Mechanical Behaviour of Materials

Chapter 17

Fatigue

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Content:

3-3.1. Introduction to fatigue
3-3.2. Fatigue test
3-3.3. S-N curve
3-3.4. Fatigue crack growth
3-3.5. Stages of fatigue

Surface Fractography

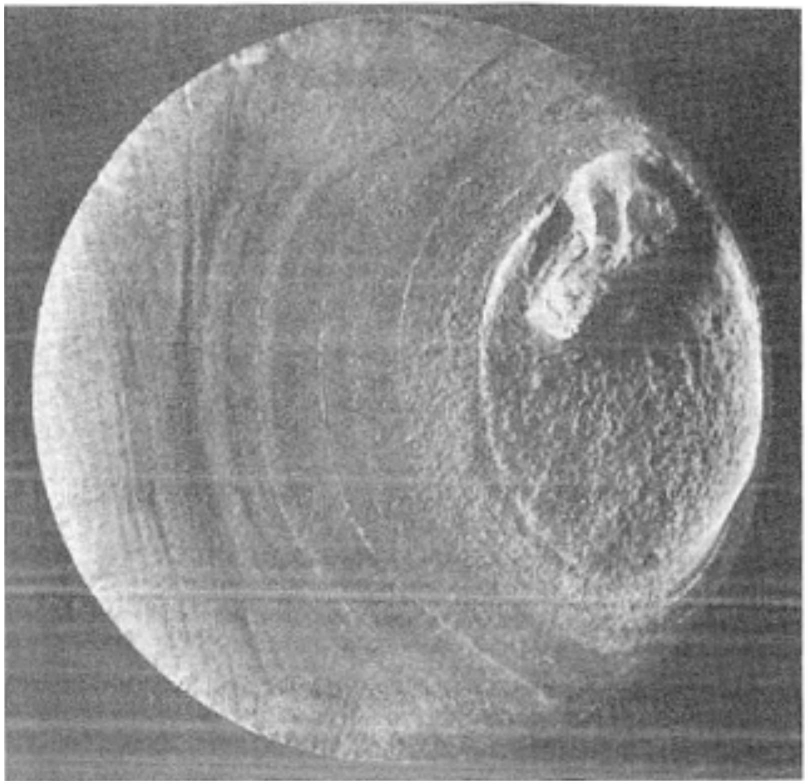


Figure 17.1. Typical clamshell markings on a fatigue fracture surface of a shaft. The fracture started at the left side of the bar and progressed to the right, where final failure occurred in a single cycle. Courtesy of W. H. Durrant.

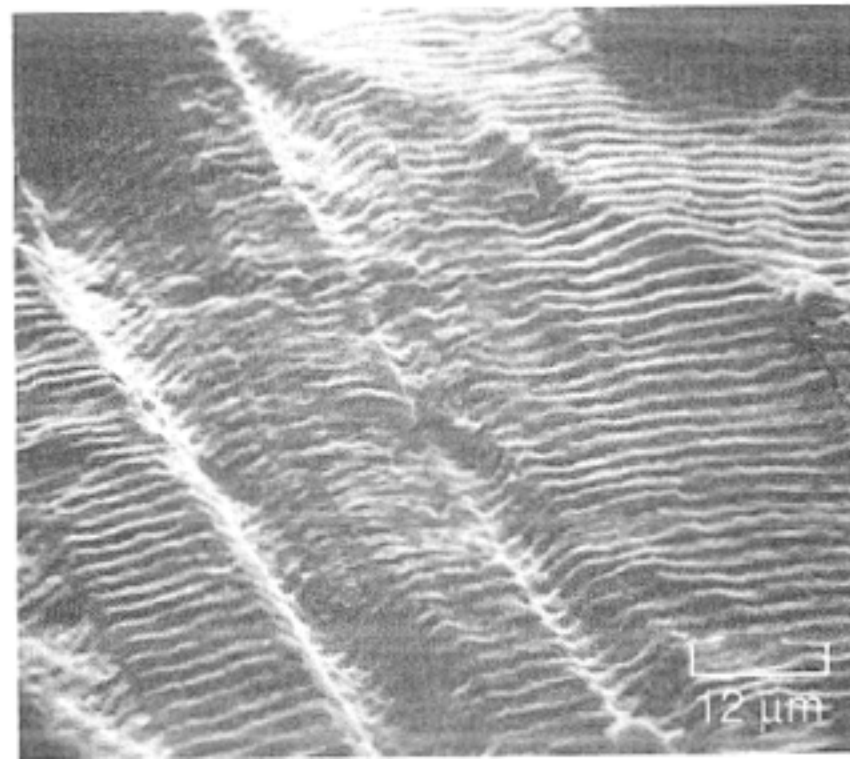


Figure 17.2. SEM picture of fatigue striations on a fracture surface of type 304 stainless steel. From *Metals Handbook*, v. 9, 8th ed., ASM (1974).

Fatigue fracture surface

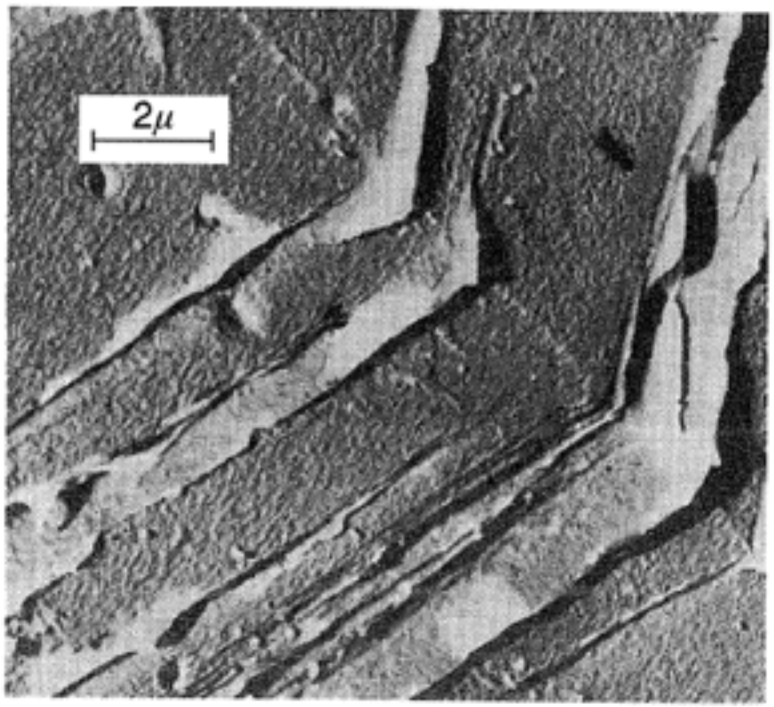


Figure 17.3. Intrusions and extrusions at the surface formed by cyclic deformation. These correspond to persistent slip bands beneath the surface. From A. Cottrell and D. Hull, *Proc. Roy. Soc. (London)*, v. A242 (1957).

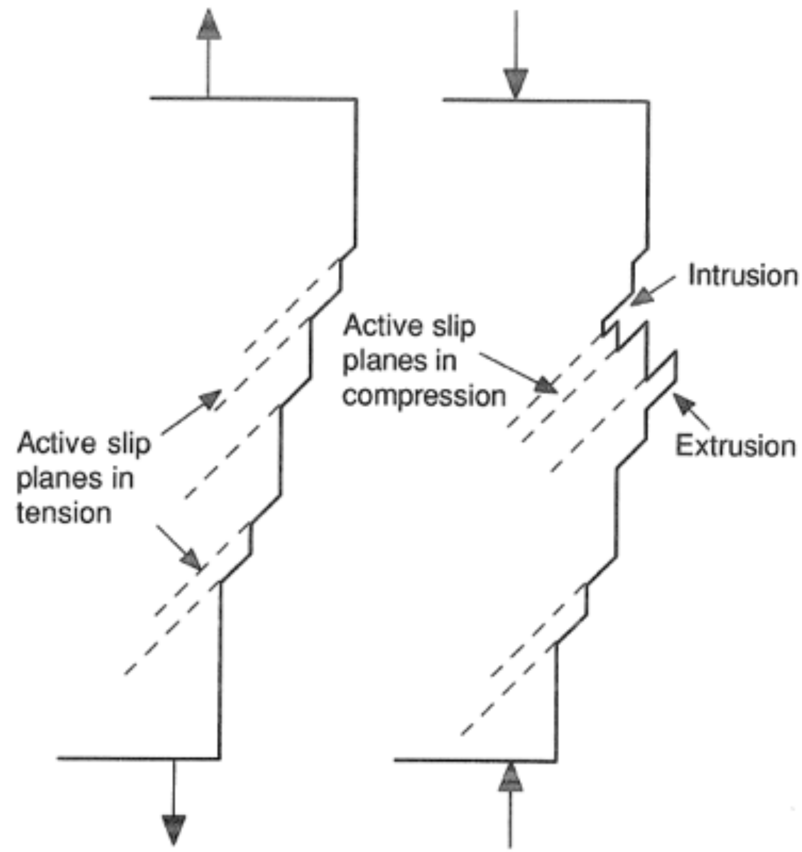
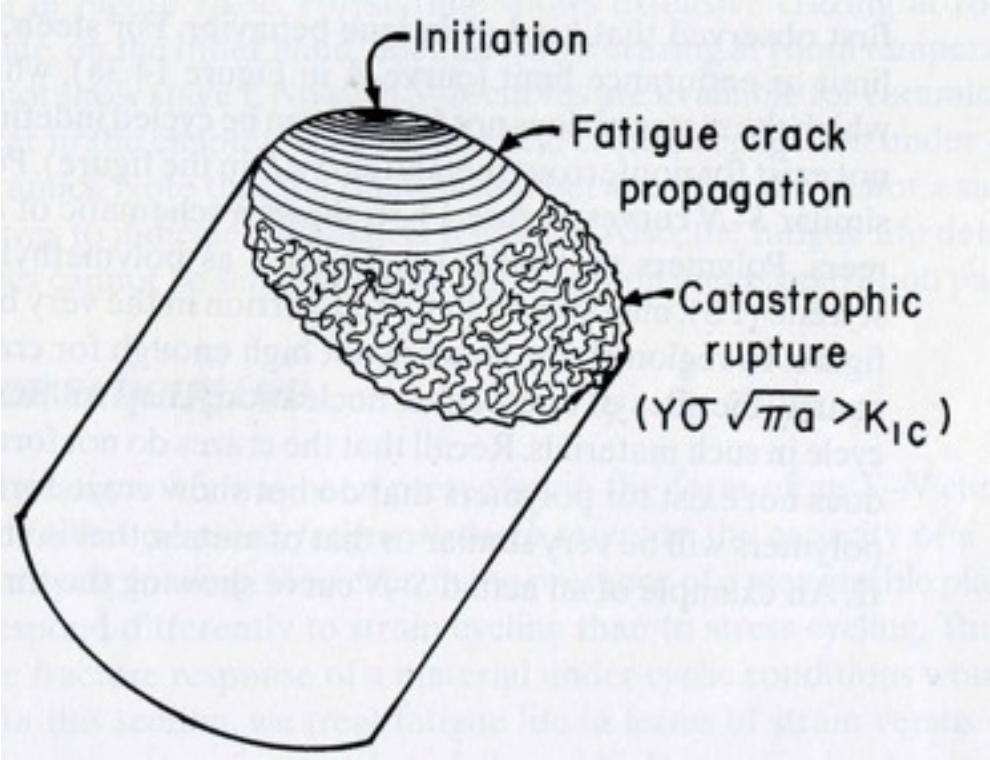


Figure 17.4. Sketch showing how intrusions and extrusions can develop if slip occurs on different planes during the tension and compression portions of the loading.

Characteristics of fatigue fracture

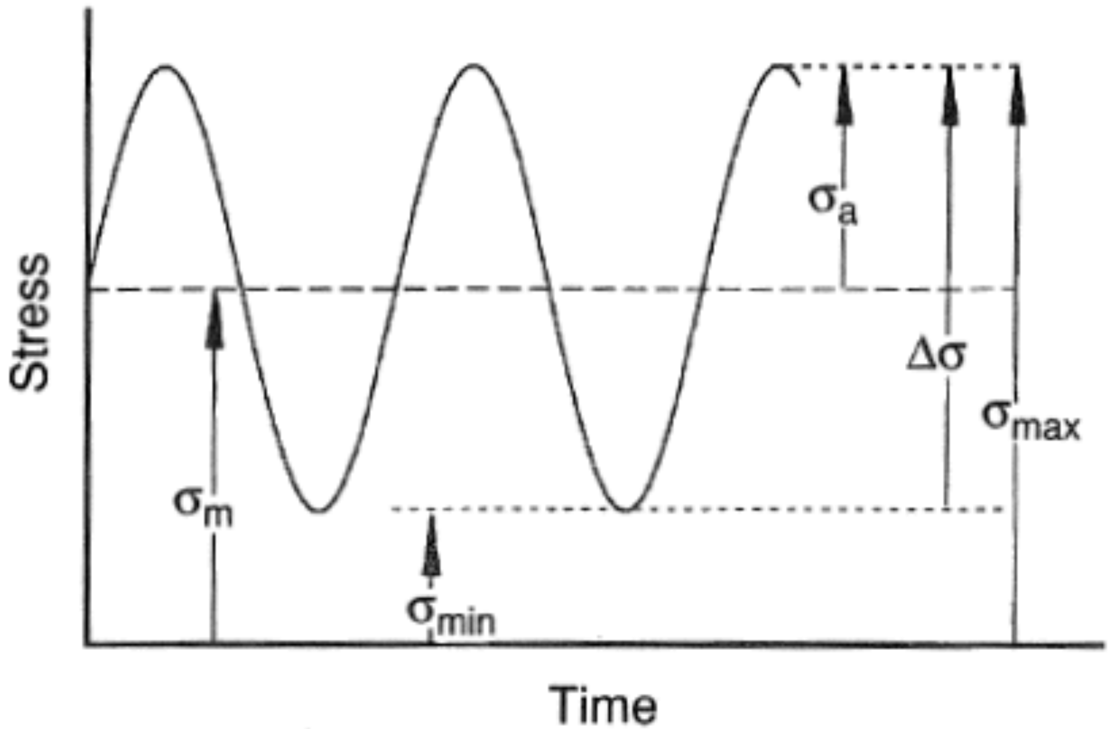
Fatigue is defined as a degradation of mechanical properties leading to failure of a material or a component under cyclic loading

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 loading

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



cyclic stress range

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

Mean stress

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

Stress ratio

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

S-N curves

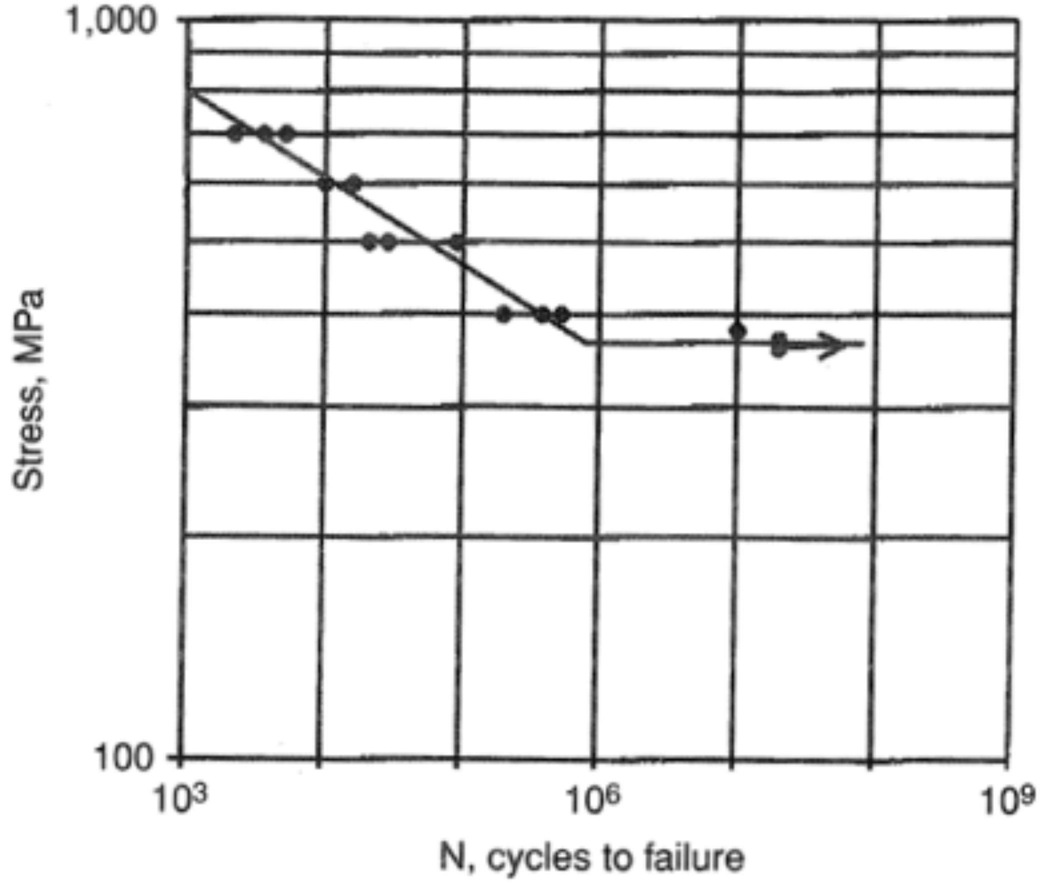


Figure 17.6. The *S-N* curve for annealed 4340 steel. Typically, the break in the curve for a material with a fatigue limit occurs at about 10^6 cycles. The points with arrows are for tests stopped before failure.

S-N curves

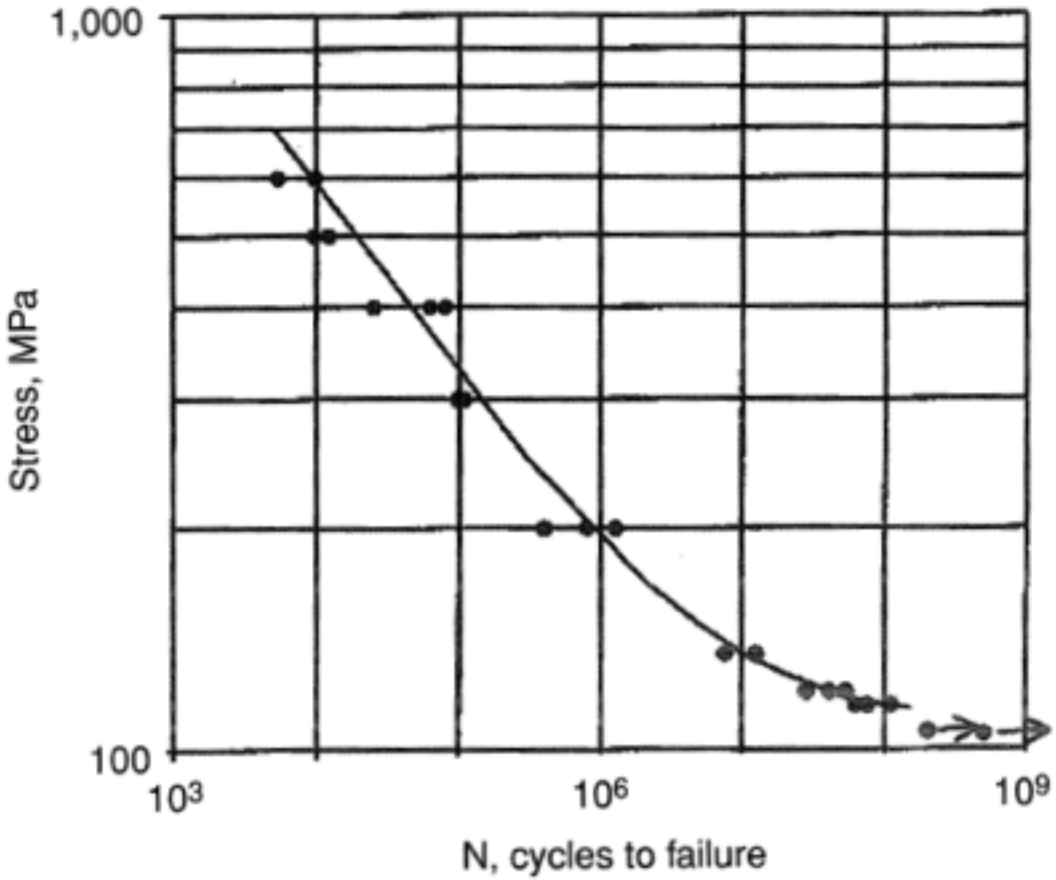
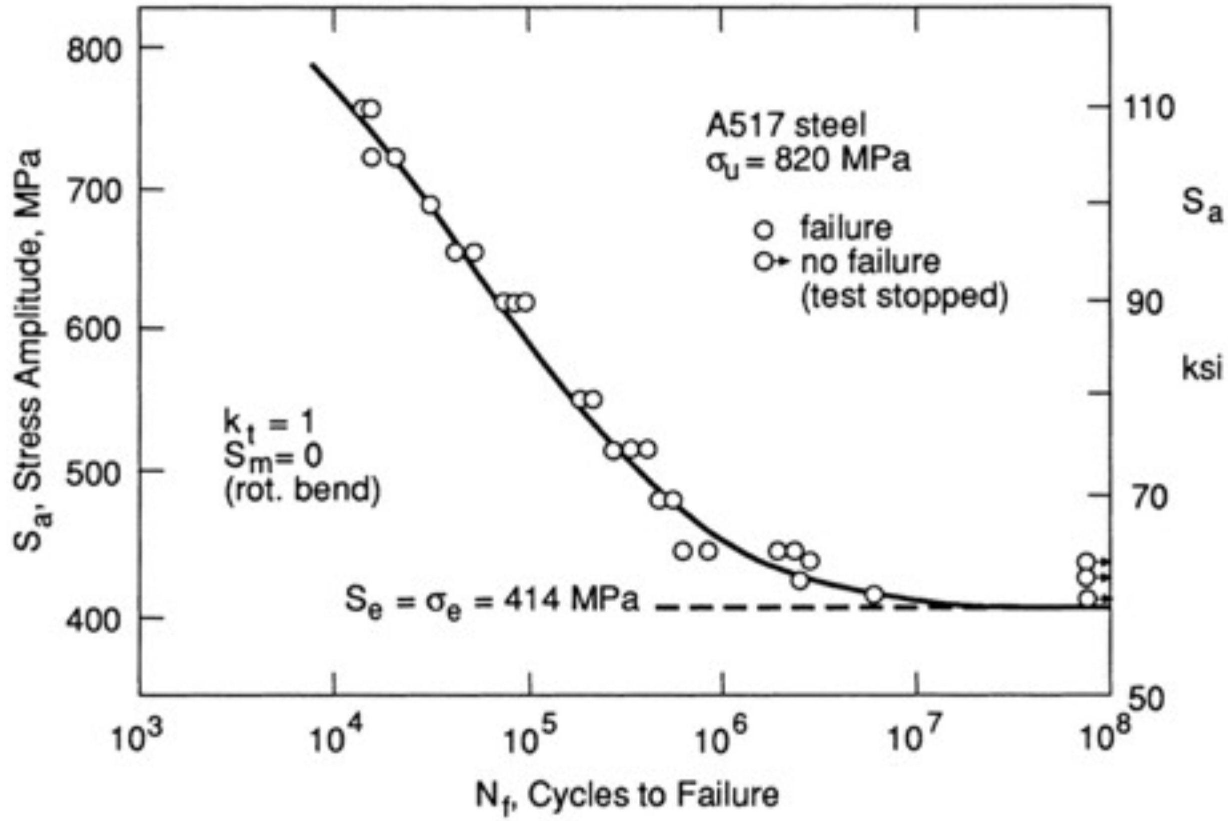


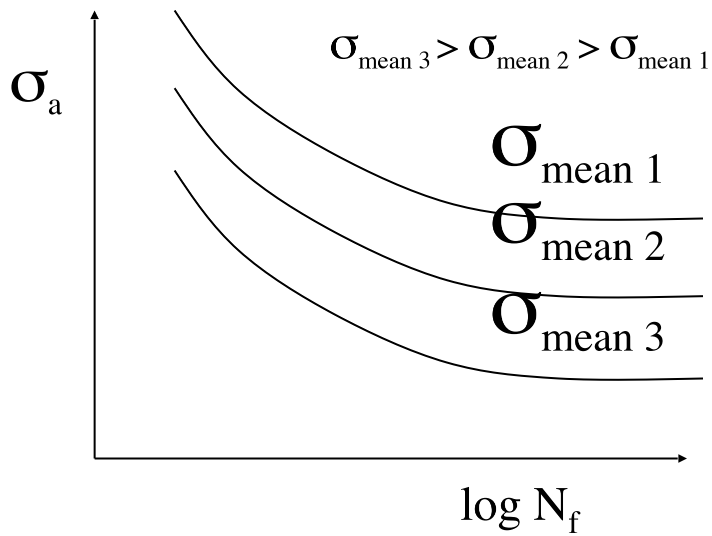
Figure 17.7. The *S-N* curve for an aluminum alloy 7075 T-6. Note that there is no true fatigue limit.

S-N curves



- 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.

Fatigue testing, S-N curves



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

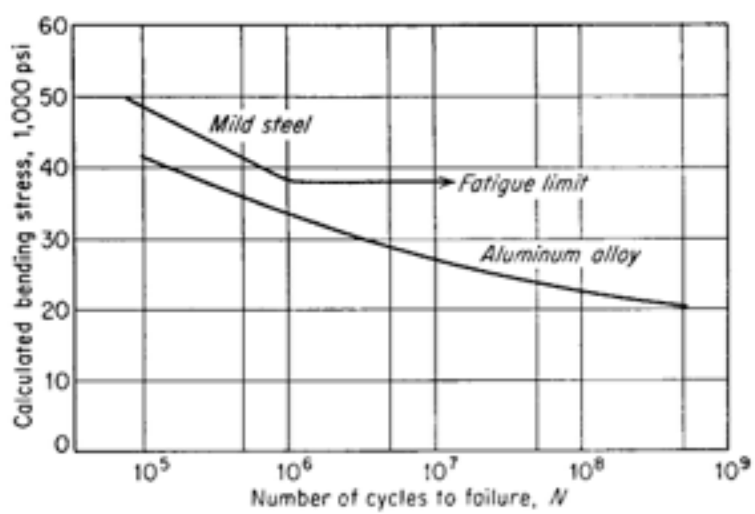
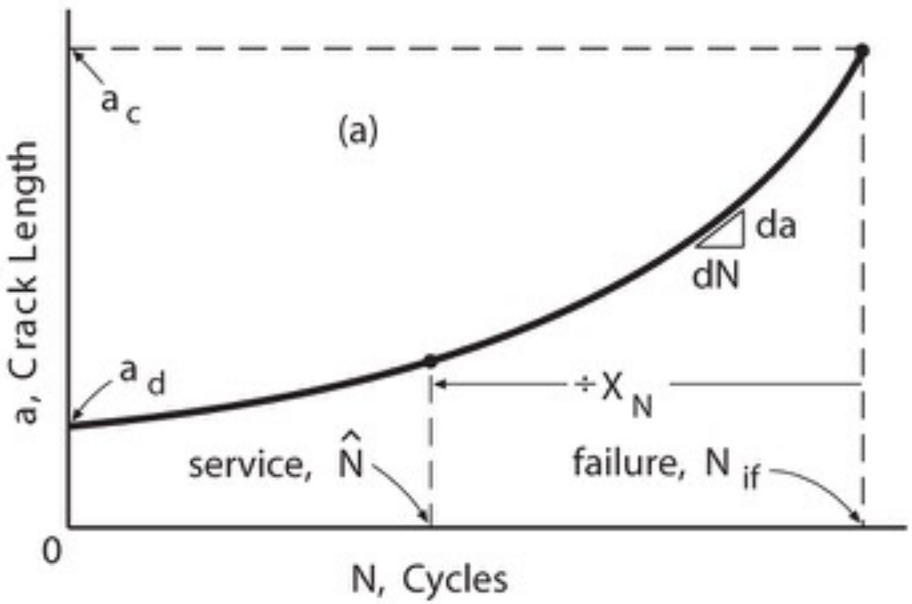


Figure 12-3 Typical fatigue curves for ferrous and nonferrous metals.

Note the presence of a fatigue limit in many steels and its absence in aluminum alloys.

[Dieter]

Determination for Fatigue Crack Growth



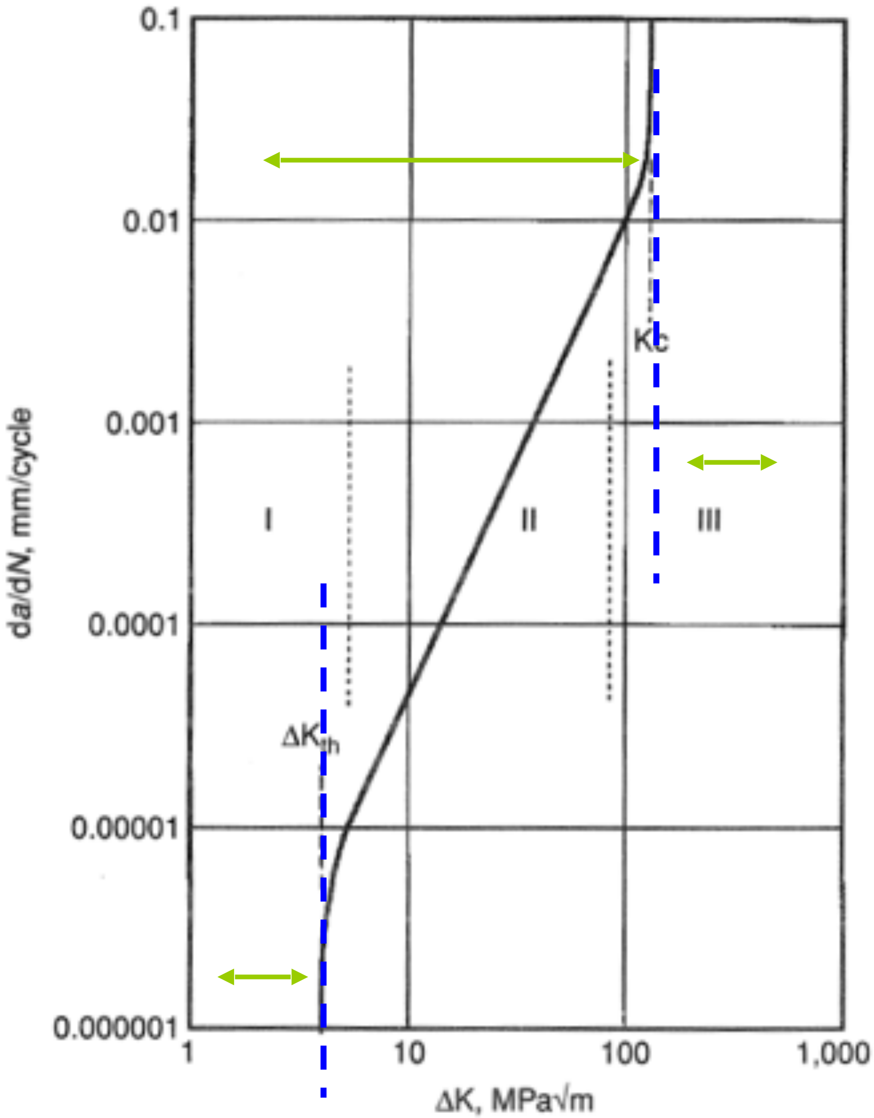
Fatigue growth rate, da/dN

$$\Delta S = S_{\max} - S_{\min} \qquad R = S_{\min} / S_{\max}$$

$$\Delta K_j = F \Delta S \sqrt{\pi a}$$

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

Fatigue Crack Growth

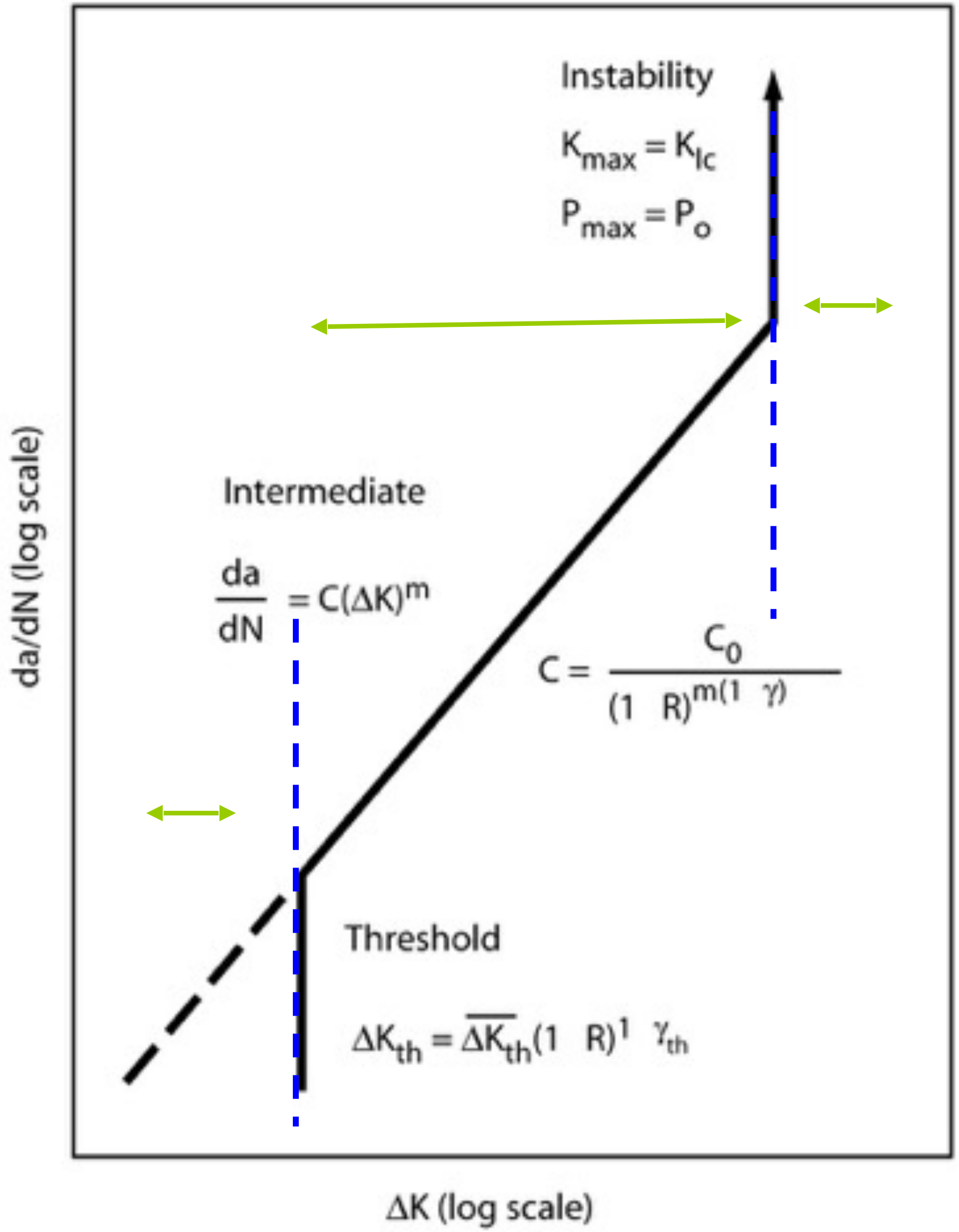


$$\frac{da}{dN} = C(\Delta K)^m$$

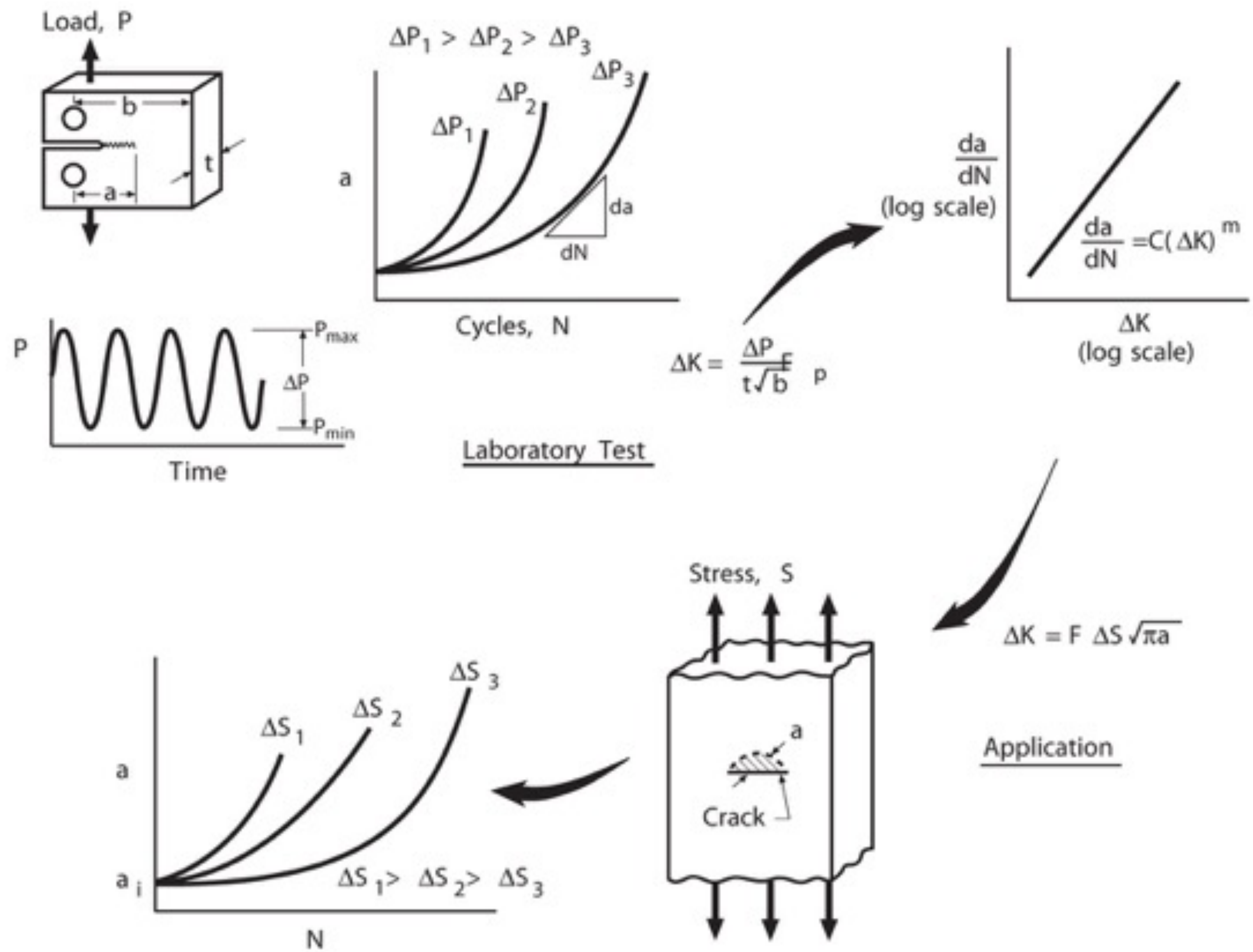
ΔK_{th} fatigue crack growth threshold

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

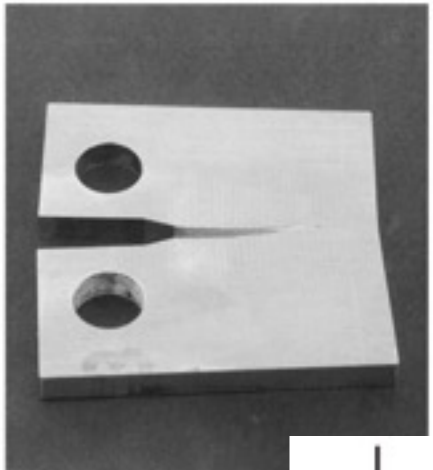
Fatigue Crack Growth



Determination for



Fatigue crack growth rate testing



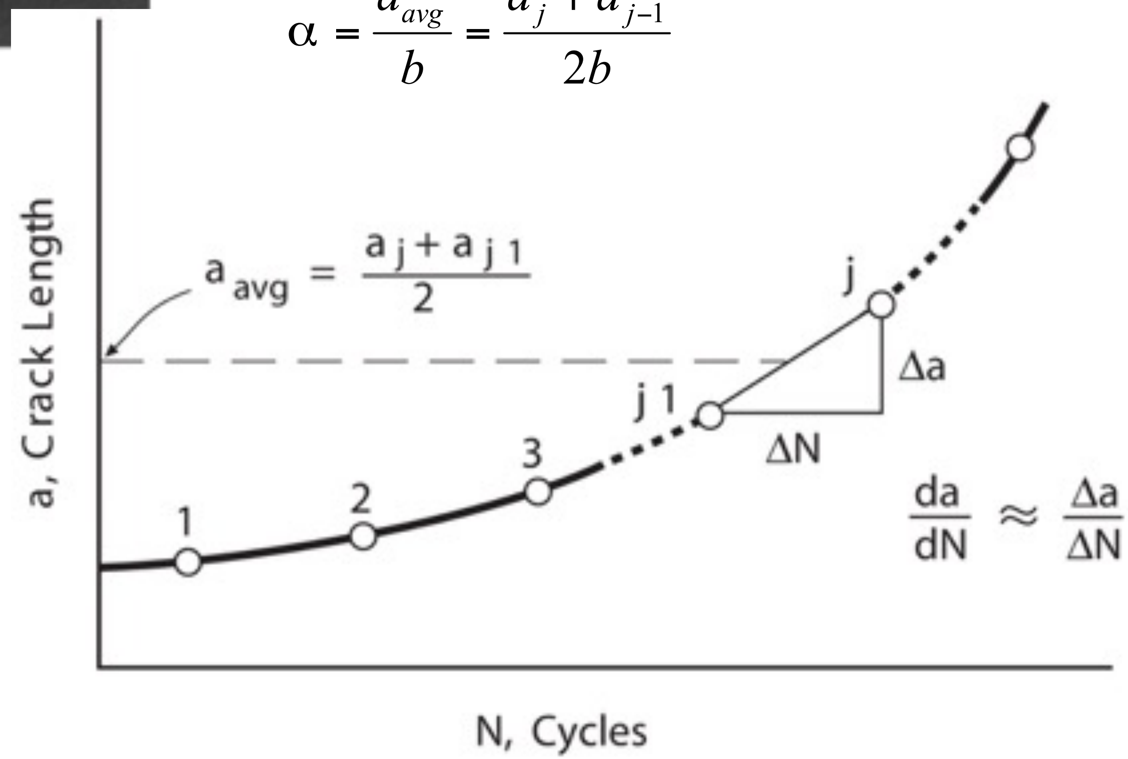
$$\left(\frac{da}{dN}\right)_j \approx \left(\frac{\Delta a}{\Delta N}\right)_j = \frac{a_j - a_{j-1}}{N_j - N_{j-1}}$$

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

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

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

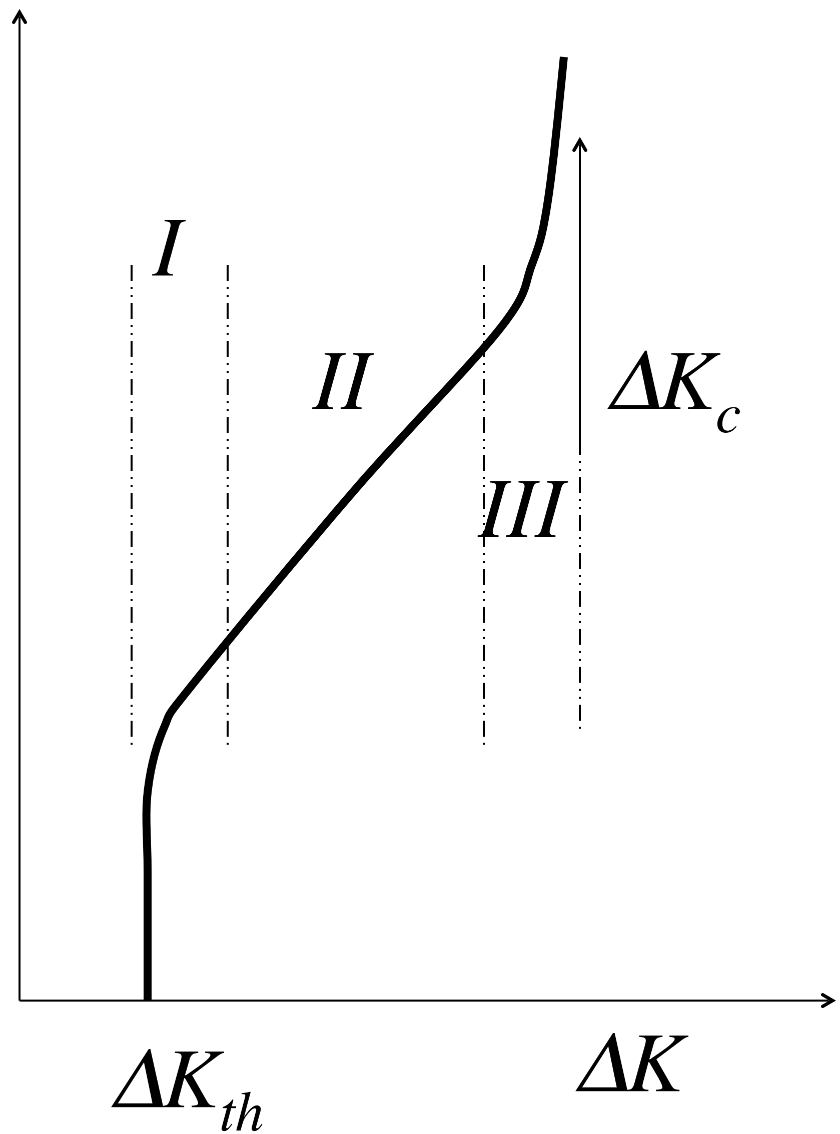
$$\Delta K_j = F_p(\alpha)\frac{\Delta P}{t\sqrt{b}}$$



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

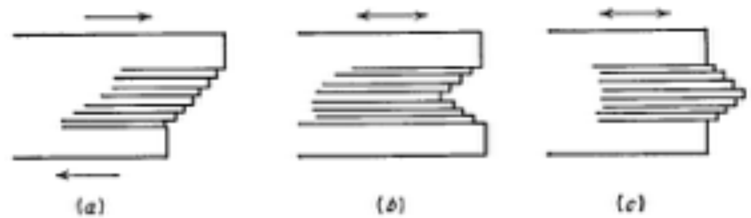


Figure 12-15 W. A. Wood's concept of microdeformation leading to formation of fatigue crack. (*a*) Static deformation; (*b*) fatigue deformation leading to surface notch (intrusion); (*c*) fatigue deformation leading to slip-band extrusion.

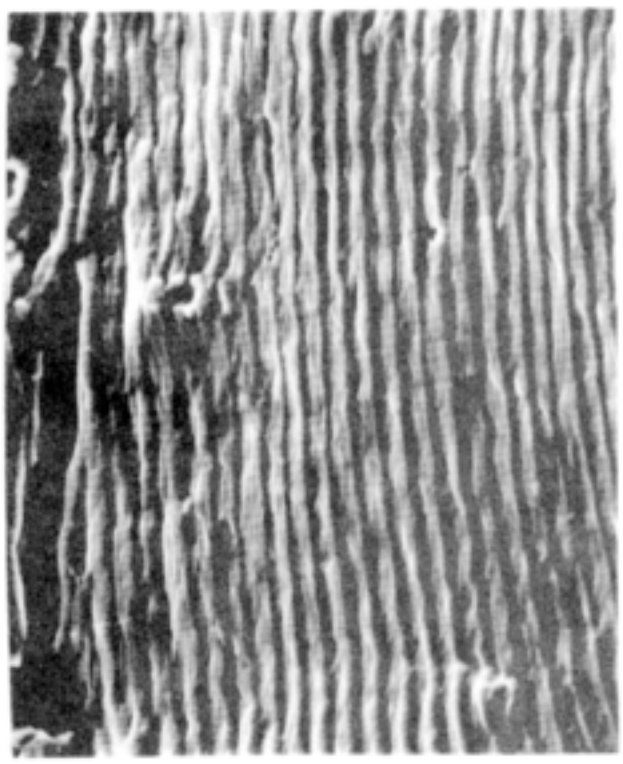


Figure 12-16 Fatigue striations in beta-annealed Ti-6Al-4V alloy (2000×). (*Courtesy of R. L. Bayles, Naval Research Laboratory.*)

Stage 2

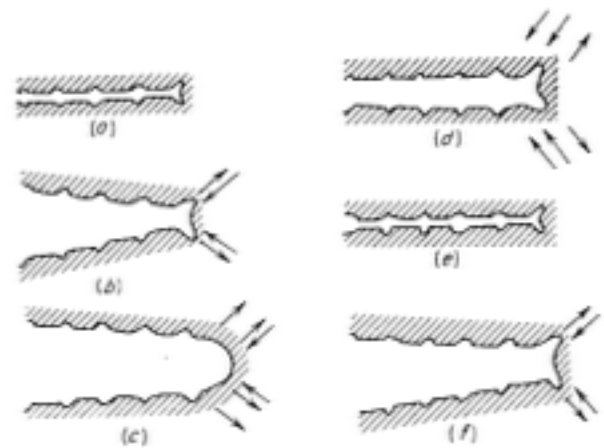
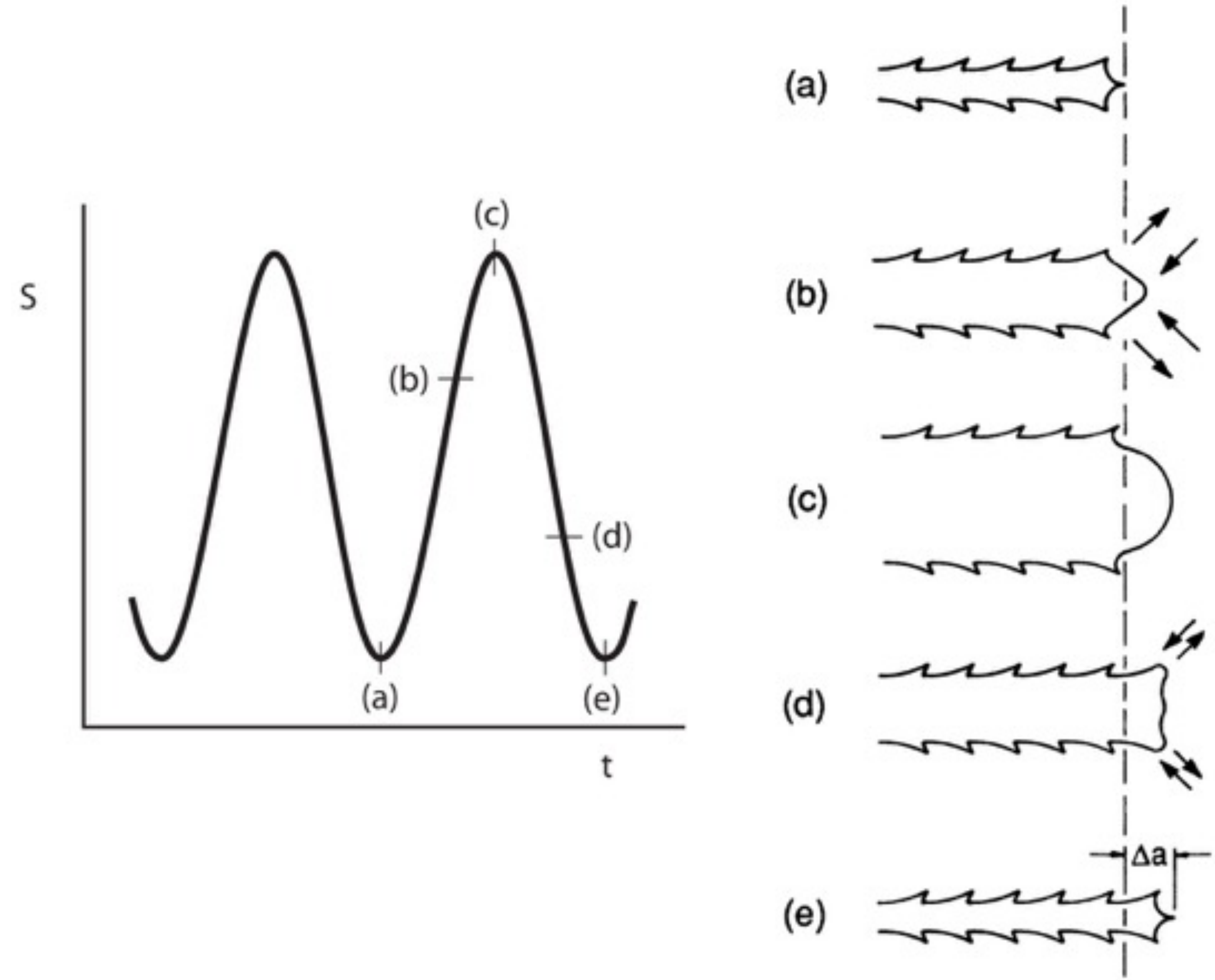


Figure 12-17 Plastic blunting process for growth of stage II fatigue crack. (*From C. Laird, ASTM Spec. Tech. Publ. 415, p. 136, 1967.*)

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.