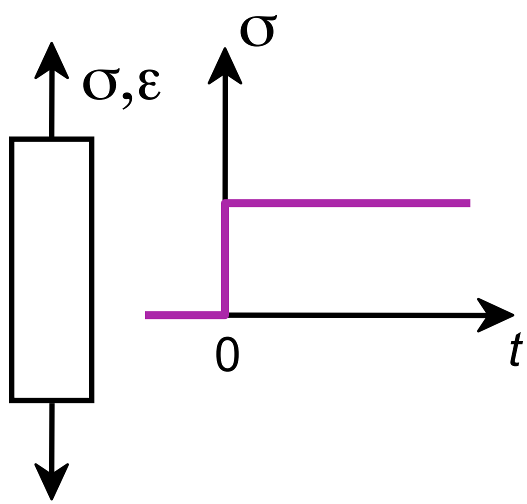
- **Thermal fatigue: induced at elevated temperatures by fluctuating thermal stresses.**

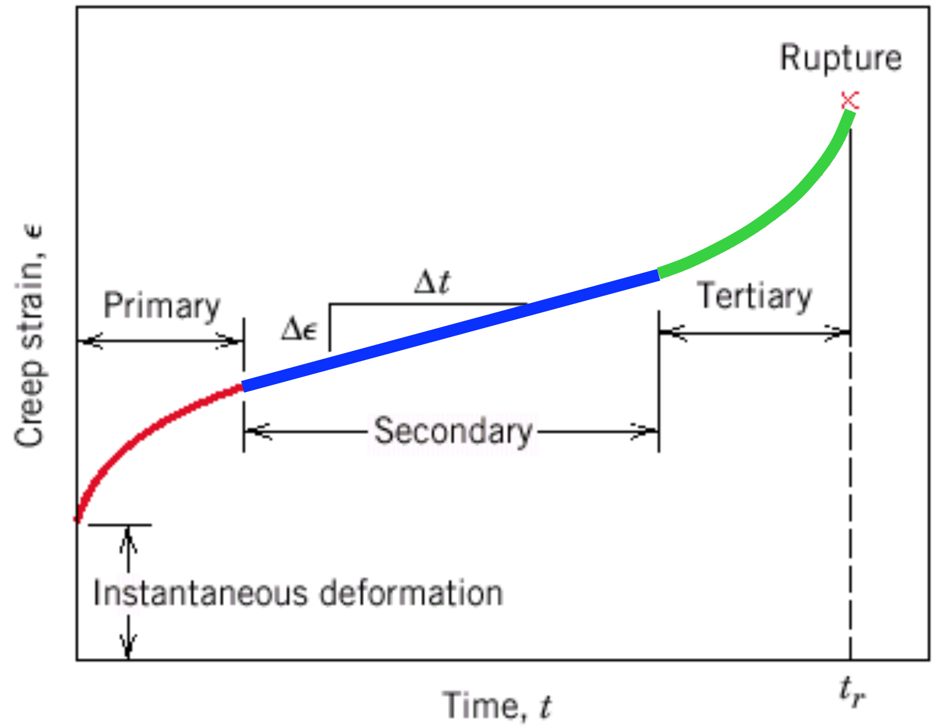
$$\sigma = \alpha_l E \Delta T$$

- **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.

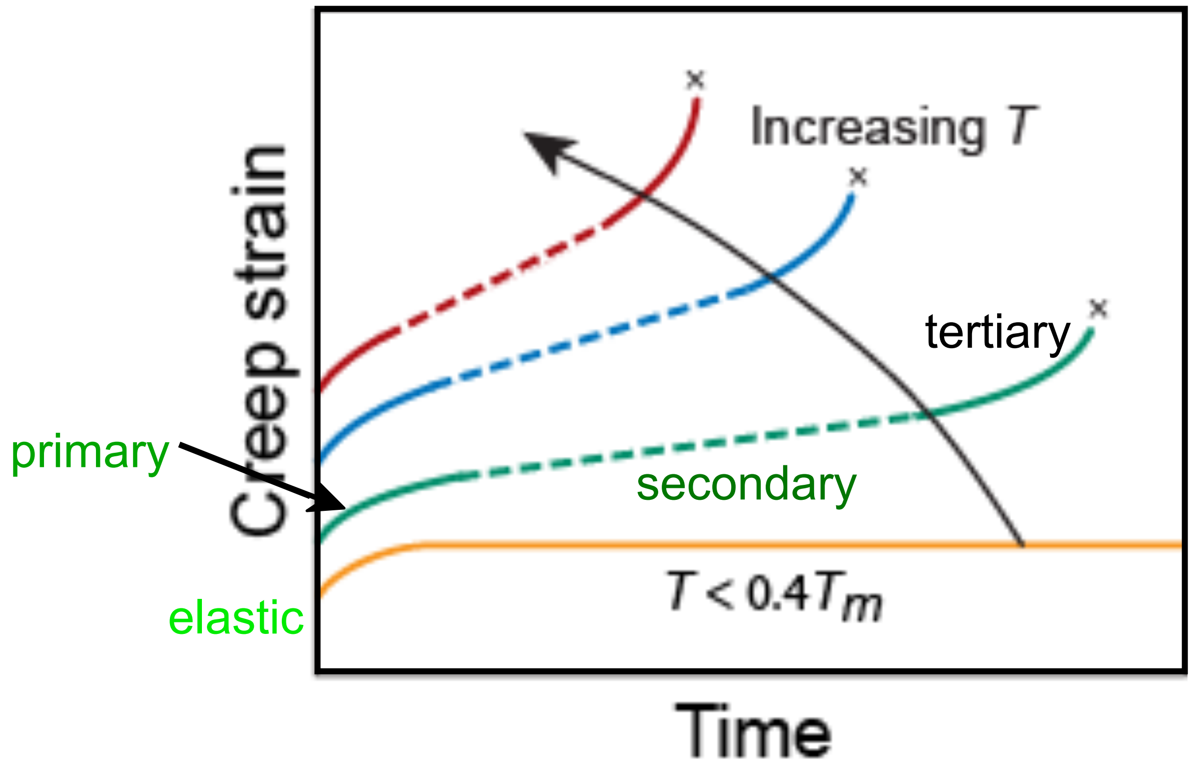
Secondary Creep: steady-state i.e., constant slope.

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.

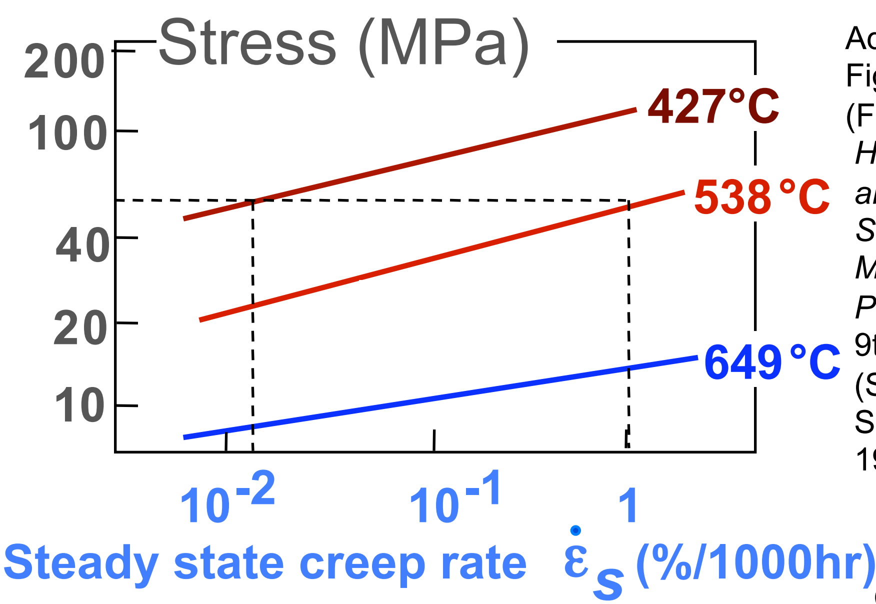
Secondary Creep

- 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)

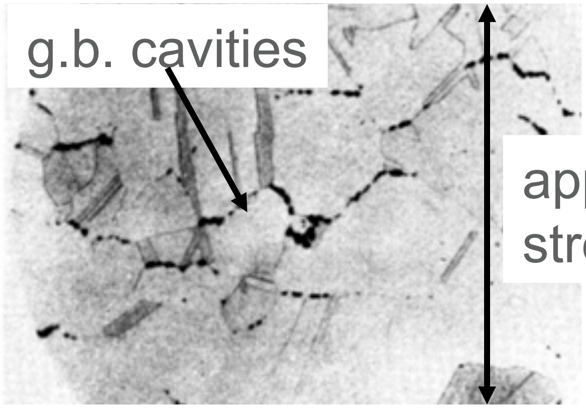
- Strain rate increases for higher T, σ



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

- 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.)

- Time to rupture, t_r

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

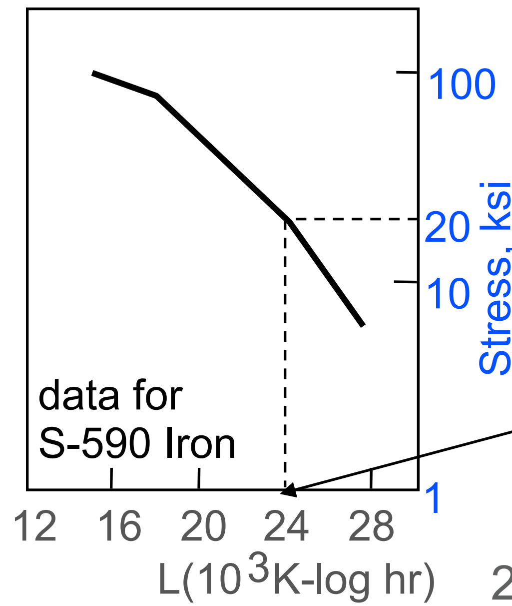
temperature → T

time to failure (rupture) → t_r

function of applied stress → L

- 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).)

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

1073K → T

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,
    - increased rate of loading.
  - 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.