When Does a Crack Propagate?

Crack propagates if above critical stress

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

or $K_t > K_c$

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

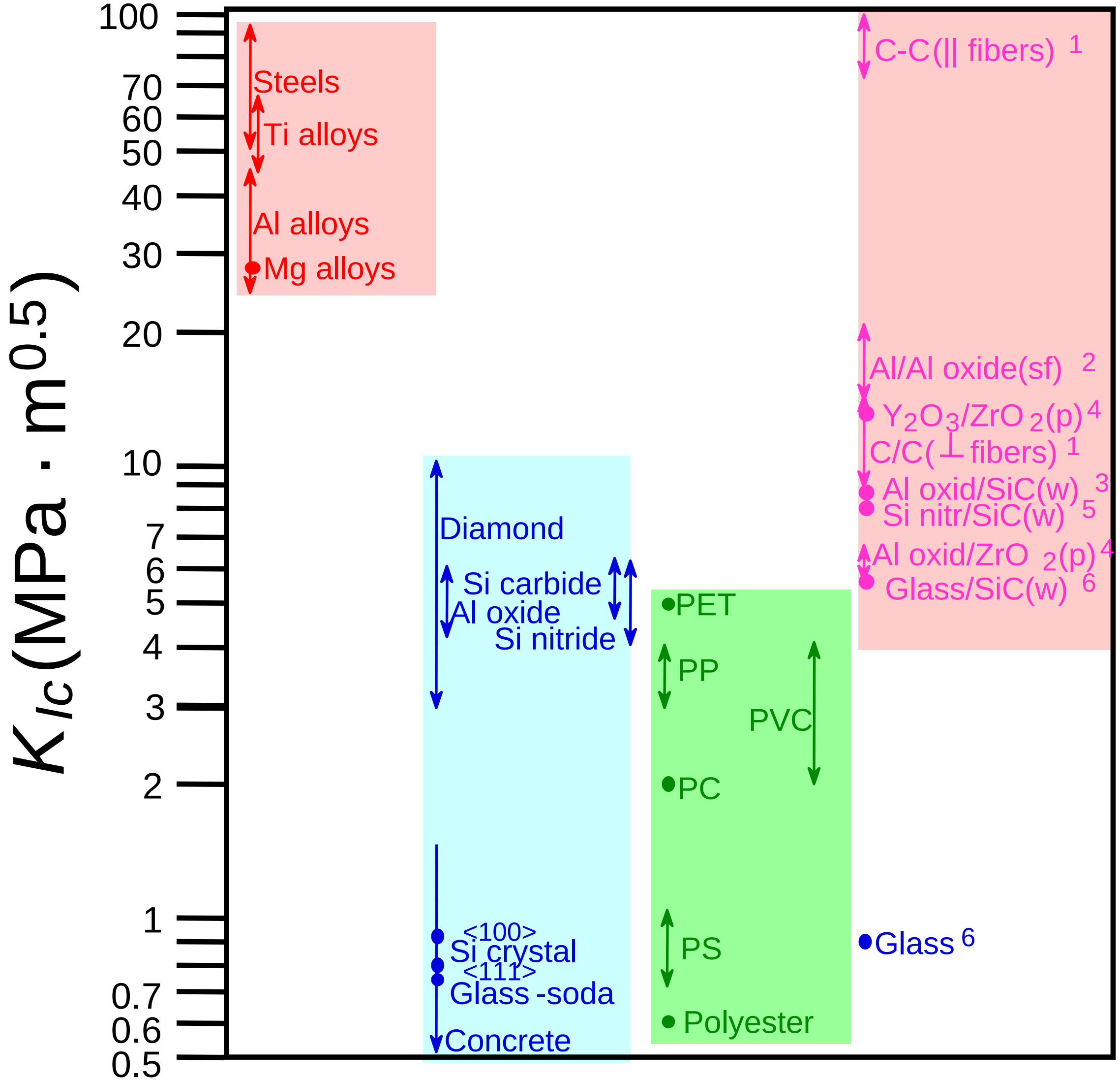
where

- 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

Fracture Toughness



Based on data in Table B5, *Callister 7e*.

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.

Lab Assignment

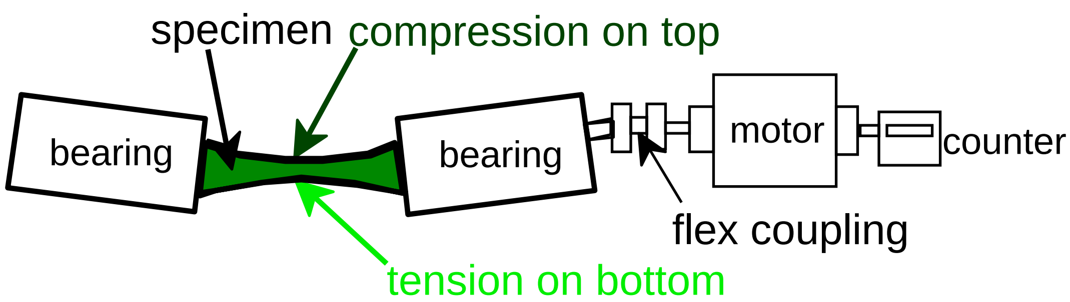
$\boxed{\text{Creep}}$

* $\boxed{\text{Fatigue}}$

- Split into groups of 3
  - Each group gets 8 paper clips
  - Bend back and forth between zero and these angles (2 paper clips each)
    - 45
    - 90
    - 135
    - 180
  - Keep track of the number of cycles to failure for each test.

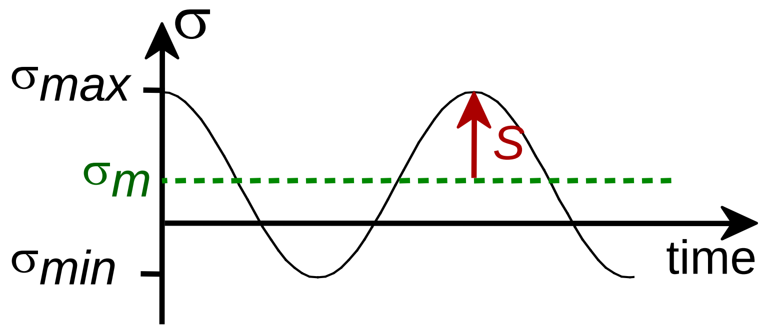
Fatigue

- Fatigue = failure under cyclic stress.

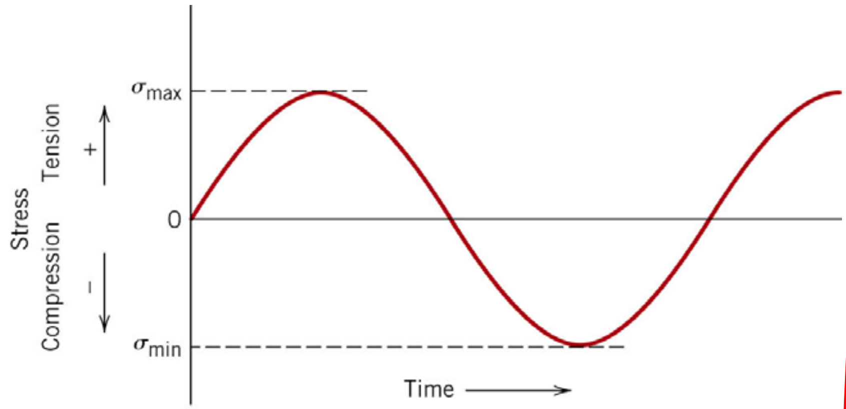


Adapted from Fig. 8.18, *Callister 7e.* (Fig. 8.18 is from *Materials Science in Engineering*, 4/E by Carl. A. Keyser, Pearson Education, Inc., Upper Saddle River, NJ.)

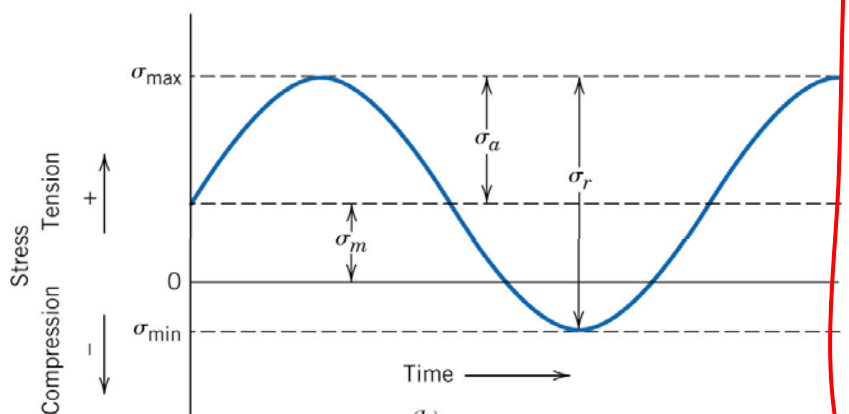
- Stress varies with time.
  -- key parameters are S, σ_m, and frequency



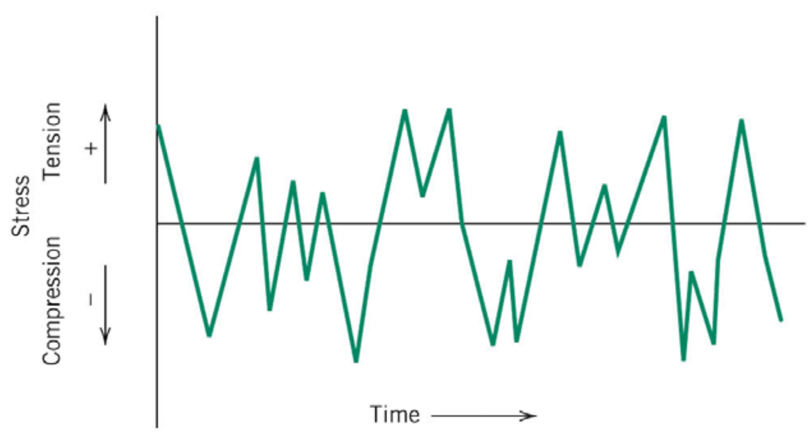
- Key points: Fatigue...
  --can cause part failure, even though $\sigma_{max} < \sigma_c$.
  --causes ~ 90% of mechanical engineering failures.



(a)



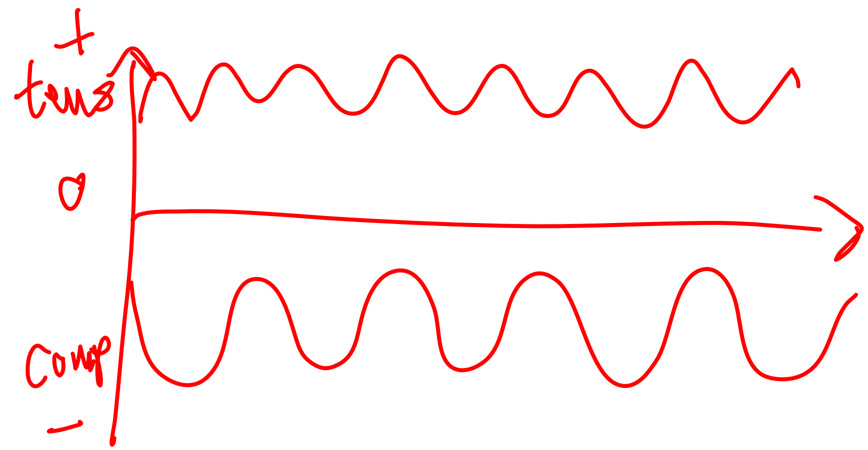
(b)



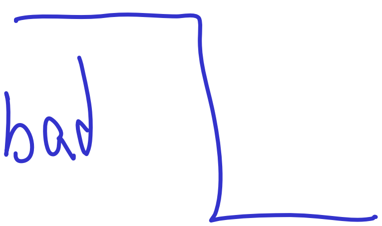
(c)

tension - tension

comp - compression cycles



bad



not as bad

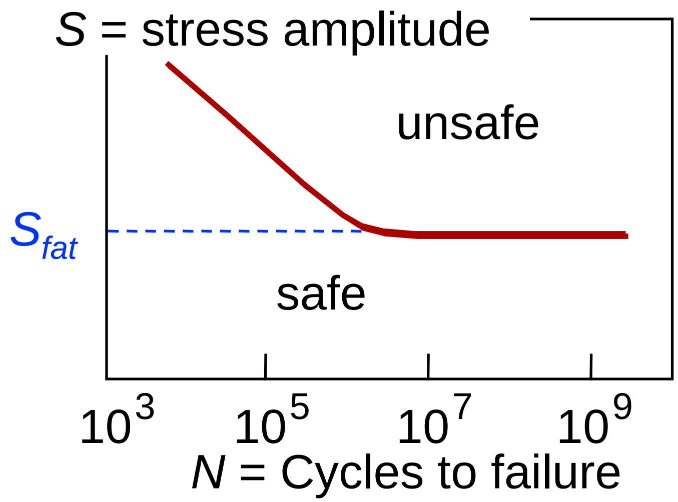
σ_s 1/3 to 1/2 of UTS
fracture stress

High cycle fatigue (HCF) below σ_y,
$> 10^4$ cycles
often need a flaw

Low cycle fatigue (LCF) above σ_y,
10^4 cycles less

Fatigue Design Parameters

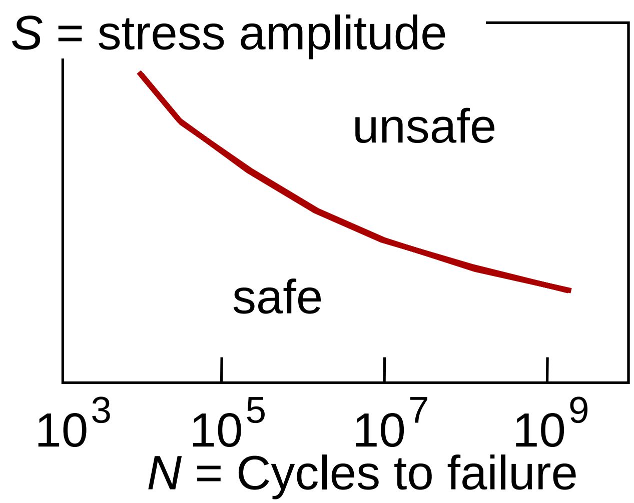
- Fatigue limit, S_{fat}:
  --no fatigue if $S < S_{fat}$



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

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

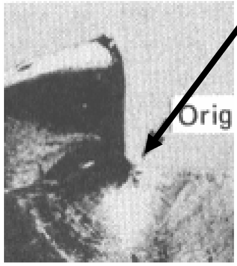
increase in crack length per loading cycle

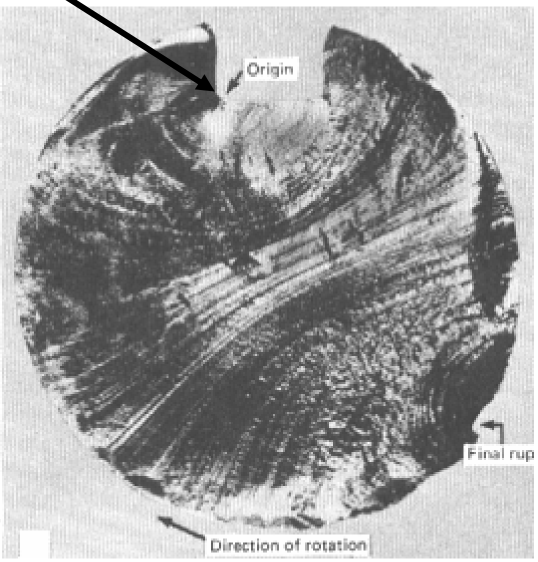
- Failed rotating shaft
  --crack grew even though

  $K_{max} < K_c$

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

crack origin

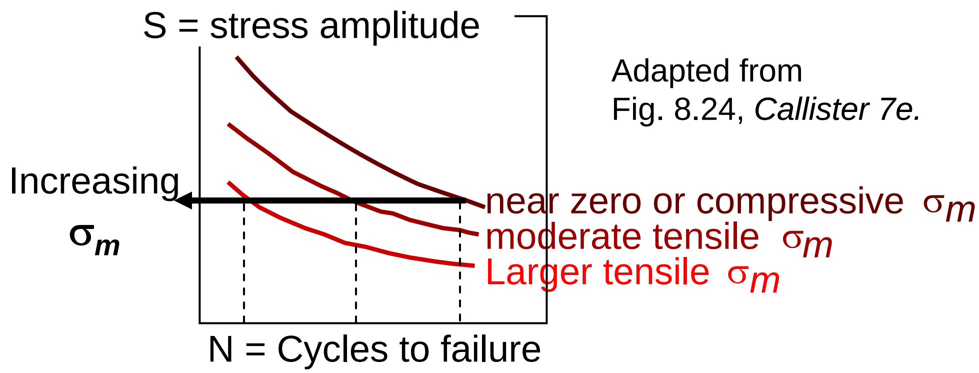




Adapted from Fig. 8.21, *Callister 7e.* (Fig. 8.21 is from D.J. Wulpi, *Understanding How Components Fail*, American Society for Metals, Materials Park, OH, 1985.)

Improving Fatigue Life

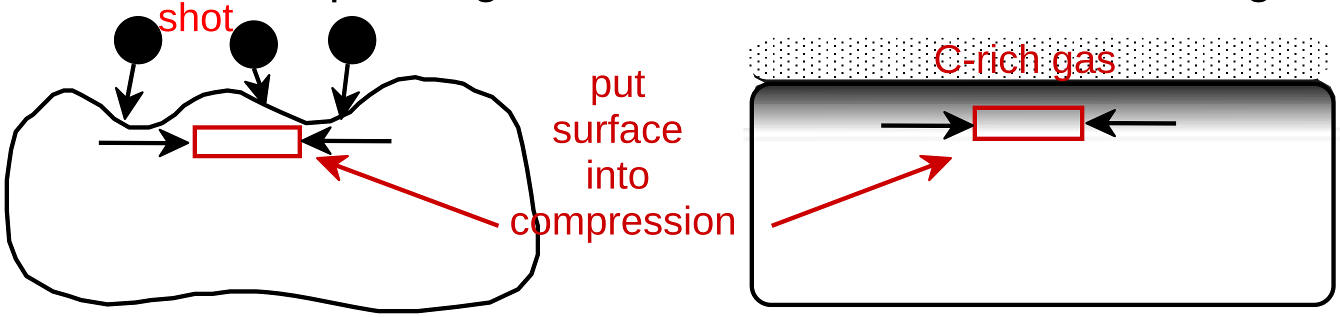
1. Impose a compressive surface stress
   (to suppress surface cracks from growing)



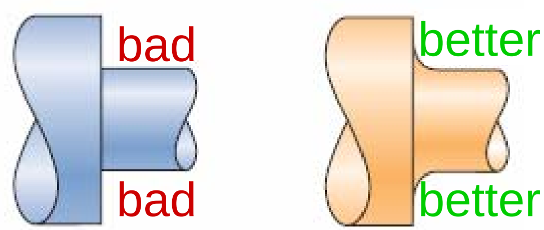
Adapted from Fig. 8.24, *Callister 7e.*

--Method 1: shot peening

--Method 2: carburizing



2. Remove stress concentrators.

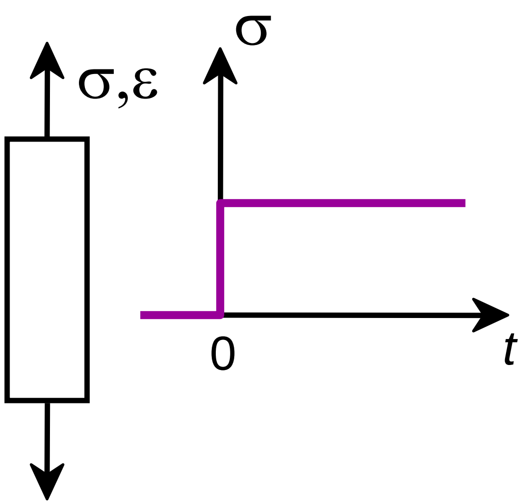


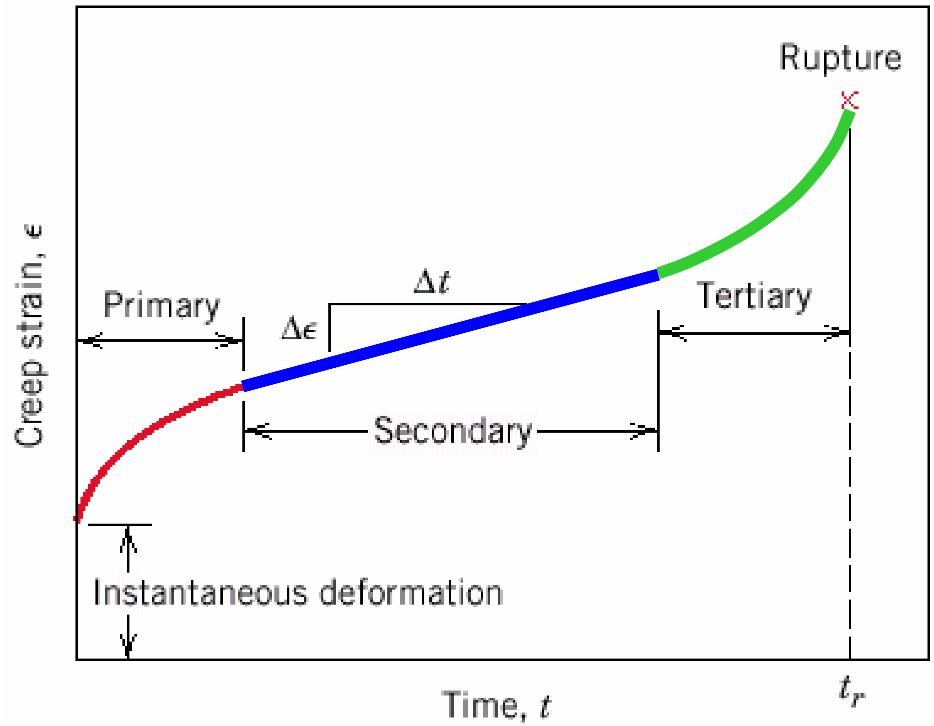
Adapted from Fig. 8.25, *Callister 7e.*

Creep

temp dependent

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





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

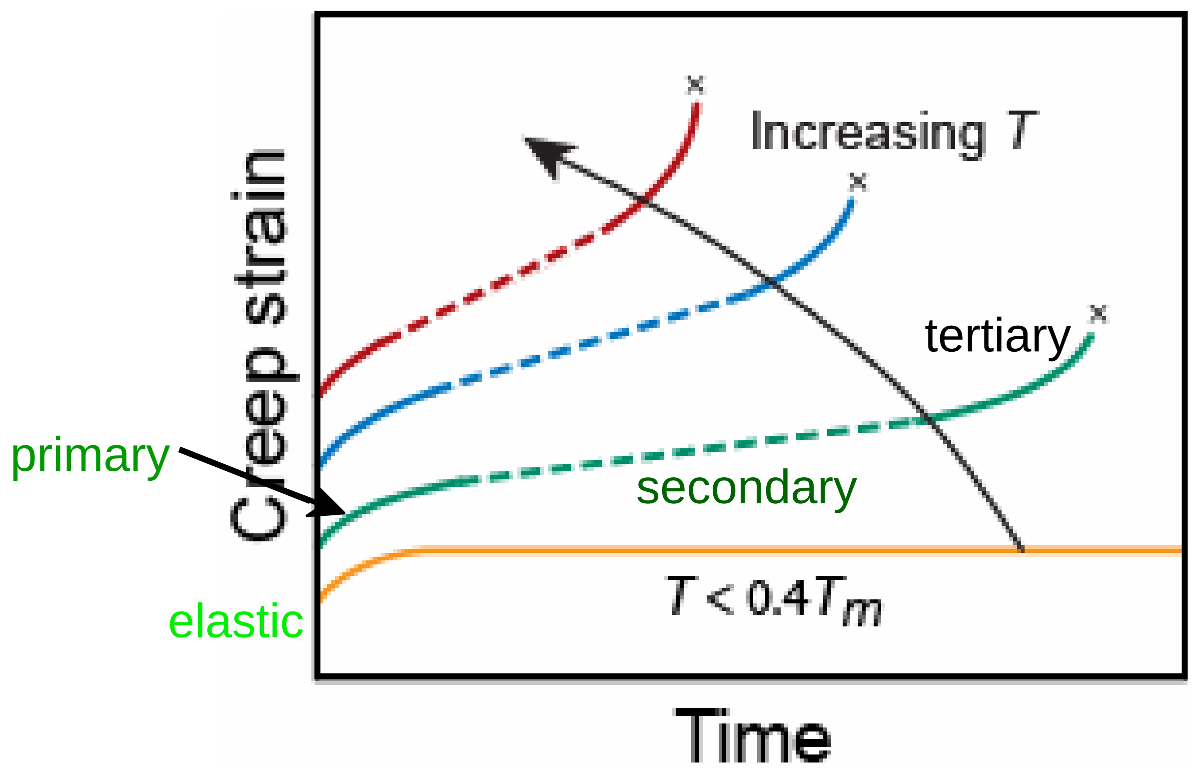
Primary Creep: slope (creep rate) decreases with time.

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

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

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

stress exponent (material parameter)

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

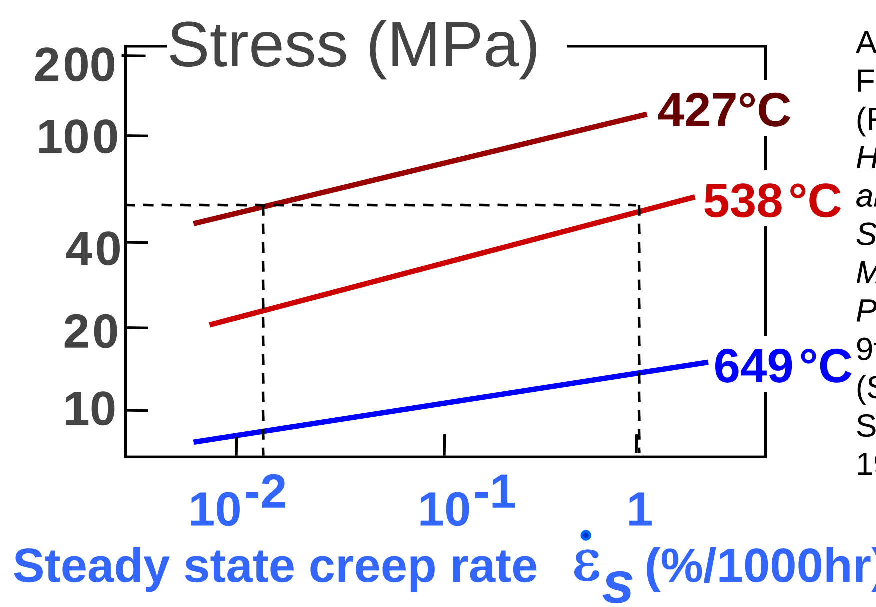
strain rate

material const.

applied stress

activation energy for creep
(material parameter)

- Strain rate increases for higher T, σ



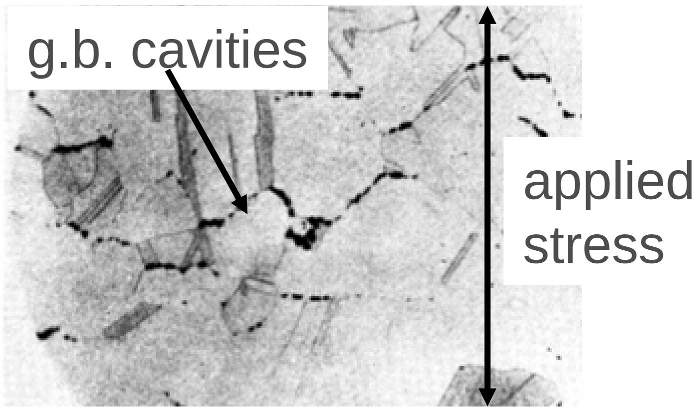
Adapted from Fig. 8.31, *Callister 7e.* (Fig. 8.31 is from *Metals Handbook: Properties and Selection: Stainless Steels, Tool Materials, and Special Purpose Metals*, Vol. 3, 9th ed., D. Benjamin (Senior Ed.), American Society for Metals, 1980, p. 131.)

8.14

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

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

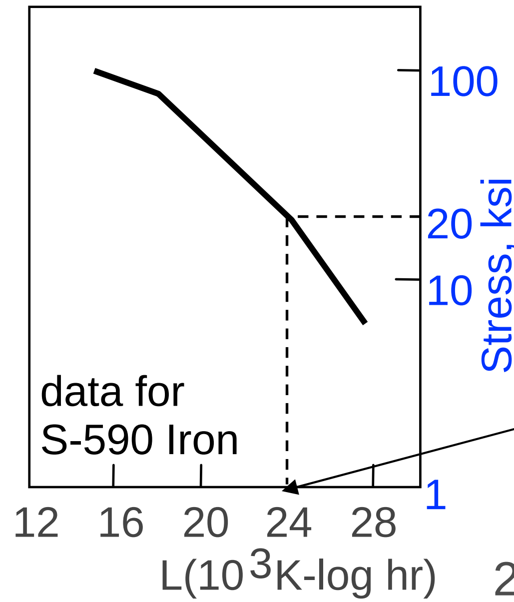
temperature

function of applied stress

time to failure (rupture)

- 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).)

24x10^3 K-log hr

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

1073K

Ans: t_r = 233 hr

Designing for Optoelectronics

optoelectronics

- Creep resistant solders for *dimensional stability*

- Non-brittle intermetallics and smooth bonding interfaces for *long term reliability*

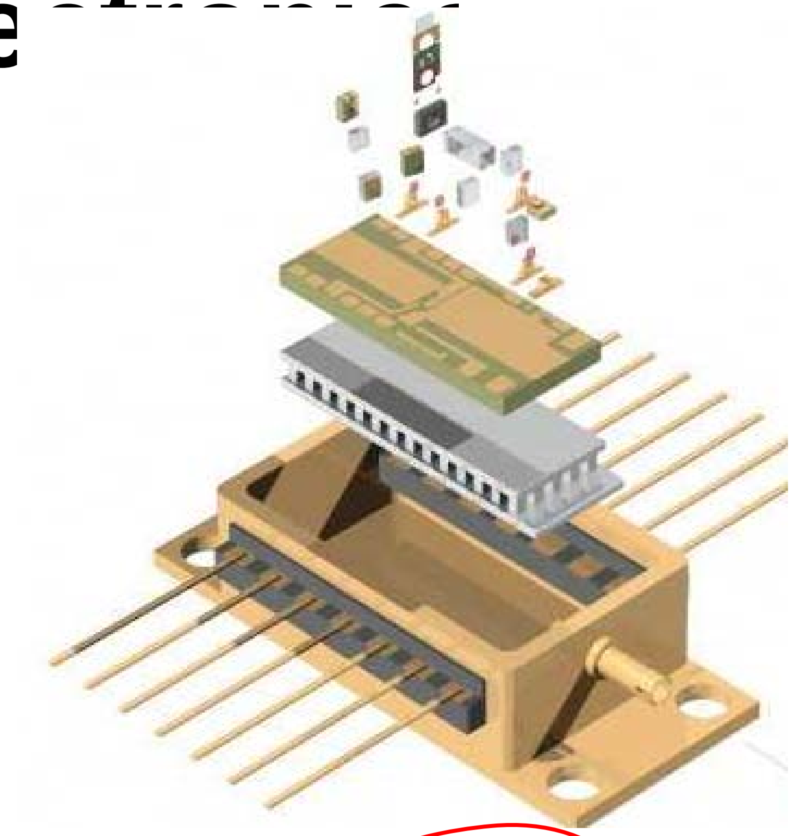
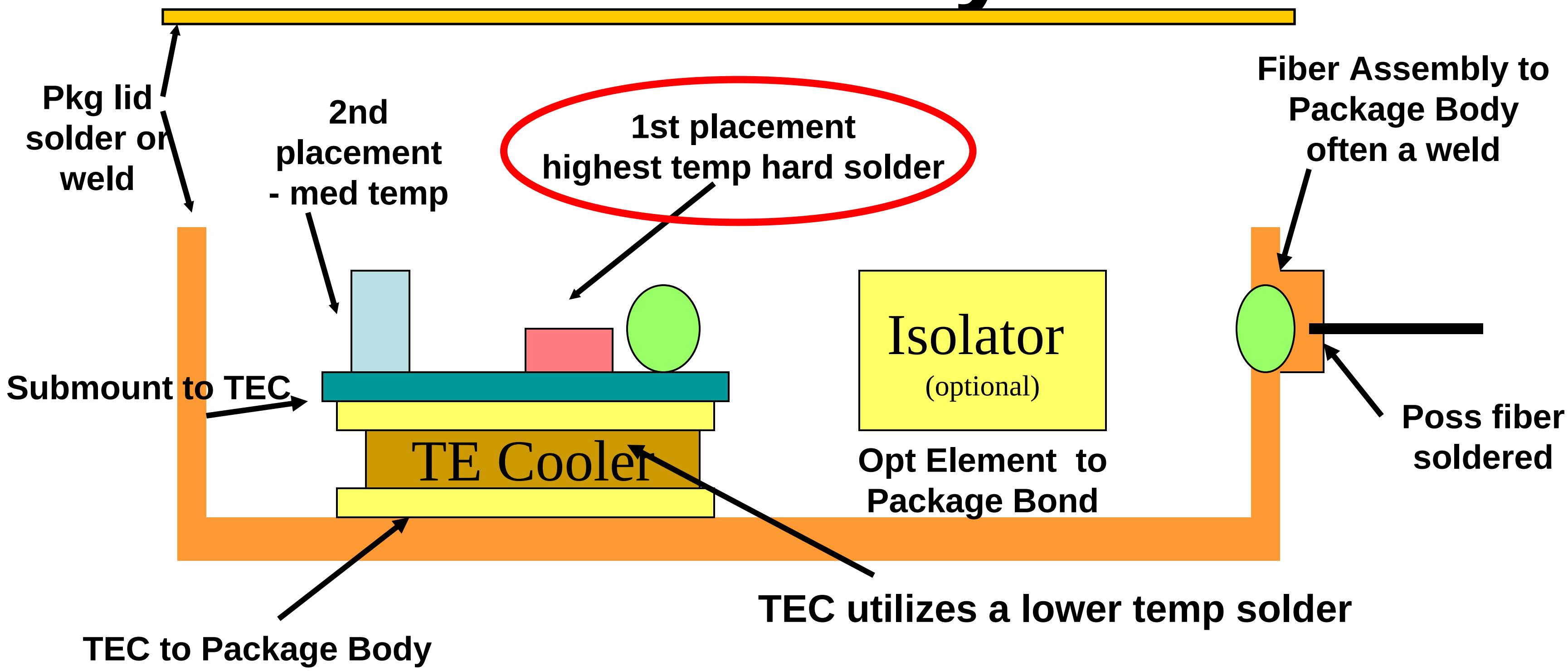


Image courtesy of Axsun, Inc.

Solders & Solder Hierarchy



Need a series of solders melting at successively lower temps

SUMMARY

Ch 8

- 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.

Ch 8 summary

WebCT

- Additional homework from Ch. 8
  - 8.14, 8.15, 8.16, 8.22, 8.25, 8.26, 8.28, 8.29
- Sections not covered, not tested
  - 8.6, 8.15