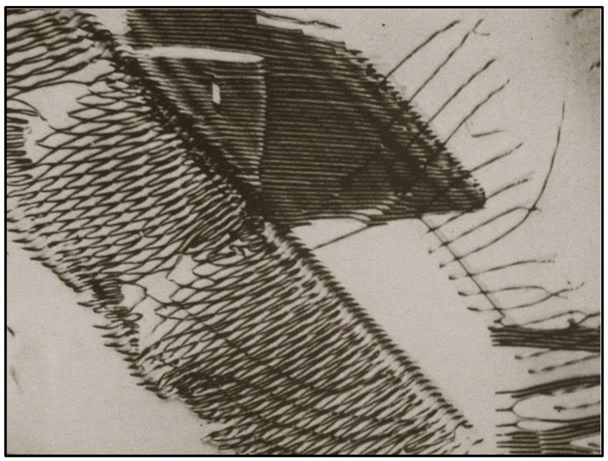
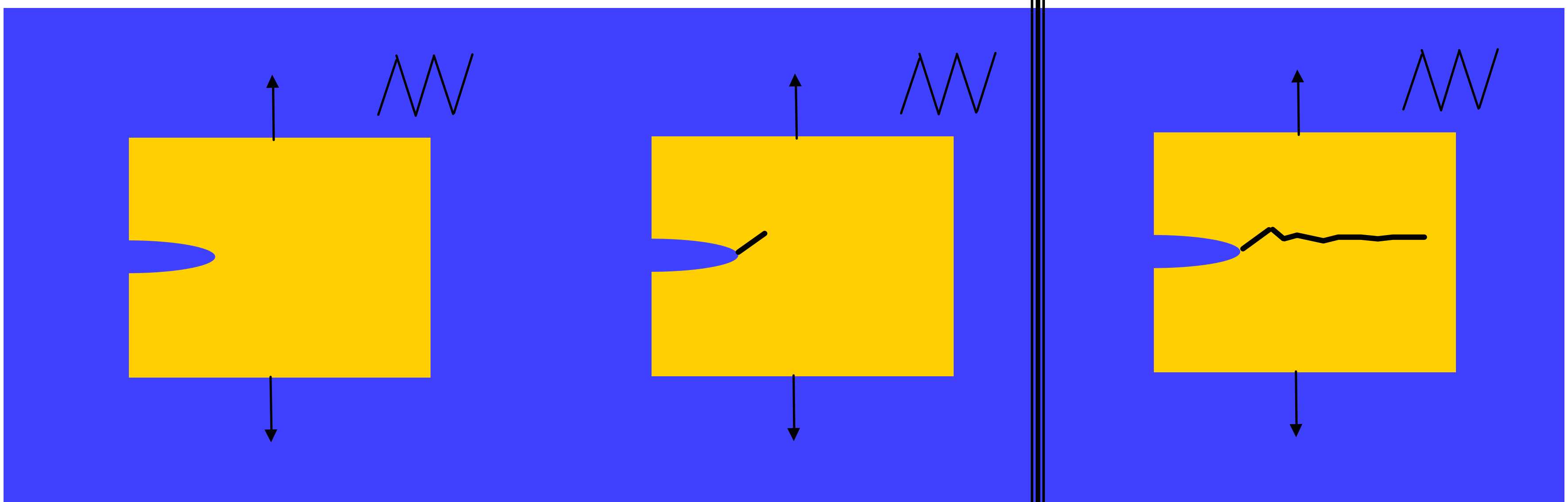
Materials Issues in Fatigue and Fracture



- 5.1 Fundamental Concepts
- **5.2 Ensuring Infinite Life**
- 5.3 Failure
- 5.4 Summary

A simple view of fatigue

1. Will a crack nucleate?
2. Will it grow?
3. How fast will it grow?



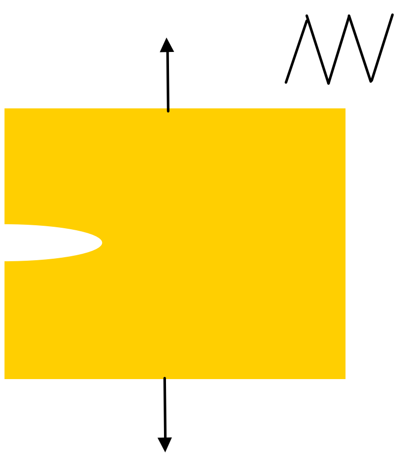
Cyclic nucleation and arrested growth

Infinite Life

Crack growth

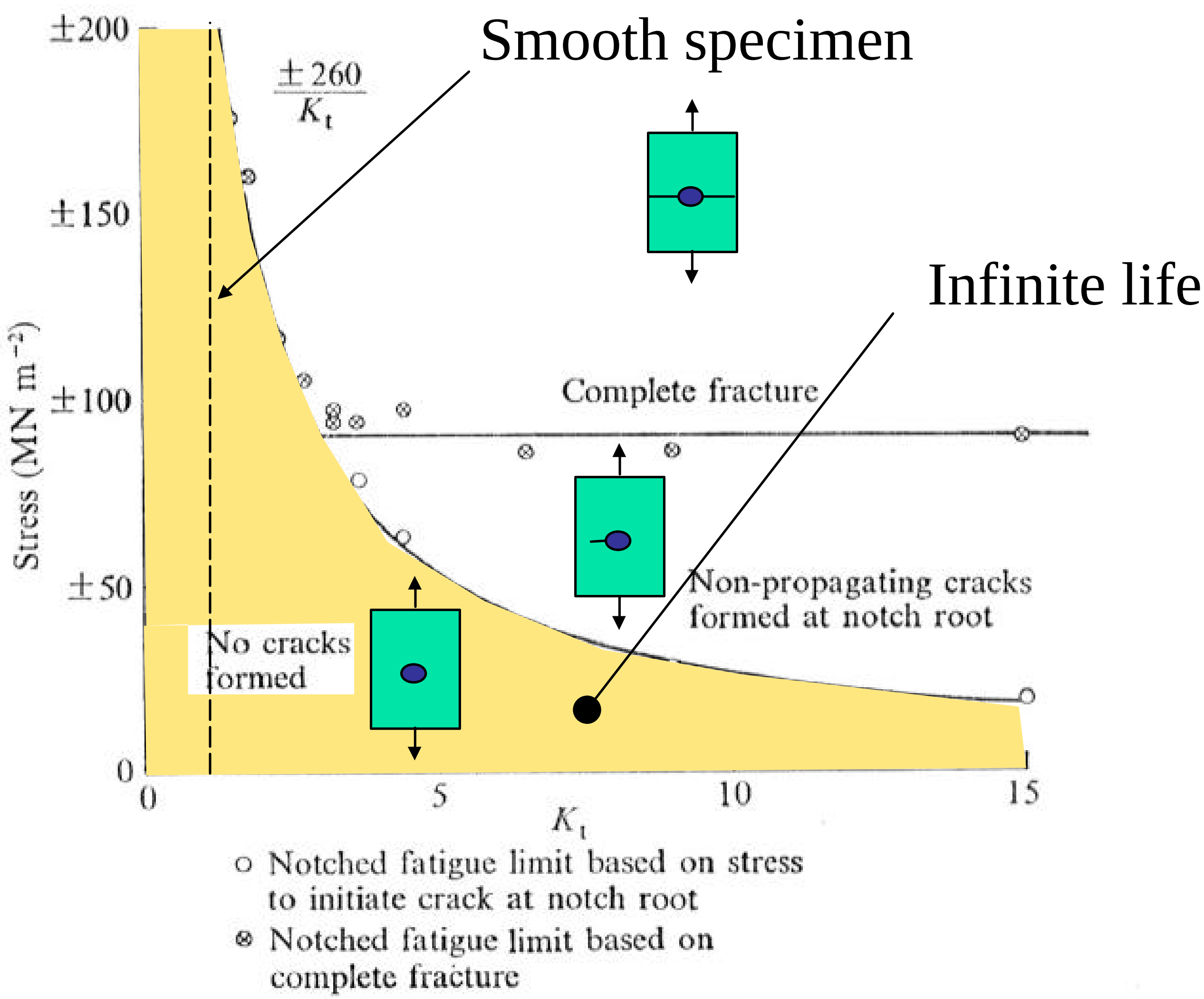
Finite Life

5.2 Ensuring Infinite Life



- **Avoiding crack nucleation**
- Avoiding crack growth
- Fatigue limit and the UTS
- UTS of structural materials

Avoiding crack nucleation

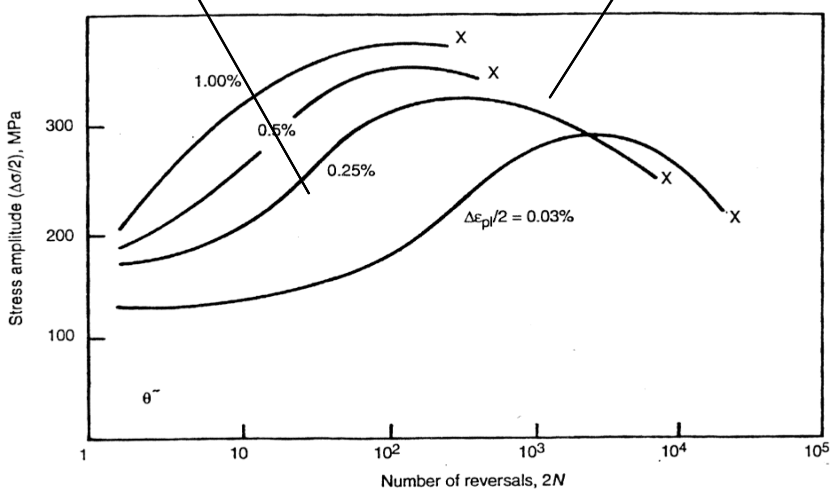


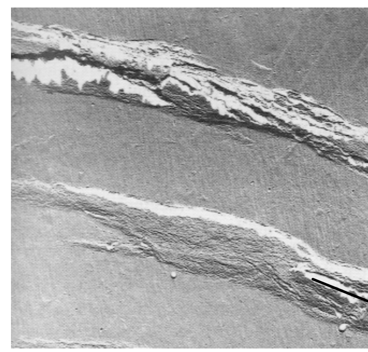
At a sufficiently low alternating stress no fatigue cracks will form.

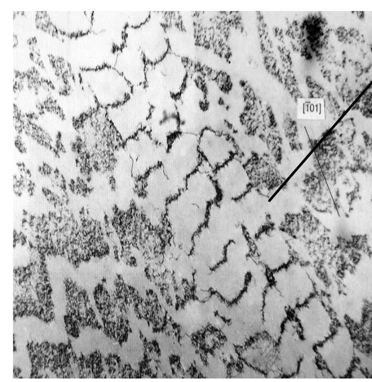
Cyclic hardening

- Development of cell structures (hardening)
- Increase in stress amplitude (under strain control)
- Break down of cell structure to form PSBs
- Localization of slip in PSBs

cyclic hardening cyclic softening



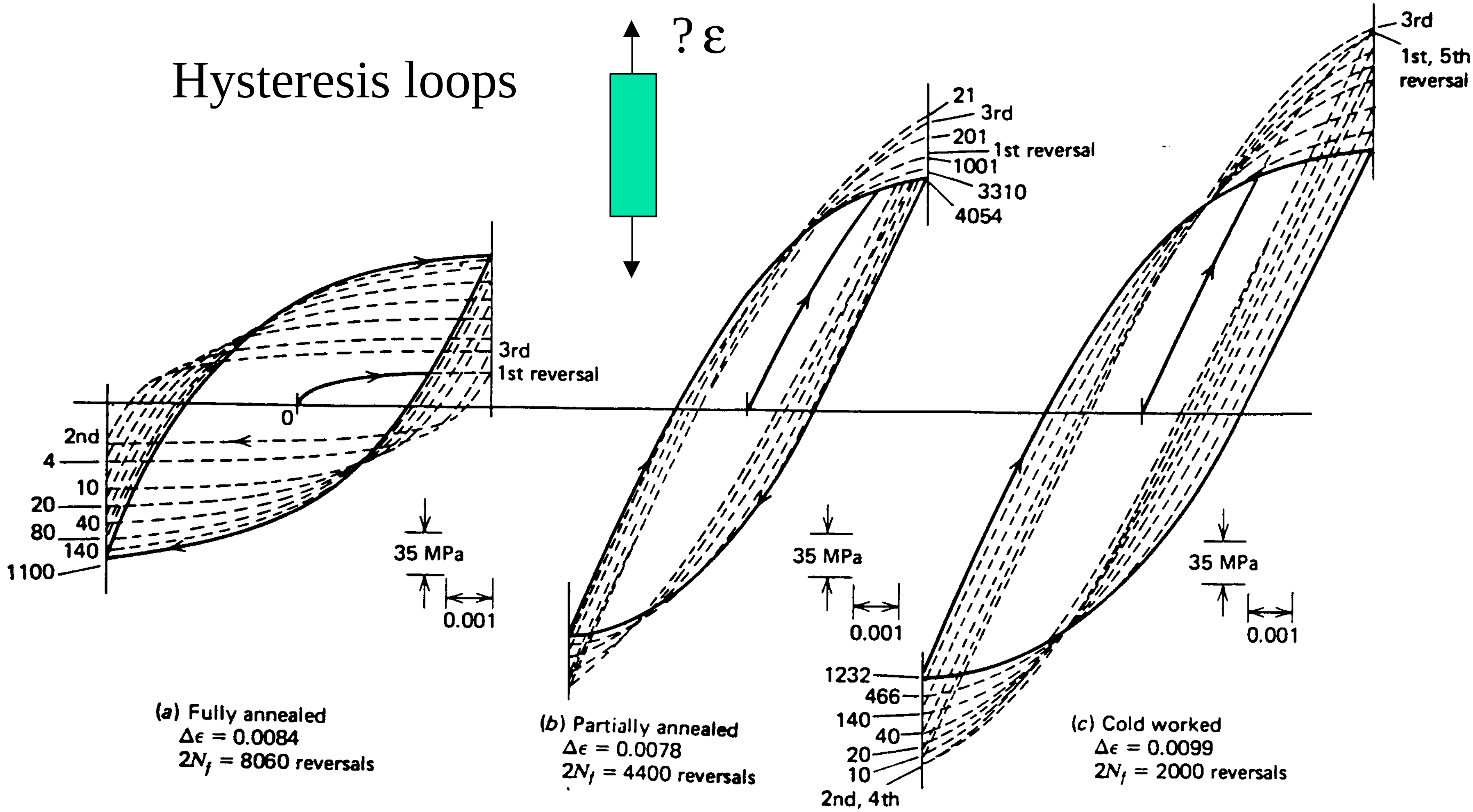




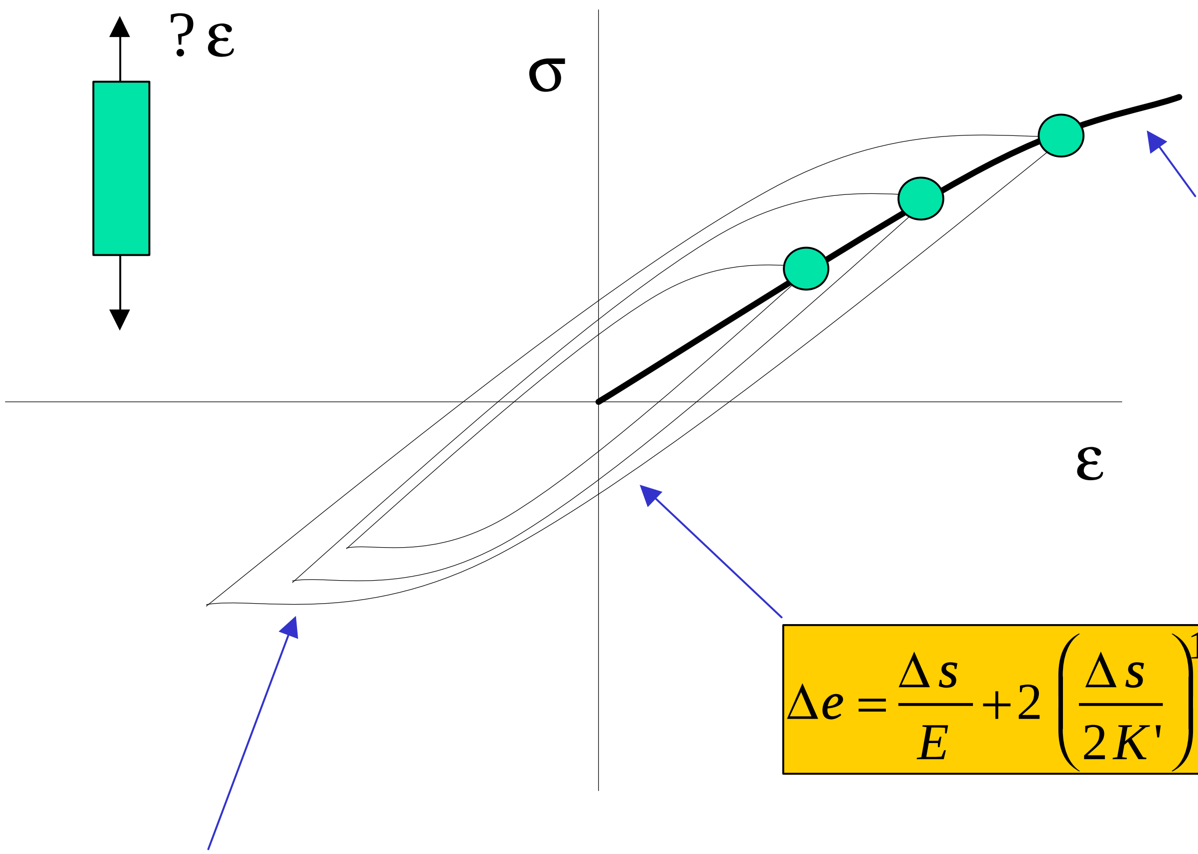
PSB

Cyclic Deformation

Hysteresis loops



Cyclic stress-strain curve



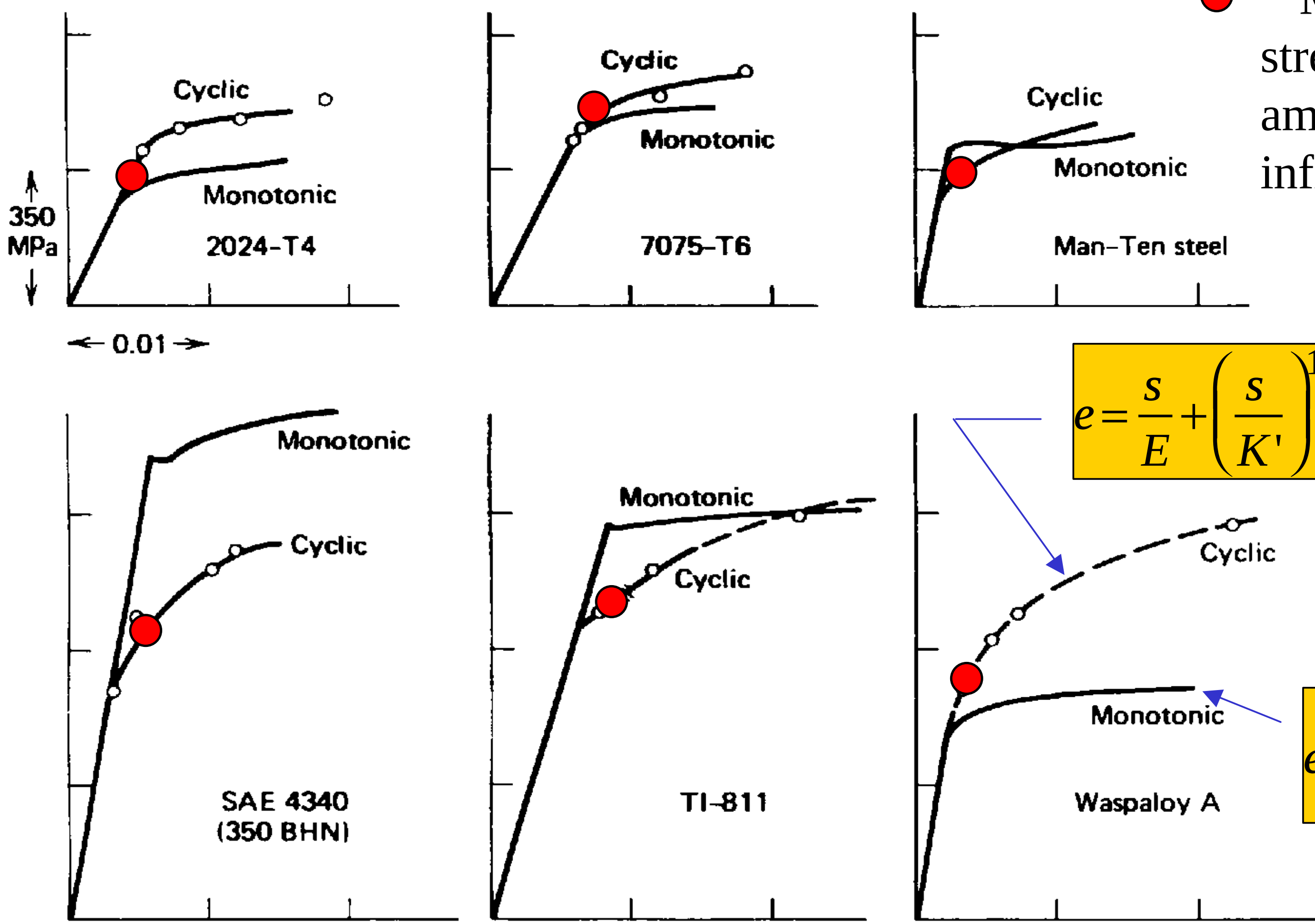
Cyclic stress-strain curve

$$e = \frac{s}{E} + \left(\frac{s}{K'}\right)^{1/n'}$$

$$\Delta e = \frac{\Delta s}{E} + 2\left(\frac{\Delta s}{2K'}\right)^{1/n'}$$

Hysteresis loops for different levels of applied strain

Cyclic stress-strain curves

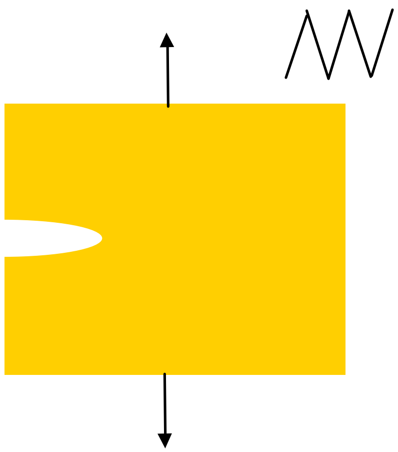


● ~ Maximum stress amplitude for infinite life.

$$e = \frac{s}{E} + \left(\frac{s}{K'}\right)^{1/n'}$$

$$e = \frac{s}{E} + \left(\frac{s}{K}\right)^{1/n}$$

5.2 Ensuring Infinite Life



- Avoiding crack nucleation
- **Avoiding crack growth**
- Fatigue limit and the UTS
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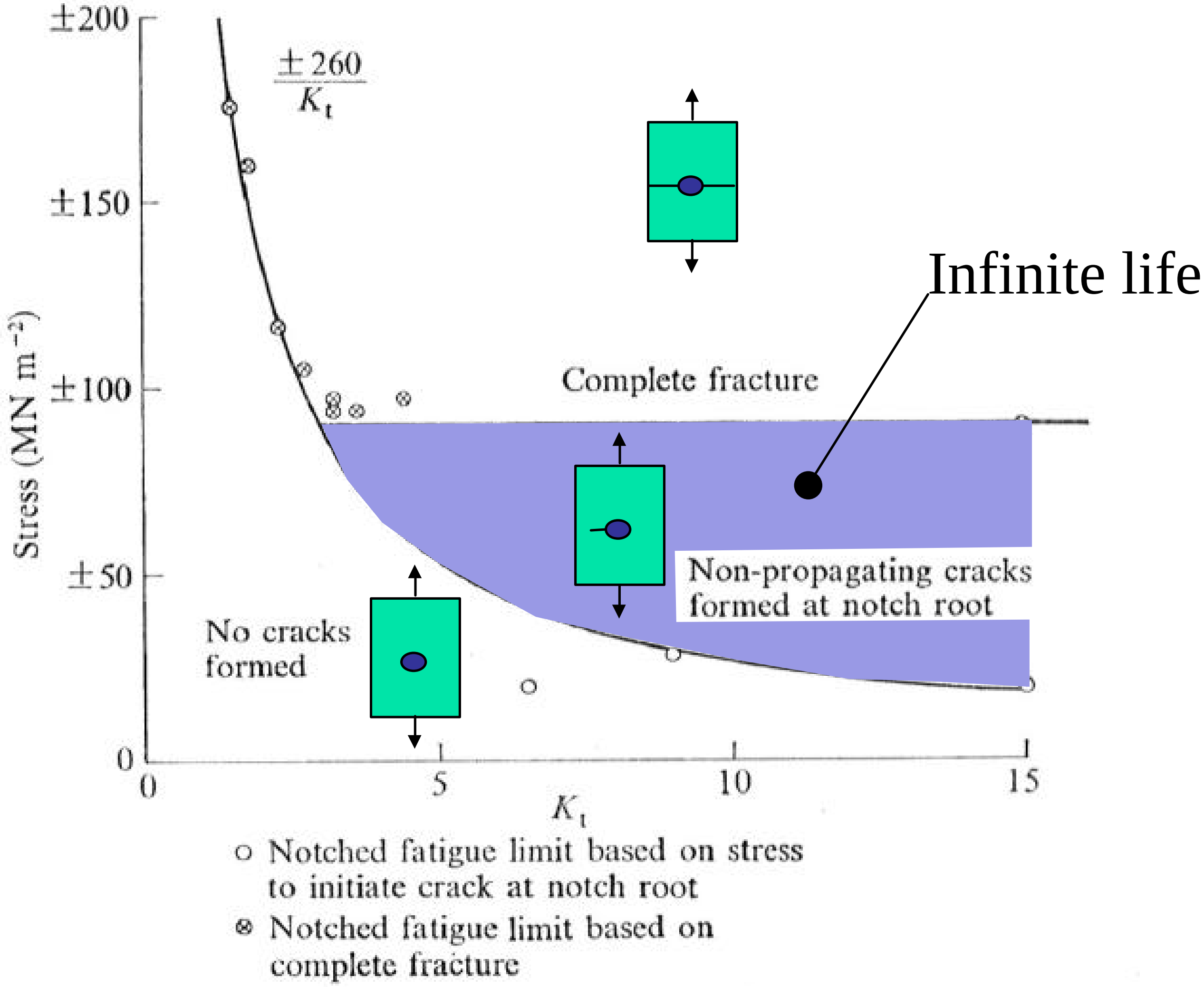
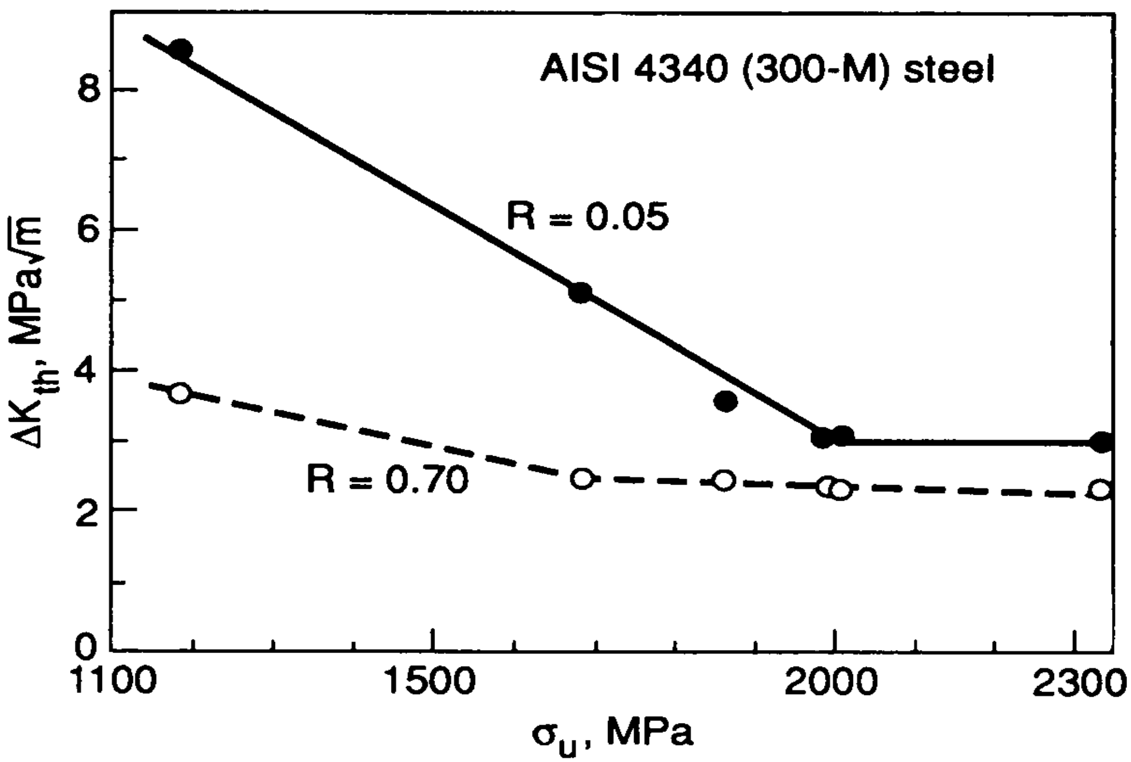
Infinite life - no crack growth

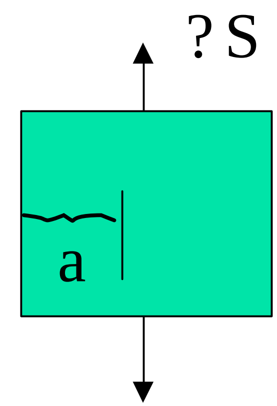


Sharp notches may nucleate cracks but the remote, alternating stress may not be large enough to cause the crack to leave the notch stress field.

Threshold Stress Intensity

The forces driving a crack forward are related to the stress intensity factor

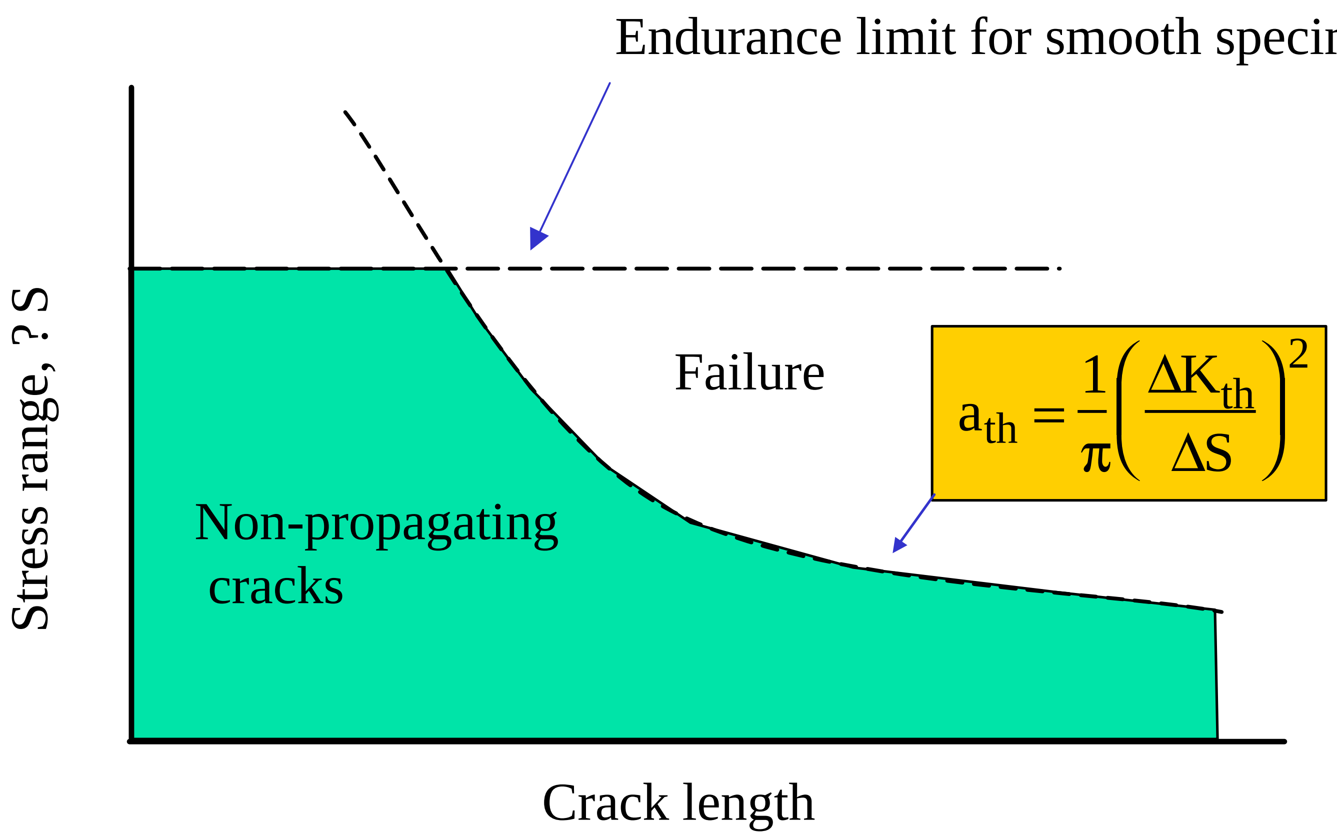




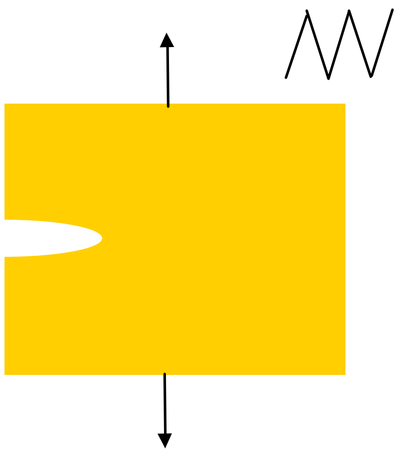
At or below the threshold value of ? K, the crack doesn't grow.

$$\Delta K = Y\ \Delta S \sqrt{pa}$$

Non-propagating cracks

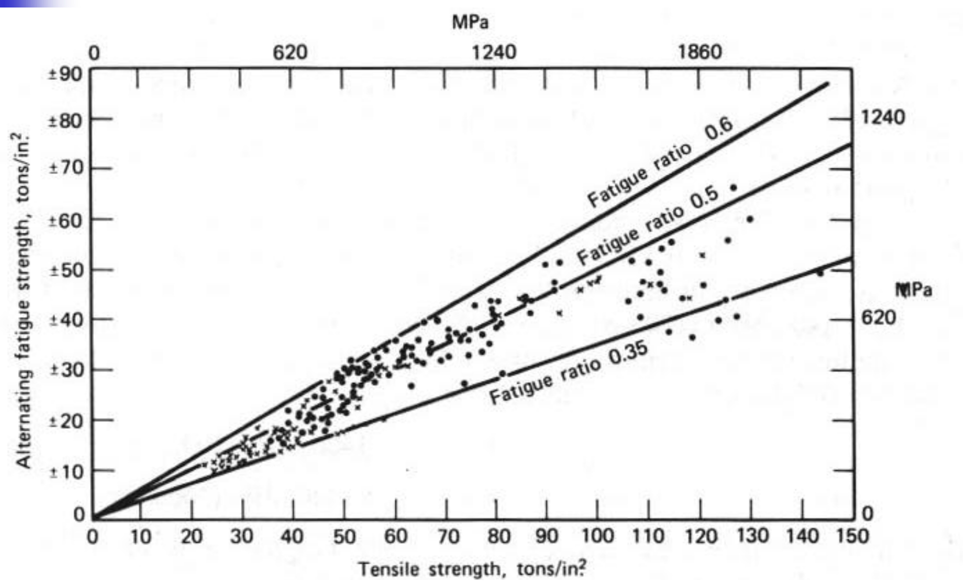


5.2 Ensuring Infinite Life

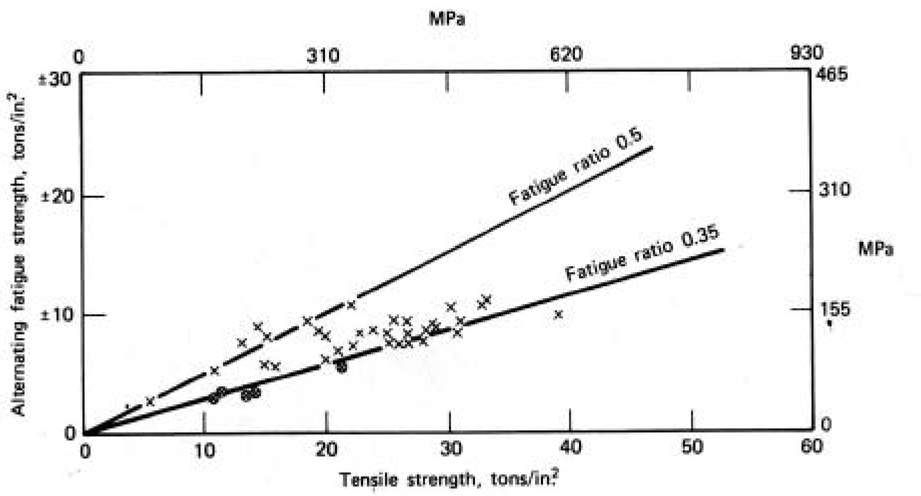


- Avoiding crack nucleation
- Avoiding crack growth
- **Fatigue limit and the UTS**
- UTS of structural materials

Fatigue limit related to UTS

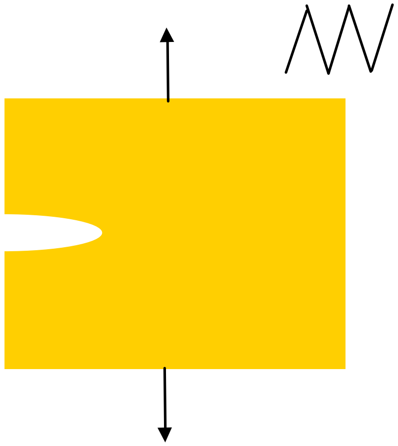


For wrought steel the fatigue strength at 1,000,000 cycles is about 0.5 UTS.



For wrought aluminum the fatigue strength at 10,000,000 cycles is about 0.35 UTS.

5.2 Ensuring Infinite Life



- Avoiding crack nucleation
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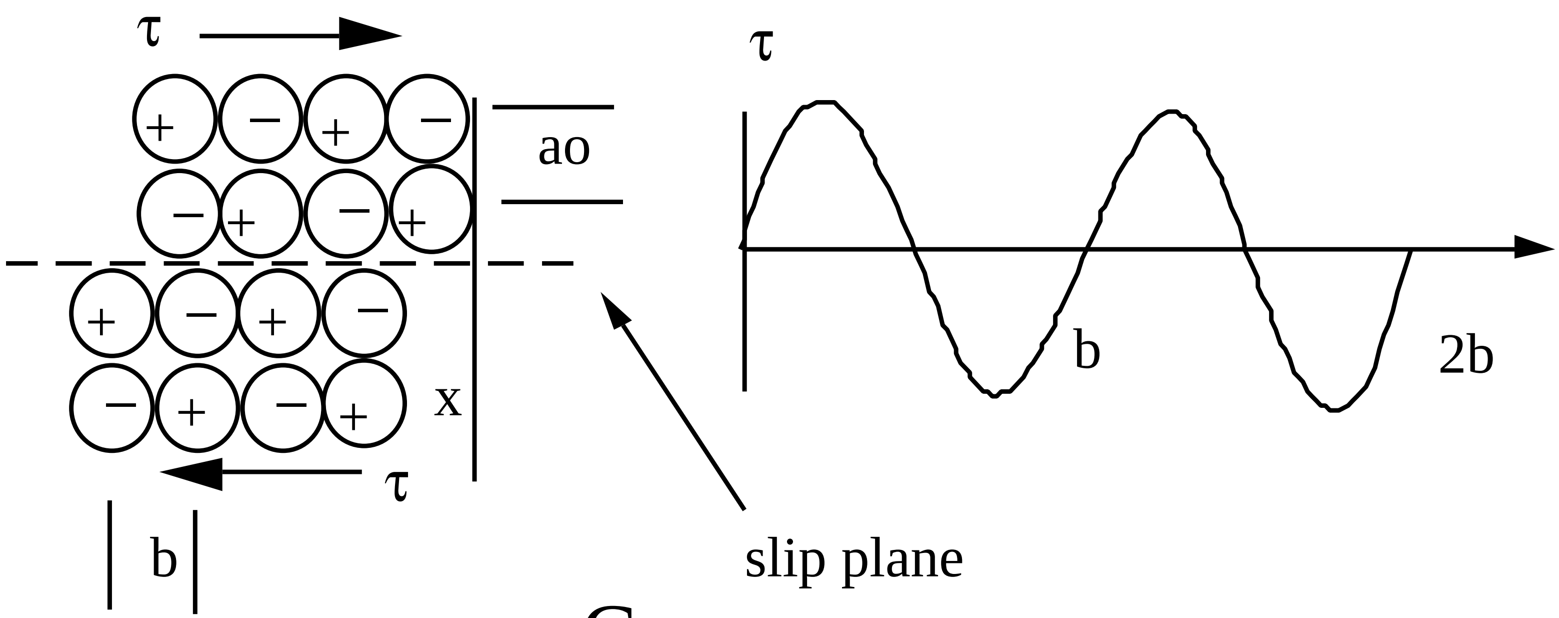
- Fatigue limit and the UTS
- **UTS of structural materials**

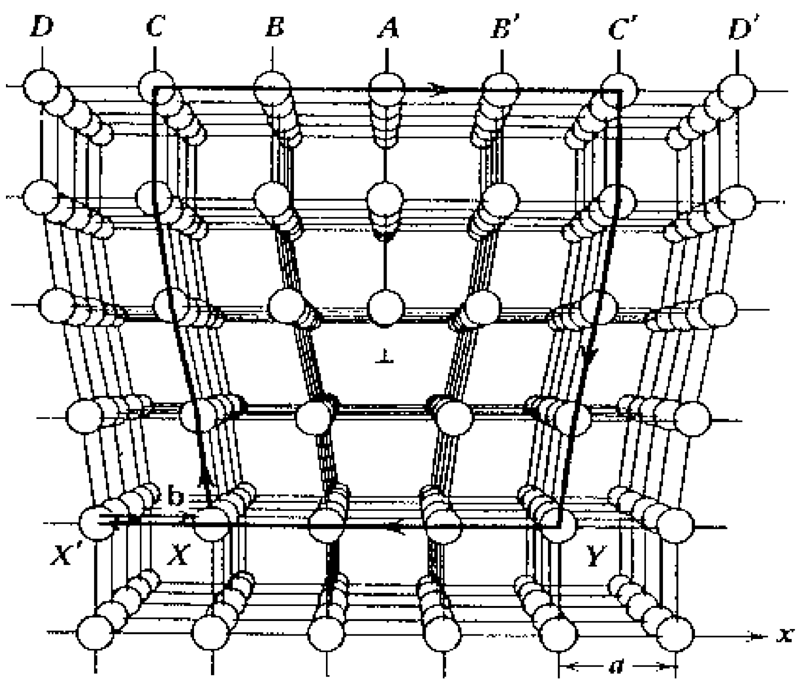
Theo. shear stress of a solid

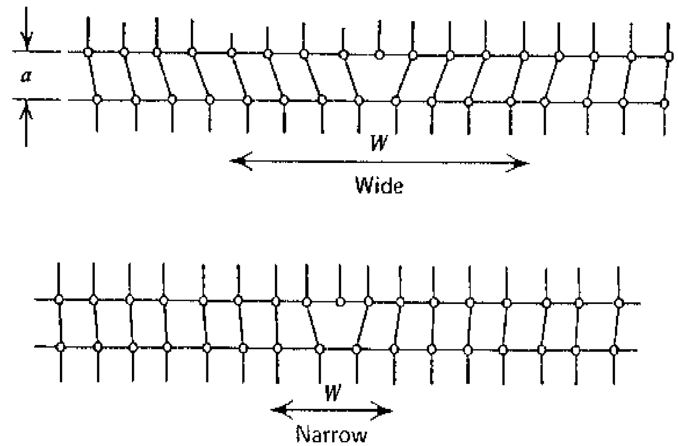


$$\tau_m - \frac{G}{2\check{s}}$$

For iron (Fe), the theoretical shear stress is about 2,000,000 psi!?!

Dislocations





$$\tau_y = G\, e^{\frac{-2\pi w}{b}} \approx G\, e^{-4\pi} \approx 50 \text{ psi.!!!}$$

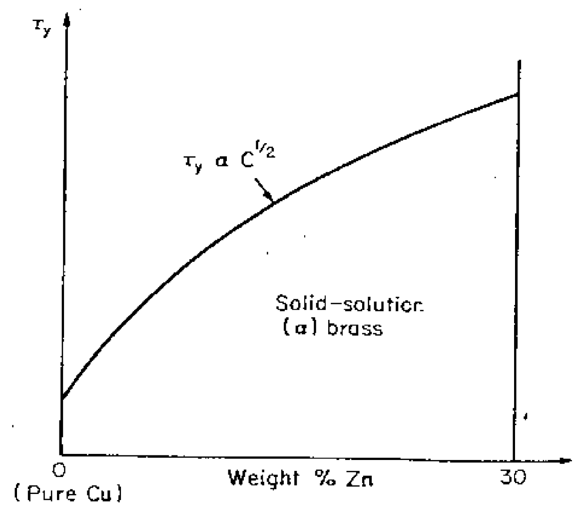
(Pierels stress)

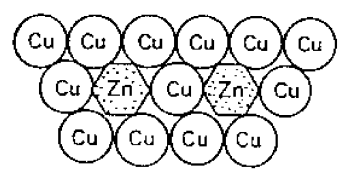
The concept of the dislocation explains why the theoretical shear strength is never achieved. However, dislocation theory would predict very low flow stresses!?! Pierels stress….

Strengthening mechanisms

$$\tau_y = \tau_{Pieierls} + \Delta\tau_{solution} + \Delta\tau_{dispersion} + \Delta\tau_{hardening}$$

Flow stress of a single crystal

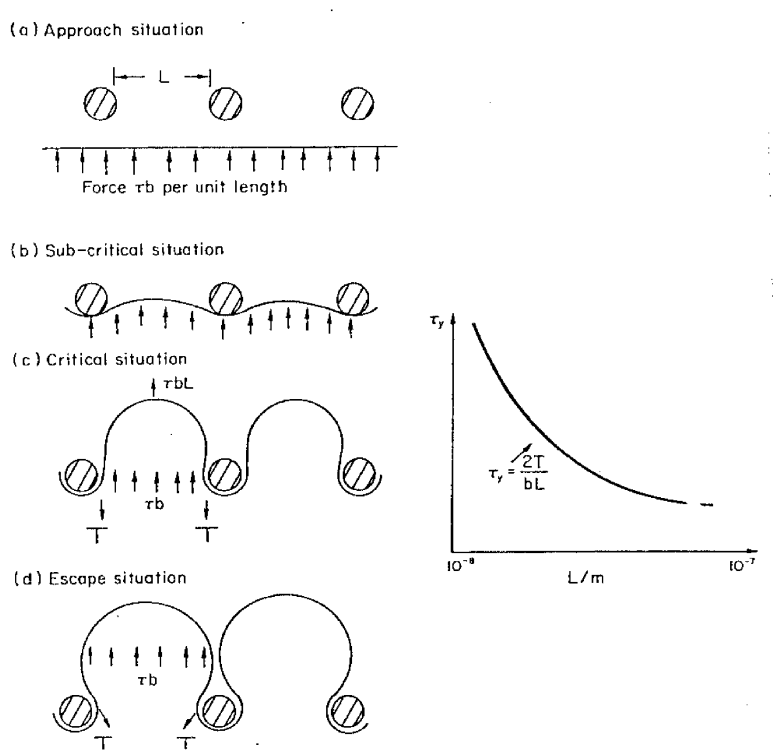




$$\tau_{y\ solution} \ \alpha \ C^{1/2}$$

Solid solution strengthening - atomic misfits set up dislocation impeding stress fields

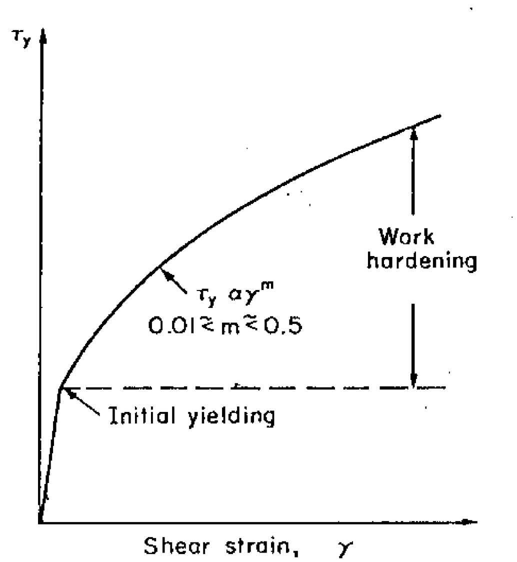
Strengthening mechanisms

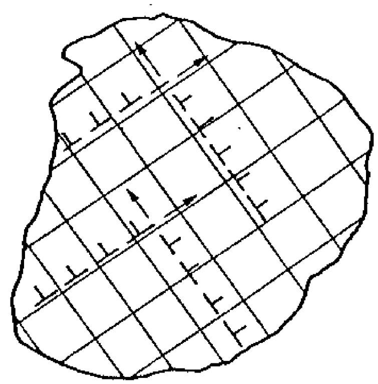


$$\tau_{y\ \mathrm{dispersion}} = \frac{2\,T}{\mathbf{b}\,L} = \frac{G\,\mathbf{b}}{L}$$

Dispersion (precipitate) strengthening - small second phase particles impede dislocation motion.

Strengthening mechanisms



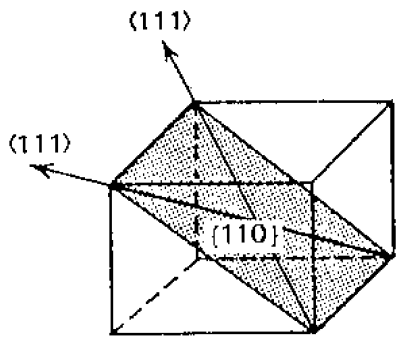


$\tau_{y\ \text{hardening}} \quad \alpha \quad \gamma^m$

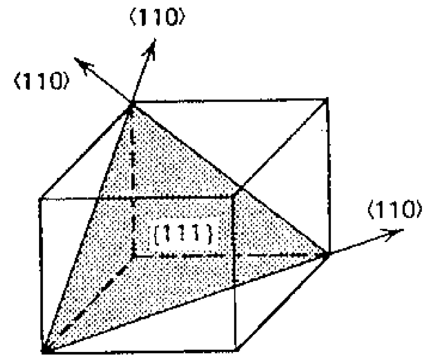
Work hardening - increasing number of dislocations reduces dislocation mobility due to dislocation interaction and entanglement.

Strengthening mechanisms

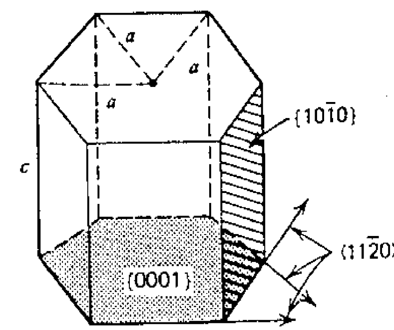
FCC
Face-centered Cubic
Aluminum
12 Slip systems



BCC
Body-centered Cubic
Iron
48 Slip systems

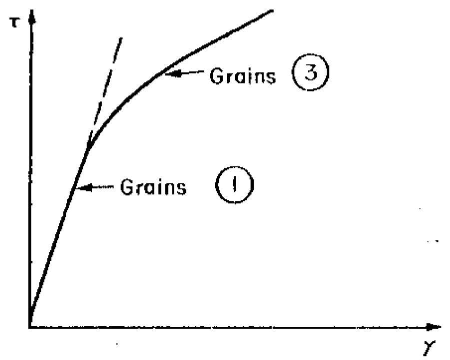


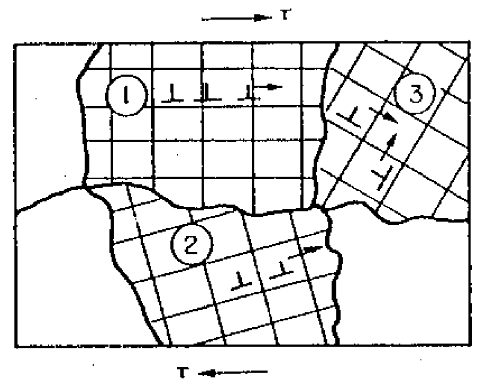
HCP
Hexagonal close-packed
Titanium
3 Slip systems



Slip system limitations lead to additional strengthening in polycrystalline metals

Strengthening mechanisms

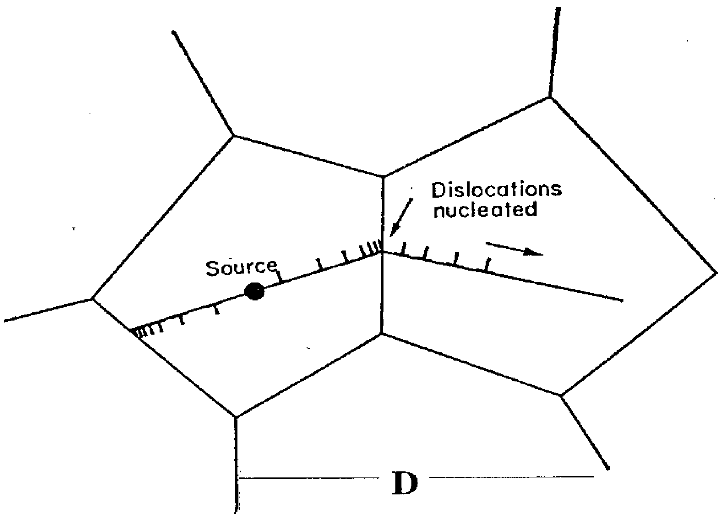




$\sigma_y = M\,\tau_y \qquad M = 3.02\ (FCC), \quad M = 2.75\ (BCC)$

Polycrystalline metals require at least 5 independent slip systems. Thus grain boundaries and accommodation strains elevate the yield strength of polycrystals above that of single crystals

Strengthening mechanisms



Dislocation pile-up at grain boundary

$$\sigma_{y\ obstacle} = \sigma_i + k\, D^{-1/2}$$

Hall-Petch relationship

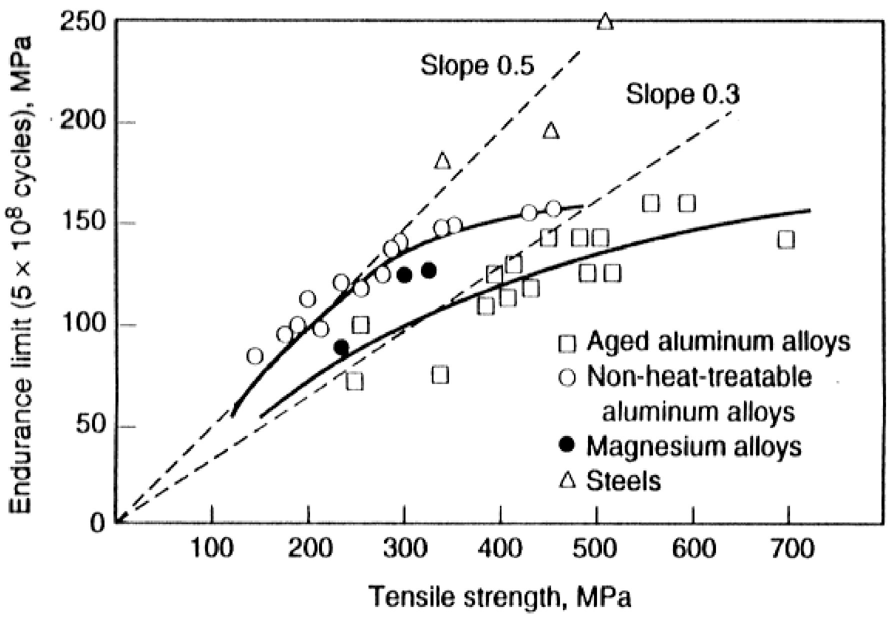
Flow stress for a poly-crystalline solid

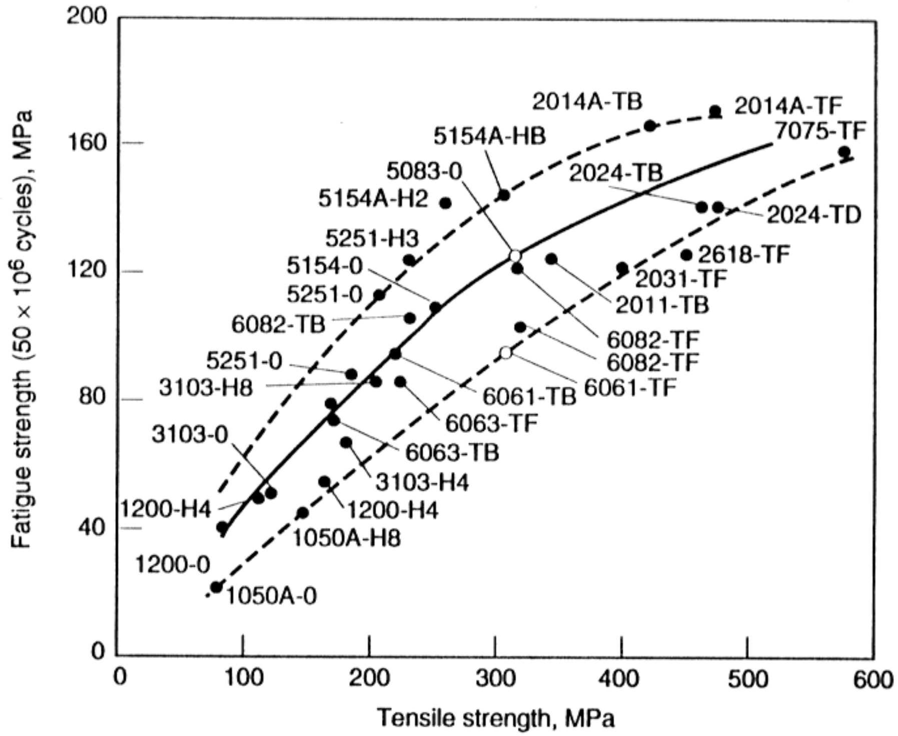
$$\sigma_y = \sigma_{Pieierls} + \left(\Delta\sigma_{ss} + \Delta\sigma_{dispersion} + \Delta\sigma_{hardening}\right) + k\, D^{-1/2}$$

$$\sigma_{y\ polycrystal} = \sigma_{thermal} + \sigma_{structural} + k\, D^{-1/2}$$

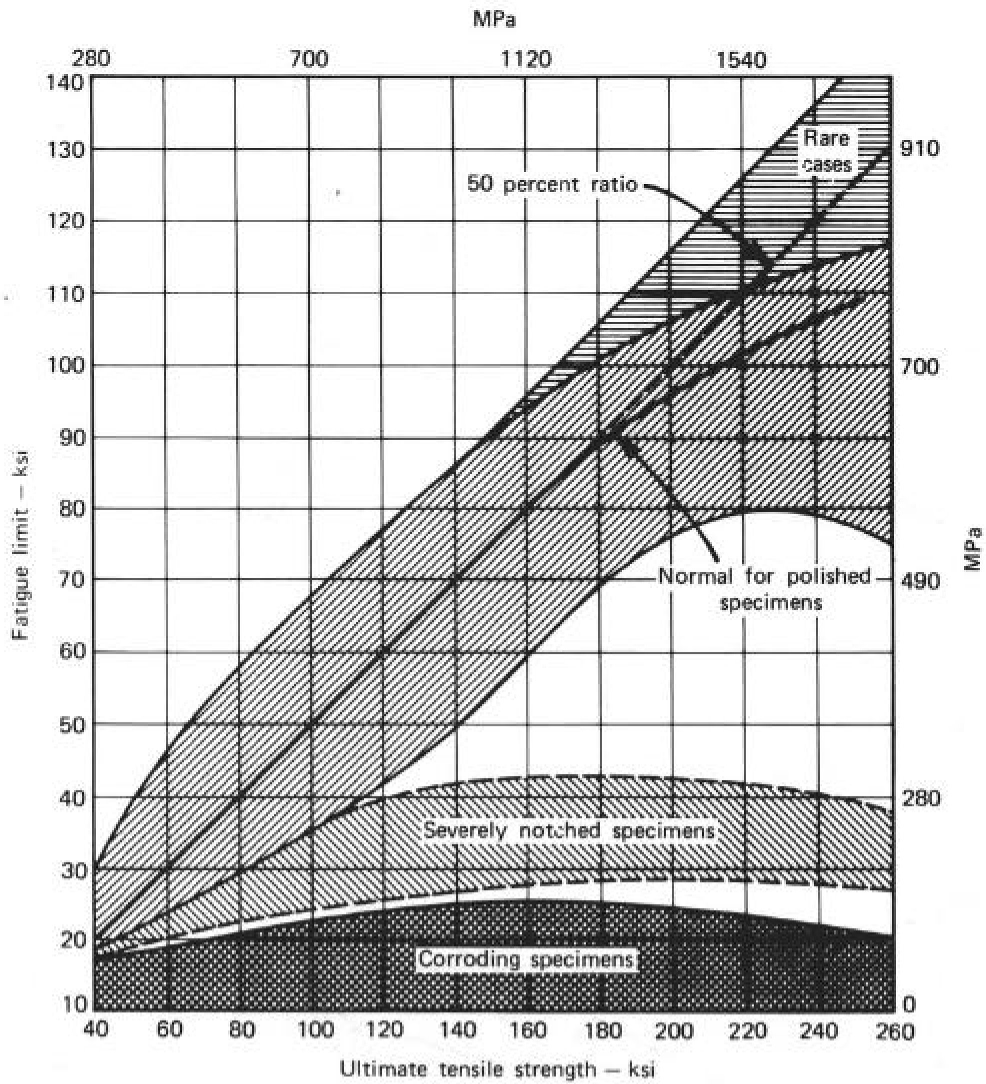
Aluminum fatigue limit

Fatigue strength correlates with UTS and small grain size.





Influence of UTS and notches



The fatigue limit of steel is a function of the UTS. However, stress concentrations resulting from either mechanical notches or corrosion pits greatly reduce the fatigue strength in proportion to the severity of the notch.