Mechanical Behaviour of Materials

Chapter 09

Fatigue

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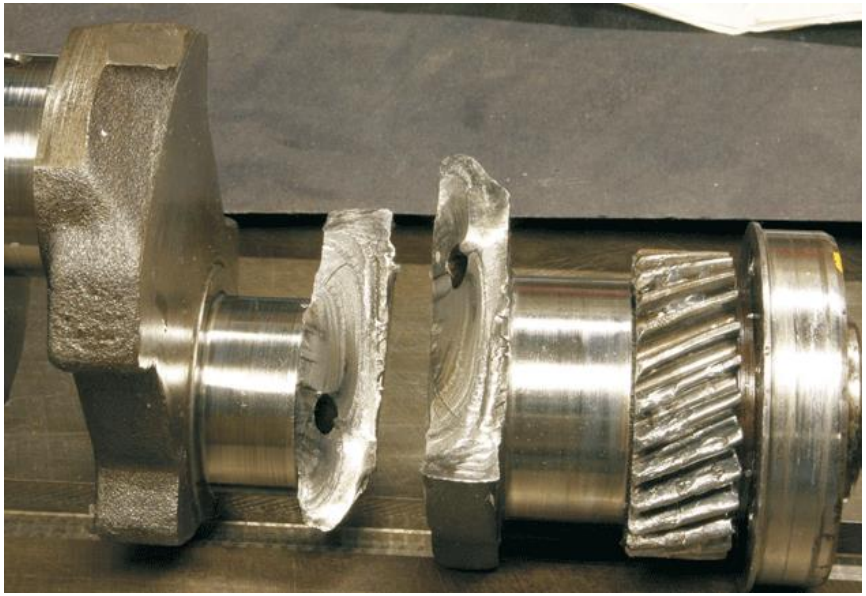
Stages of fatigue

Cyclic loading examples

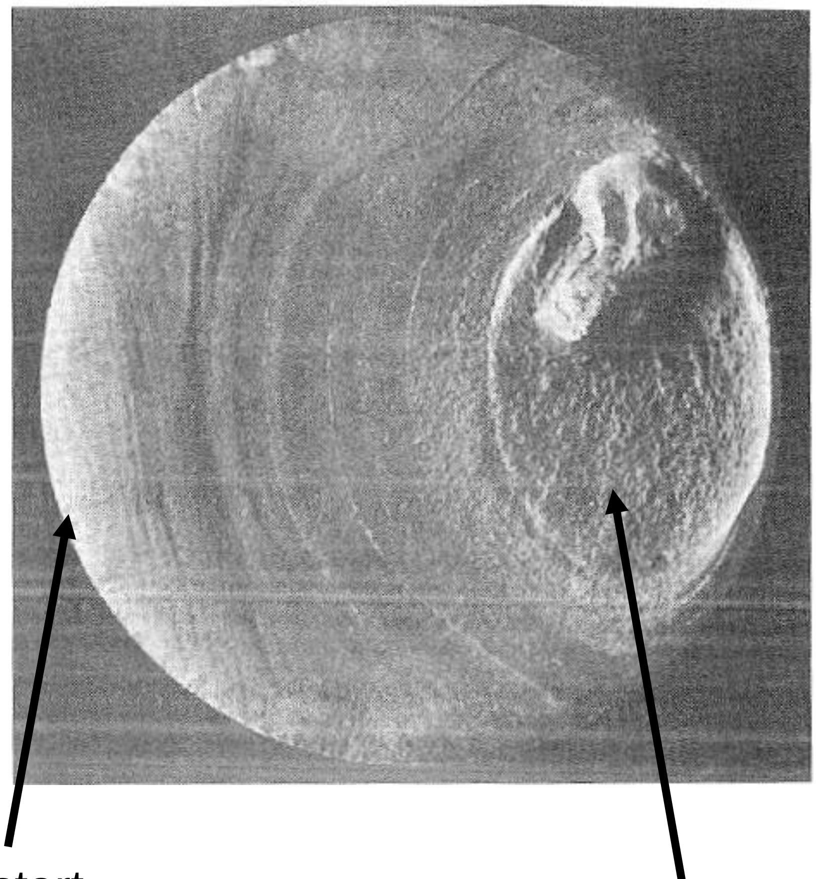


Crankshaft: Rotating shaft

Aircraft fuselage at takeoff and landing

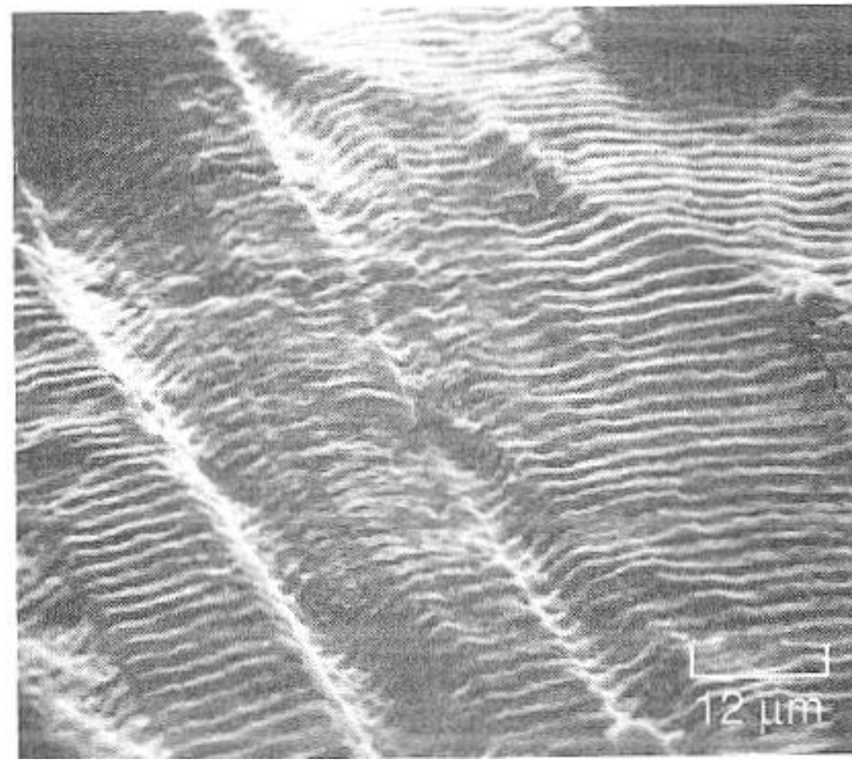
Surface Fractography

Typical clam shell markings



Courtesy of W.H. Durrant

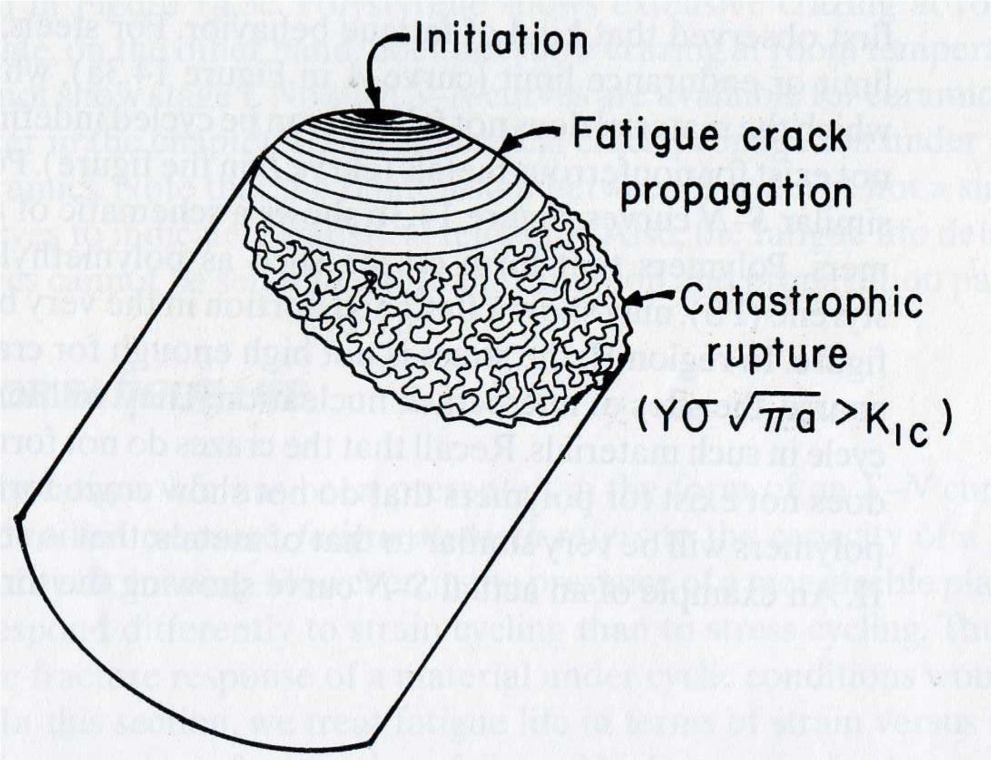
Fatigue striations in 304 stainless steel



From Metals Handbook, v9, 8th ed, ASM , 1974

Characteristics of fatigue fracture

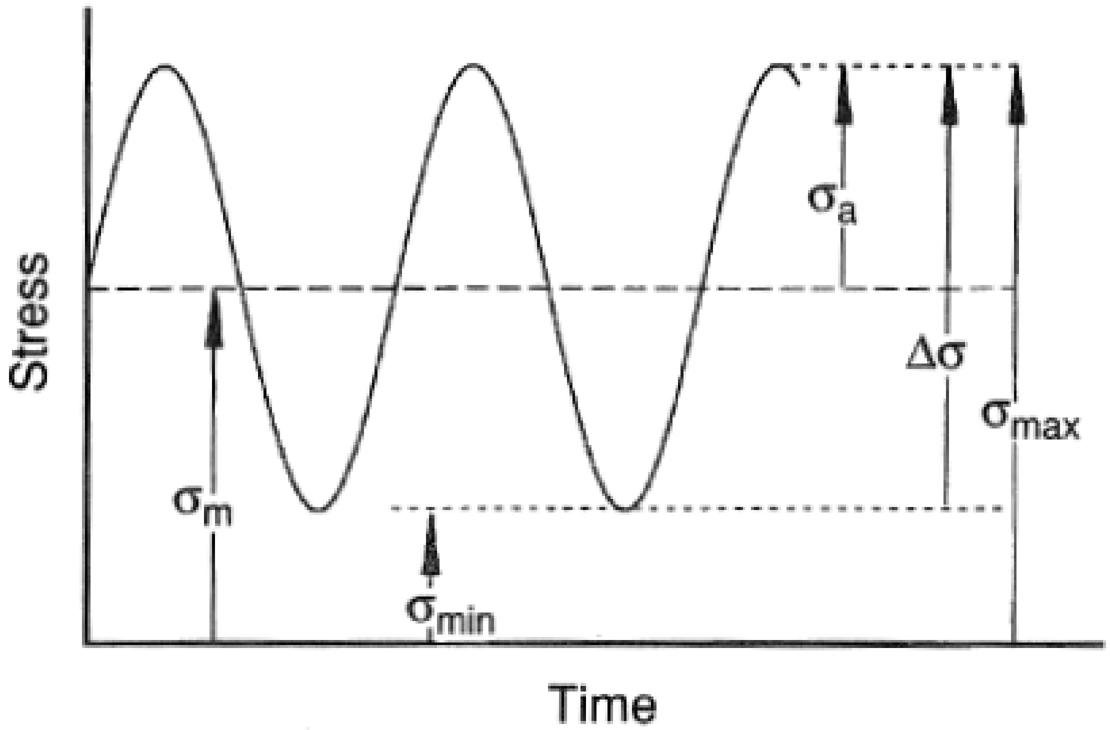
Fatigue is defined as a degradation of mechanical properties leading to failure of a material or a component under cyclic loading



It is estimated that 90% of service failures of metallic components that undergo movement of one form or another can be attributed to fatigue.

Nomenclature of cyclic stress-controlled fatigue

$$\sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2}$$



cyclic stress range

$$\Delta\sigma = \sigma_{\max} - \sigma_{\min}$$
$$= 2\sigma_a$$

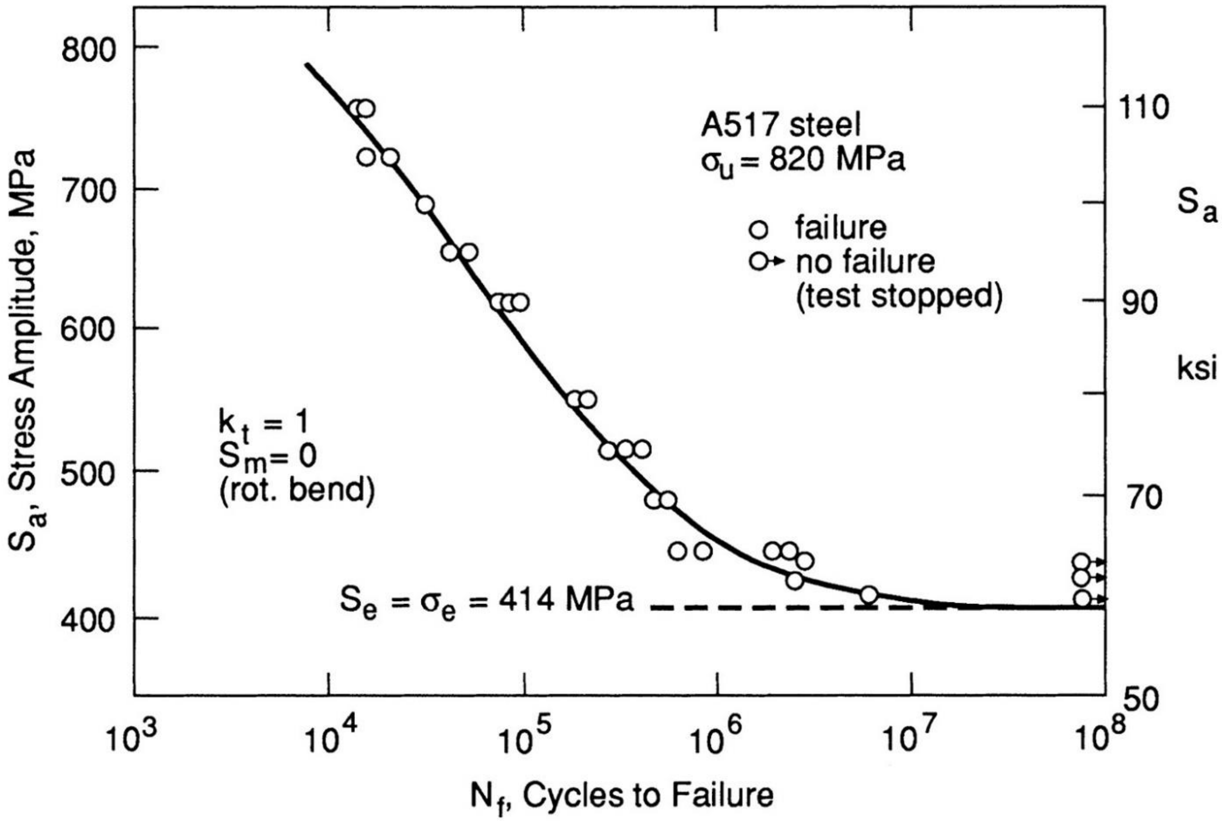
Mean stress

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2}$$

Stress ratio

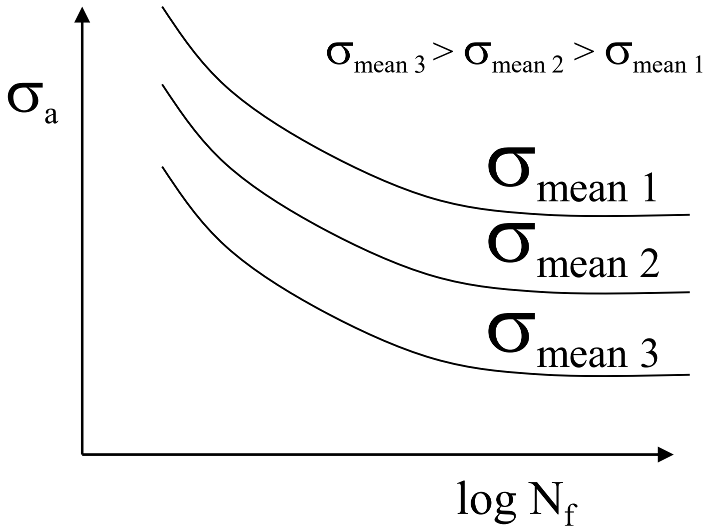
$$R = \frac{\sigma_{\min}}{\sigma_{\max}}$$

What is S-N curve



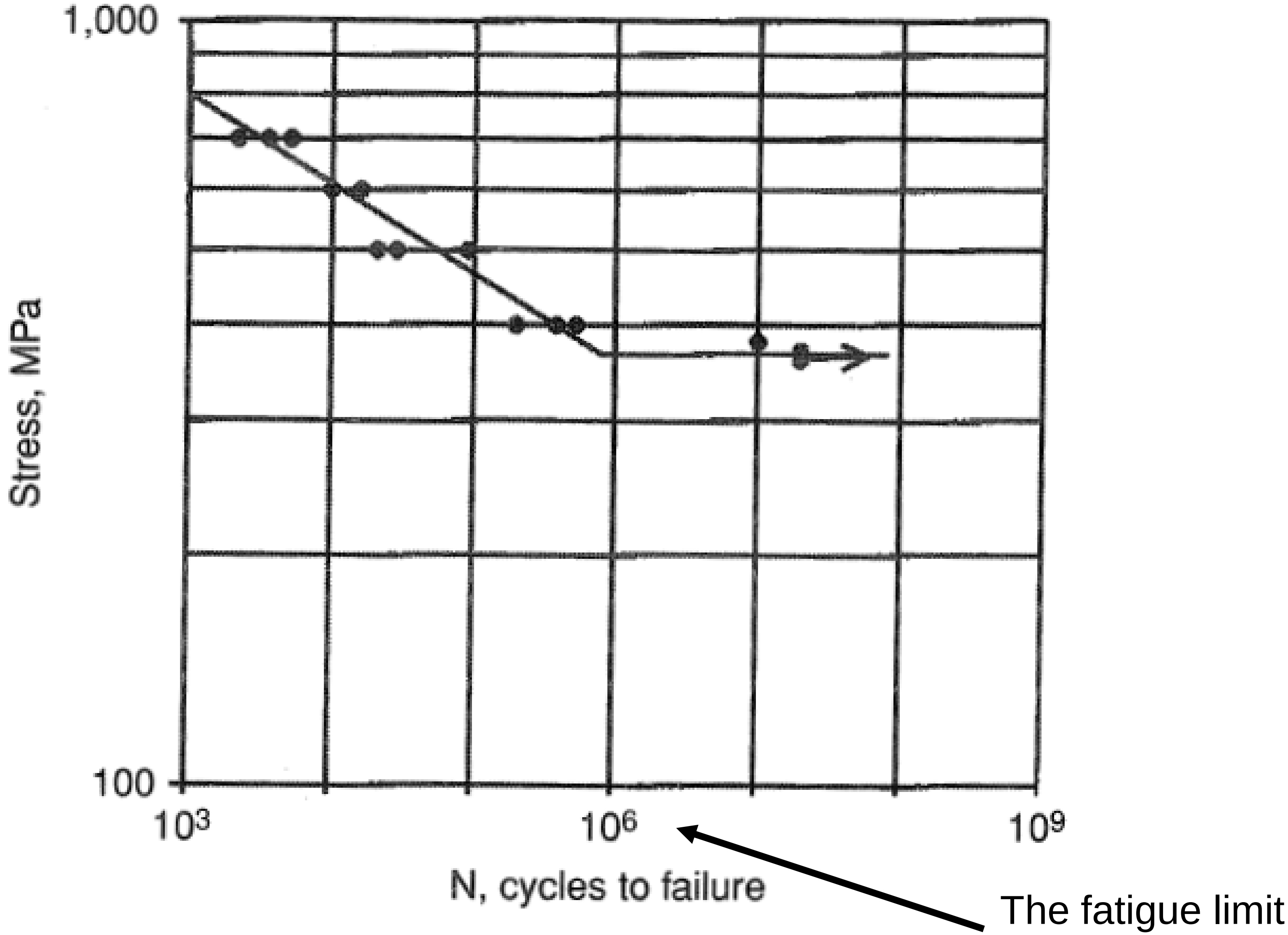
- Traditionally, the behavior of a material under fatigue is described by the S-N (σ-N) curves, where S (σ) is the stress and N is the number of cycles to failure. The S-N –curve is called a Woehler curve.

Effect of mean stress on fatigue life

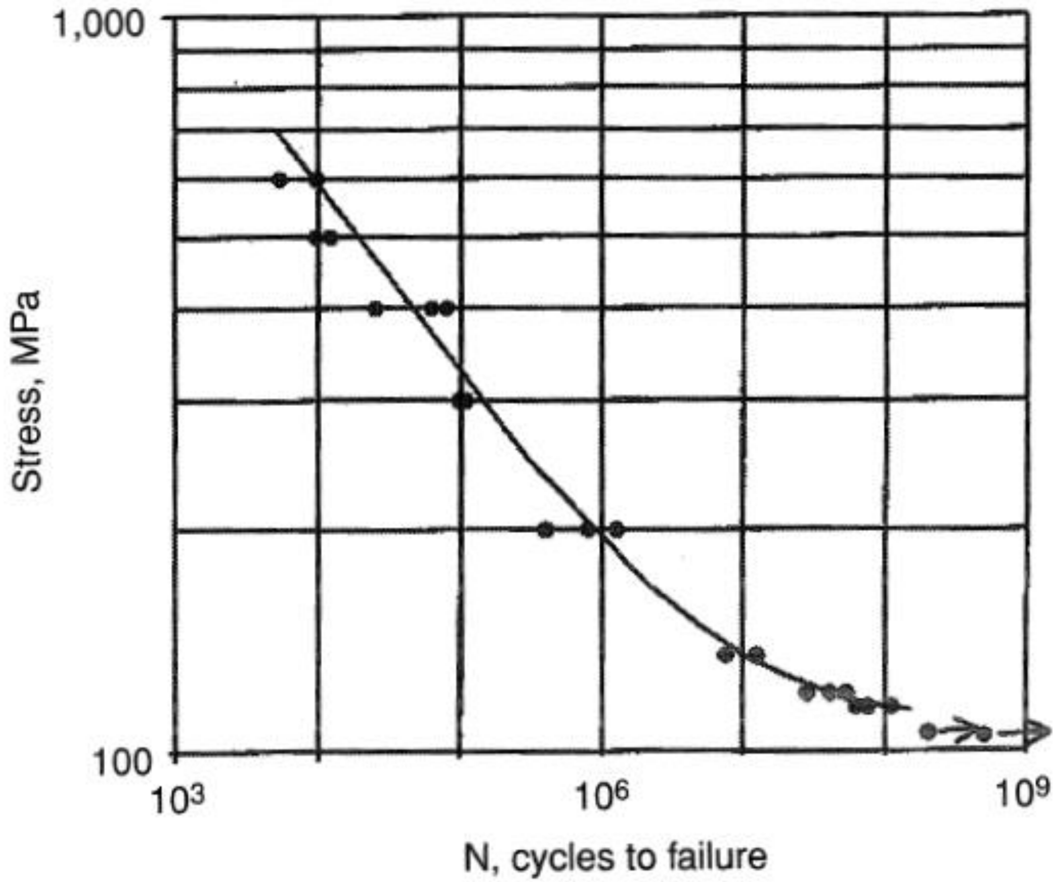


The greater the number of cycles in the loading history, the smaller the stress that the material can withstand without failure.

Example of S-N curve for annealed 4340 steel

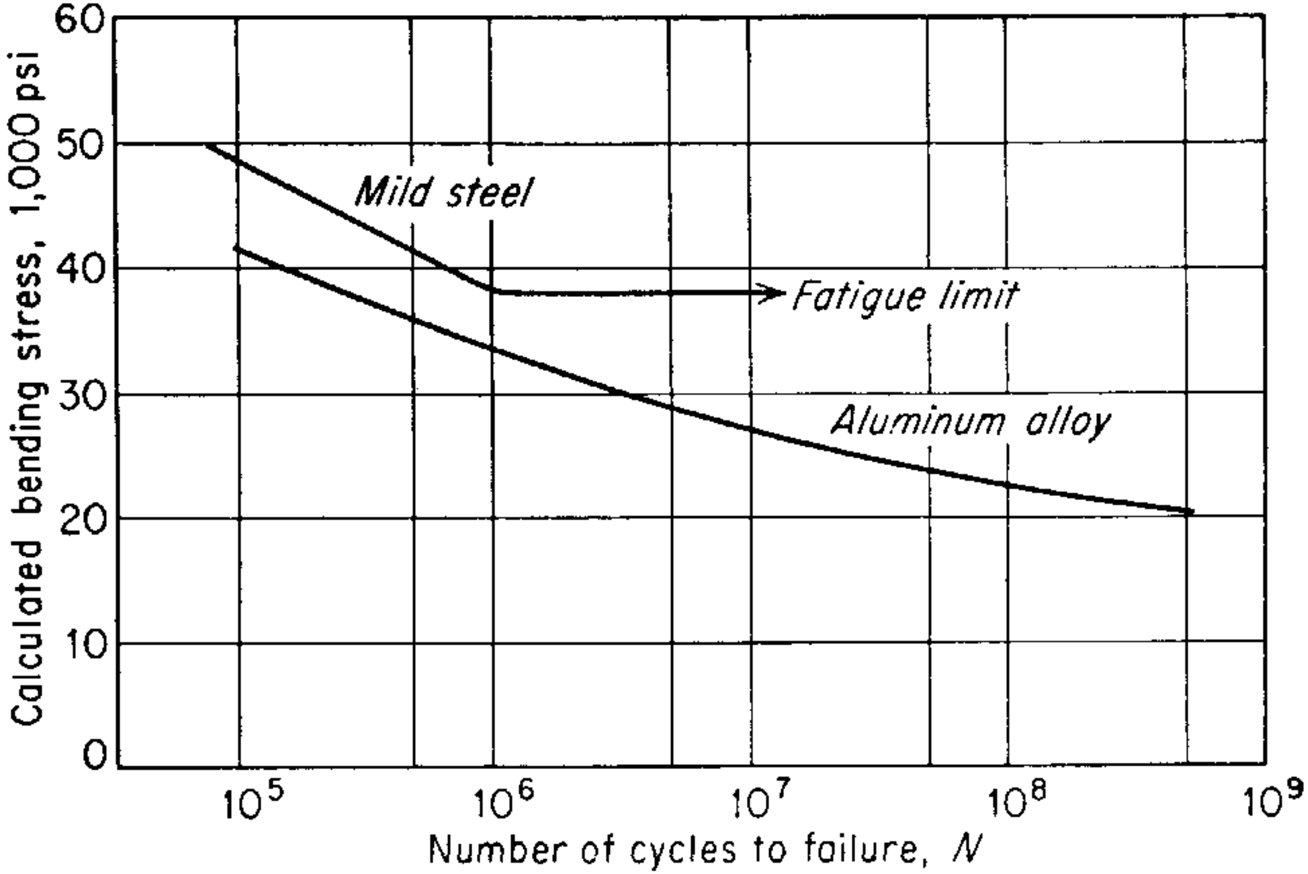


Example of S-N curve for Al alloy 7075 T6



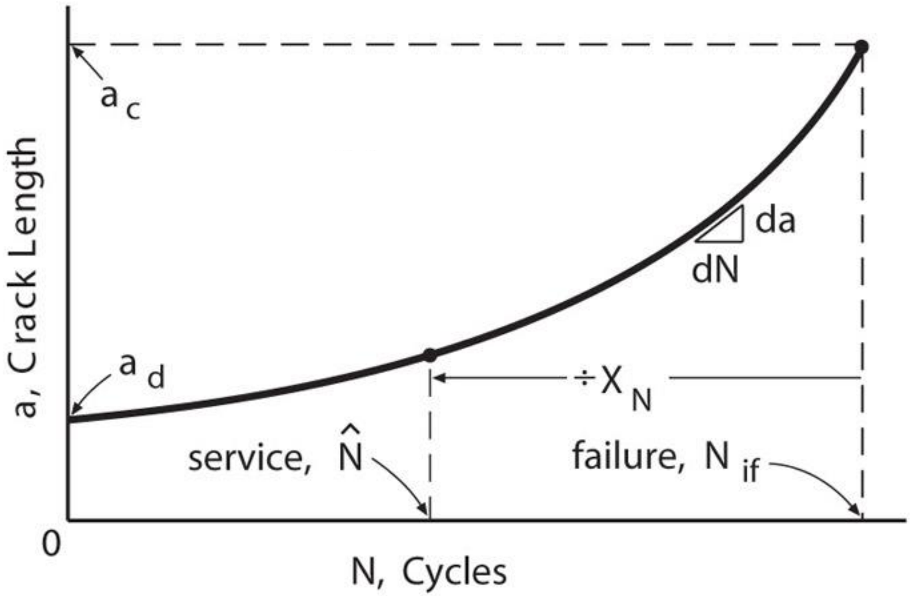
No true fatigue limit

S-N curve between steels and aluminum alloys



[Dieter]

Determination for Fatigue Crack Growth



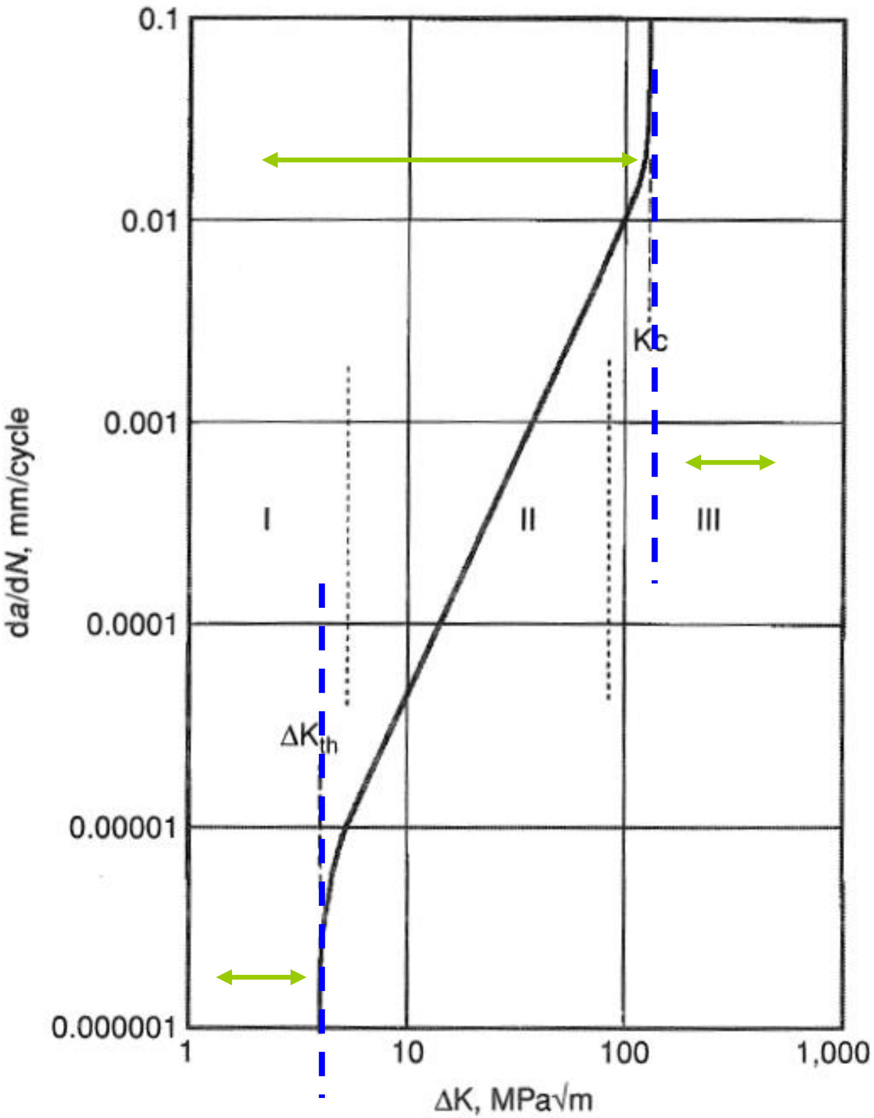
Fatigue growth rate, da/dN

$$\Delta\sigma = \sigma_{\max} - \sigma_{\min} \qquad R = \sigma_{\min} / \sigma_{\max}$$

$$\Delta K_j = f(a/w)\Delta\sigma\sqrt{\pi a}$$

$$\Delta K = K_{\max} - K_{\min}$$

Fatigue Crack Growth

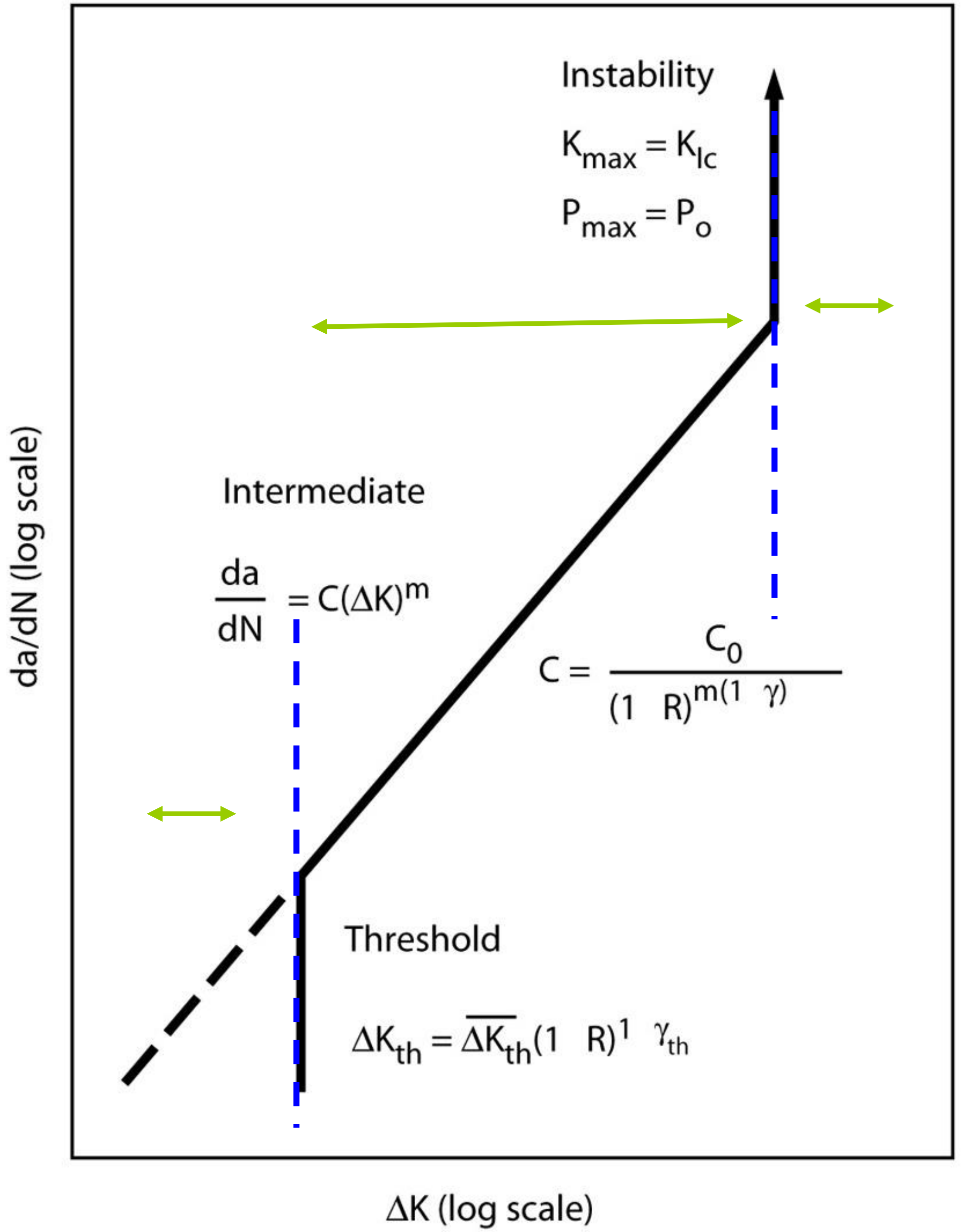


$$\frac{da}{dN} = C(\Delta K)^m$$

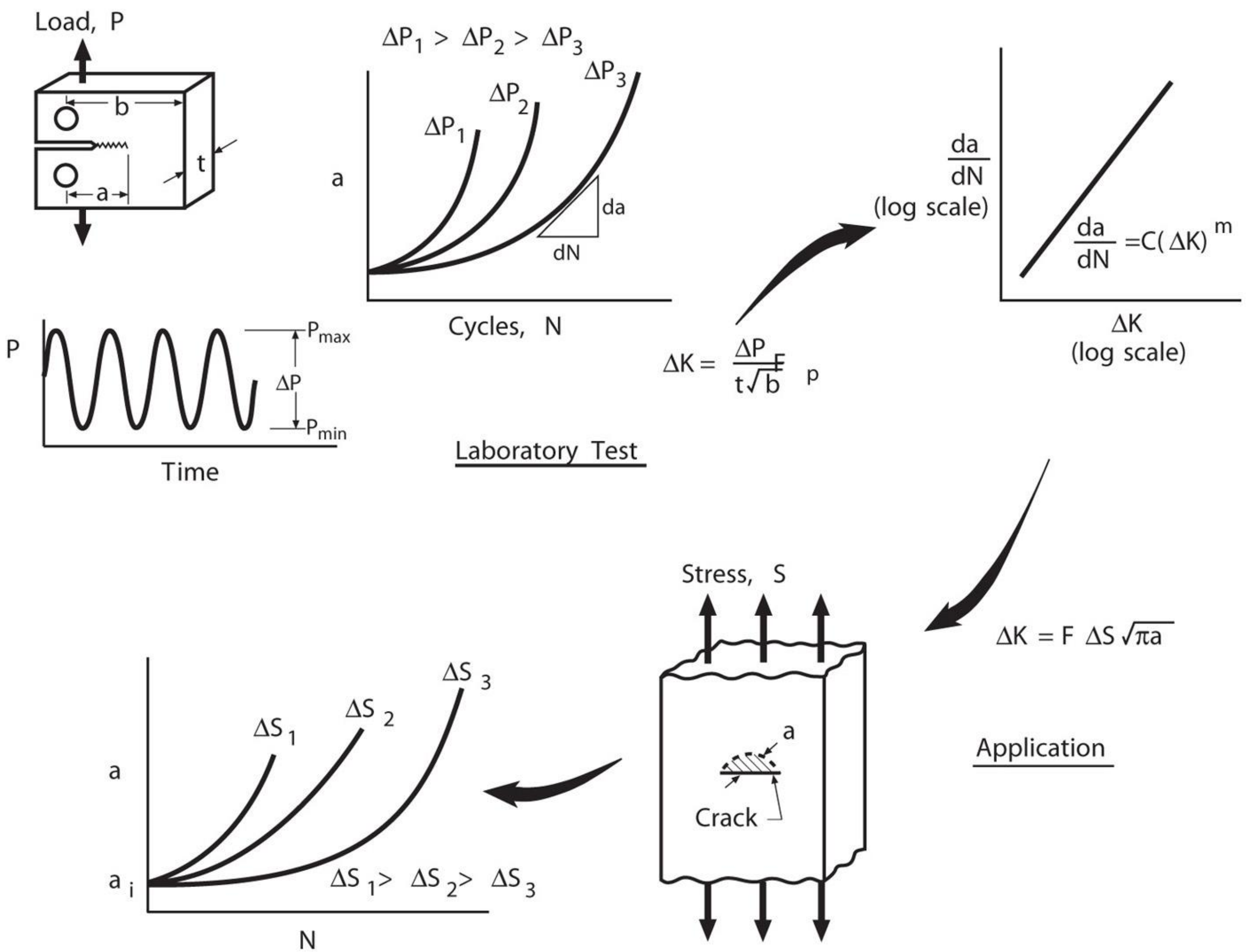
ΔK_{th} fatigue crack growth threshold

If ΔK below this value ΔK_{th}, crack growth does not occur.

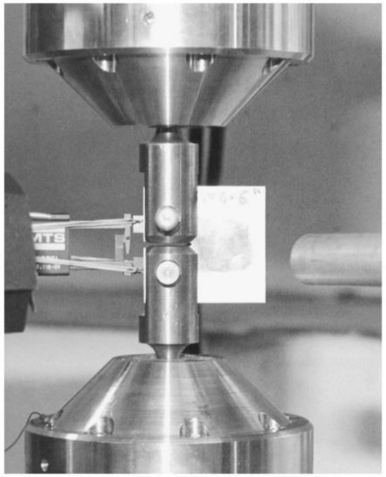
Fatigue Crack Growth

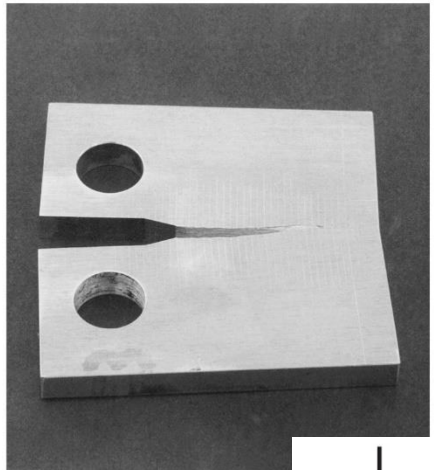


Determination for



Fatigue crack growth rate testing





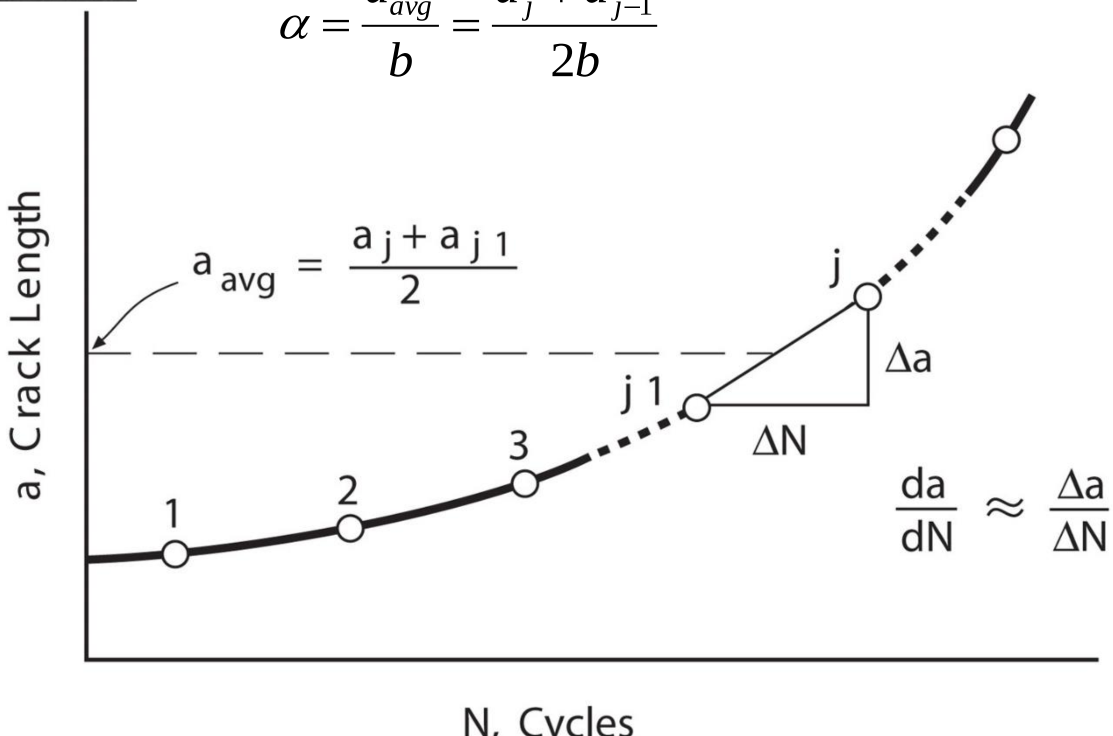
$$\left(\frac{da}{dN}\right)_j \approx \left(\frac{\Delta a}{\Delta N}\right)_j = \frac{a_j - a_{j-1}}{N_j - N_{j-1}}$$

$$a_{avg} = \frac{a_j + a_{j-1}}{2}$$

$$\alpha = \frac{a_{avg}}{b} = \frac{a_j + a_{j-1}}{2b}$$

$$\Delta K_j = F(\alpha)\Delta S\sqrt{\pi a_{avg}}$$

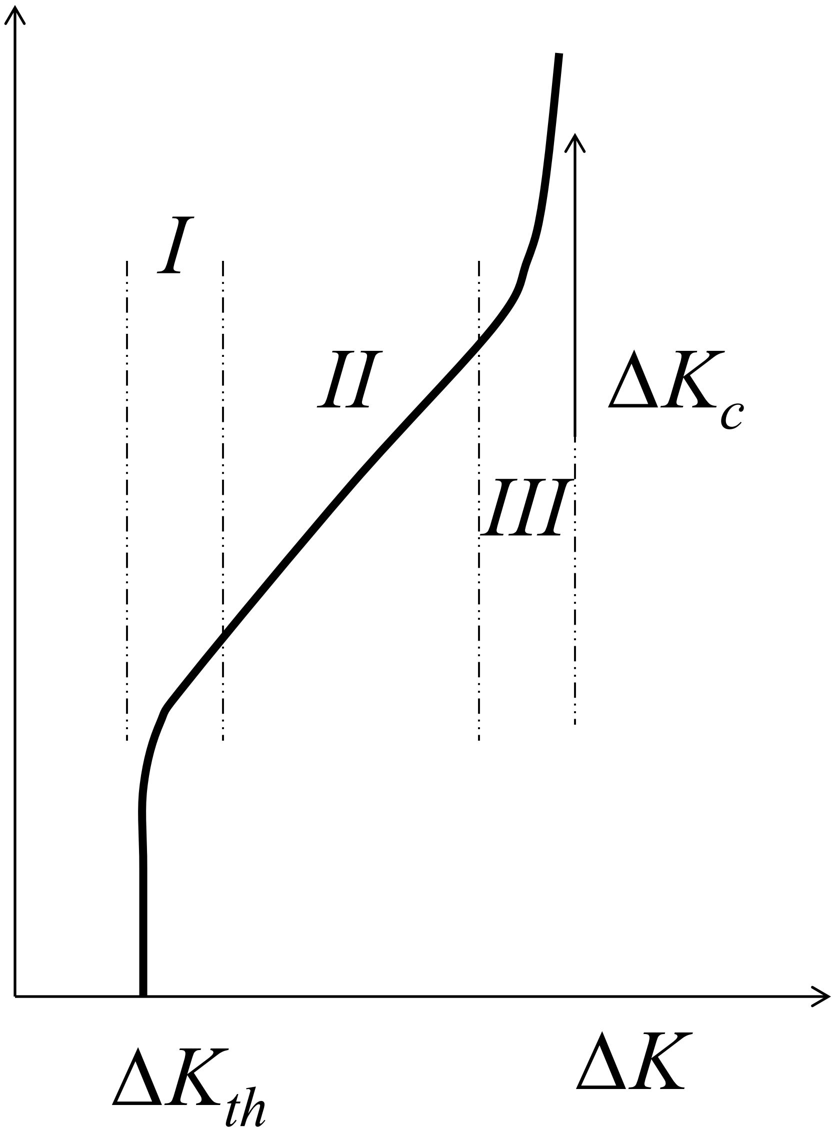
$$\Delta K_j = F_p(\alpha)\frac{\Delta P}{t\sqrt{b}}$$



Mechanisms of crack nucleation

Fatigue crack growth

- Three stages of crack growth, I, II and III.
- Stage I: transition to a finite crack growth rate from no propagation below a threshold value of ΔK.
- Stage II: “power law” dependence of crack growth rate on ΔK.
- Stage III: acceleration of growth rate with ΔK, approaching catastrophic fracture.



Fatigue crack stages

Stage 1

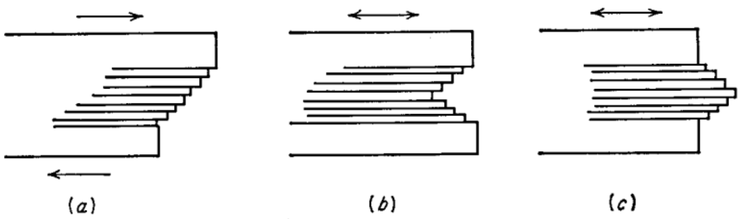


Figure 12-15 W. A. Wood's concept of microdeformation leading to formation of fatigue crack. (*a*) Static deformation; (*b*) fatigue deformation leading to surface notch (intrusion); (*c*) fatigue deformation leading to slip-band extrusion.

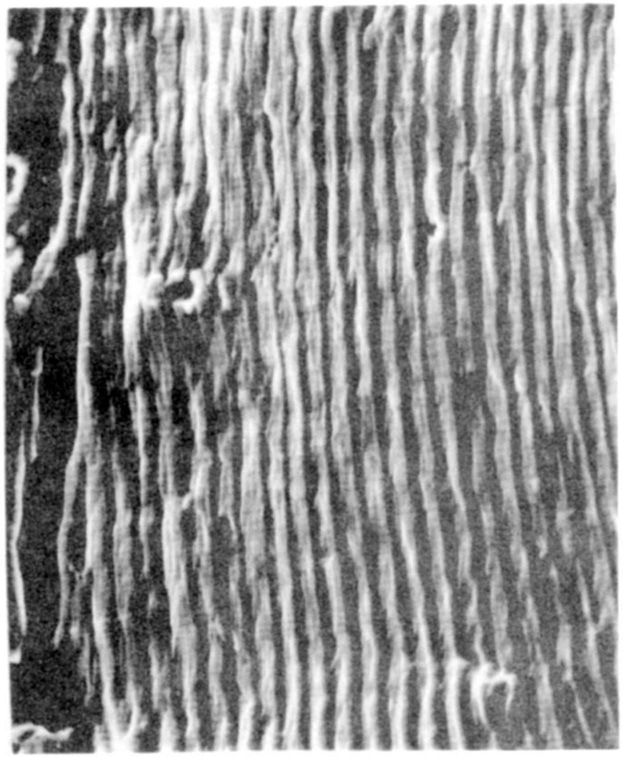


Figure 12-16 Fatigue striations in beta-annealed Ti-6Al-4V alloy (2000 ×). (*Courtesy of R. A. Bayles, Naval Research Laboratory.*)

Stage 2

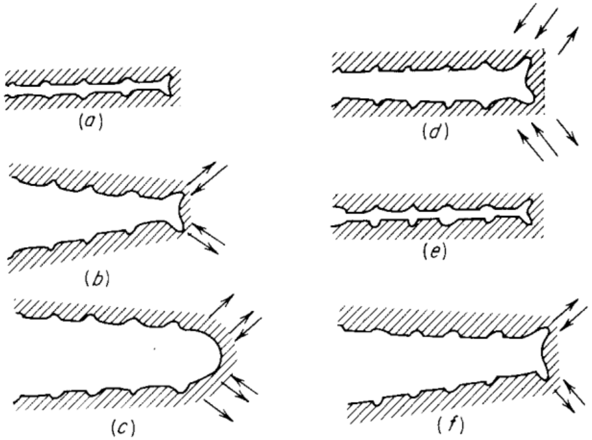
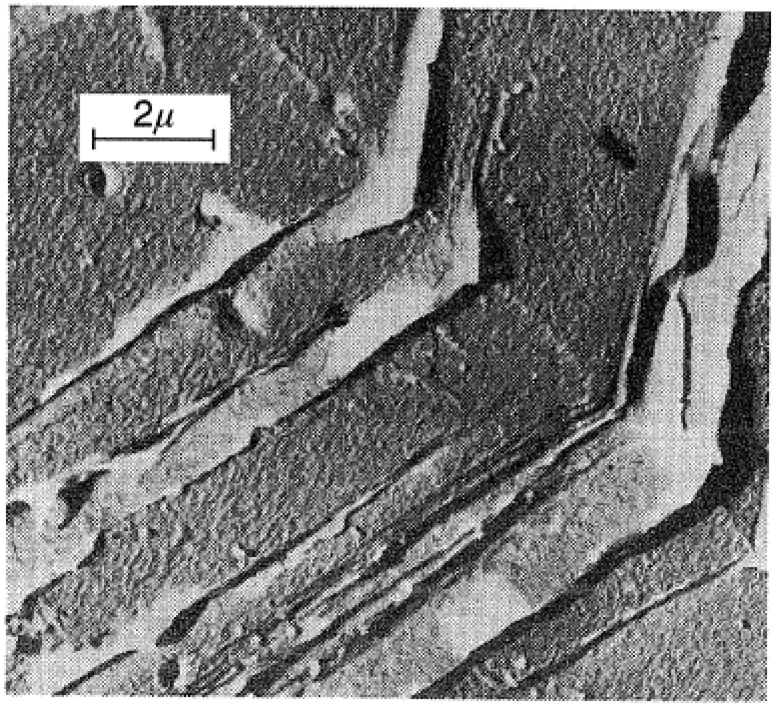
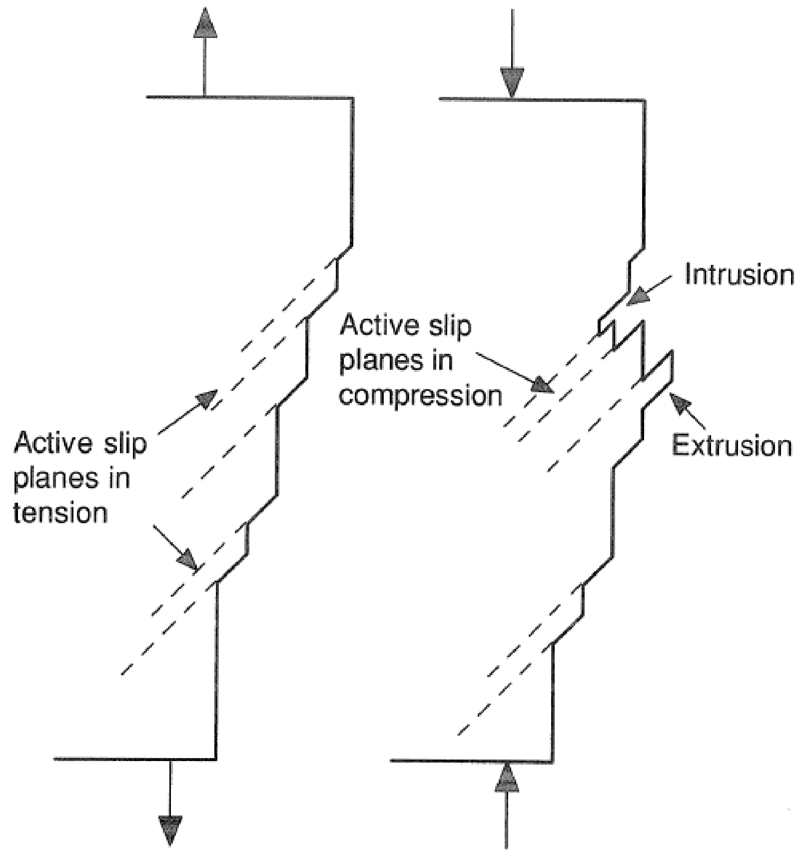


Figure 12-17 Plastic blunting process for growth of stage II fatigue crack. *(From C. Laird, ASTM Spec. Tech. Publ. 415, p. 136, 1967.)*

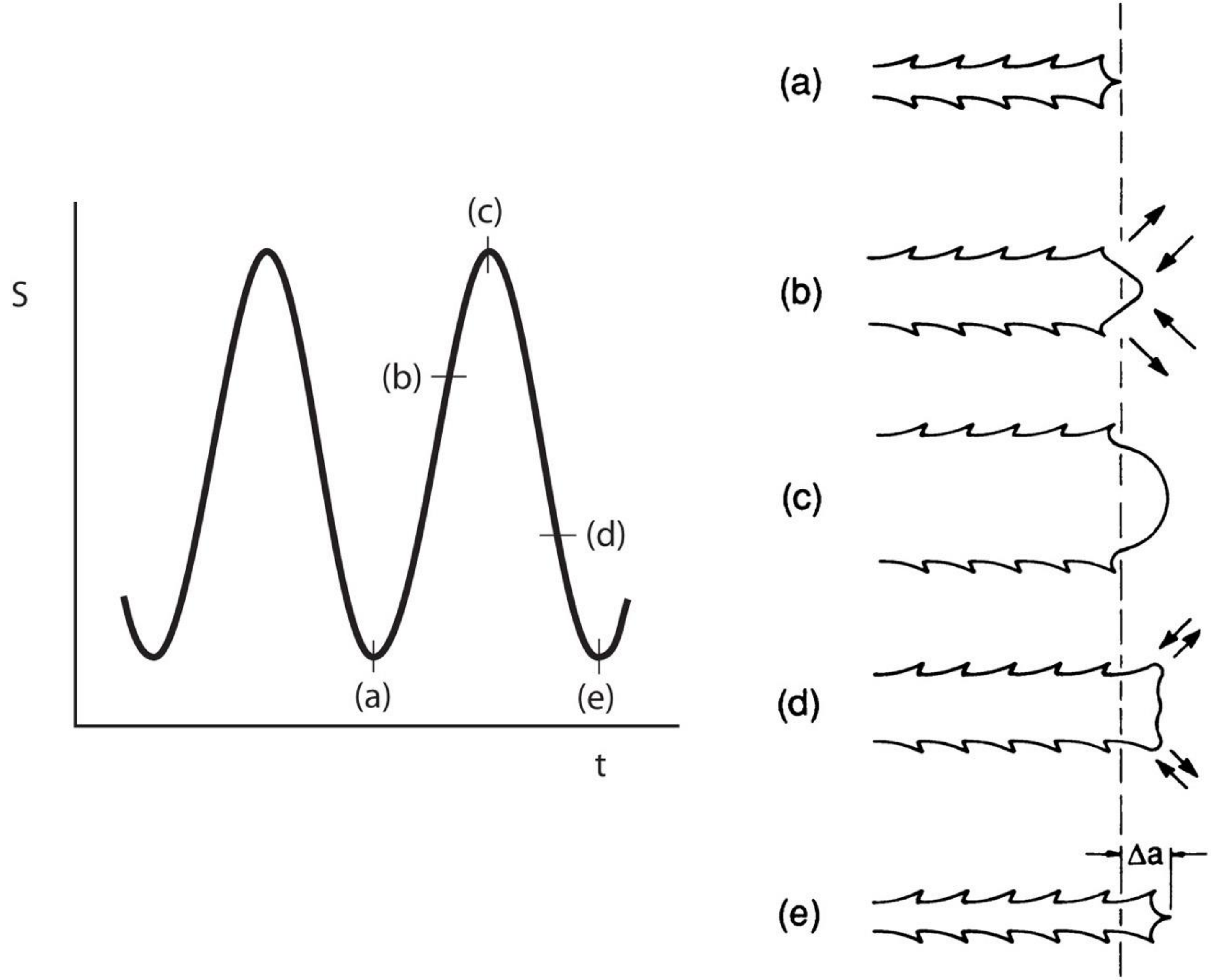
Intrusions and extrusions at the surface





From A. Cottrell and D. Hull, Proc. Roy. Soc. A242 (1957)

Fatigue crack stages



Fatigue Crack Propagation

- Crack Nucleation stress intensification at crack tip.
- Stress intensity crack propagation (growth);
  - stage I growth on shear planes (45°),
  strong influence of microstructure
  - stage II growth normal to tensile load (90°)
  weak influence of microstructure.
- Crack propagation catastrophic, or ductile failure at crack length dependent on boundary conditions, fracture toughness.

Fatigue Crack Nucleation

- Flaws, cracks, voids can all act as crack nucleation sites, especially at the surface.
- Therefore, smooth surfaces increase the time to nucleation; notches, stress risers decrease fatigue life.
- Dislocation activity (slip) can also nucleate fatigue cracks.

Dislocation Slip → Crack Nucleation

- Dislocation slip -> tendency to localize slip in bands.
- Persistent Slip Bands (PSB's) characteristic of cyclic strains.
- Slip Bands -> extrusion at free surface.
- Extrusions -> intrusions and crack nucleation.