Mechanical Behaviour of Materials

Chapter 04-4

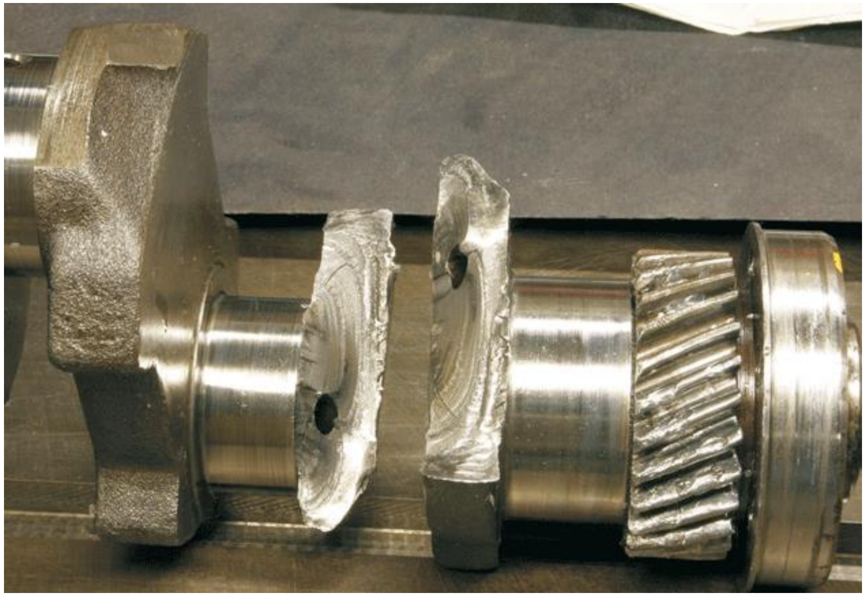
Fatigue

Dr.-Ing. 郭 瑞 昭

Content:

Introduction to fatigue
Fatigue resistance (S-N curve)
Fatigue crack growth rate
Micromechanism of fatigue

Cyclic loading examples

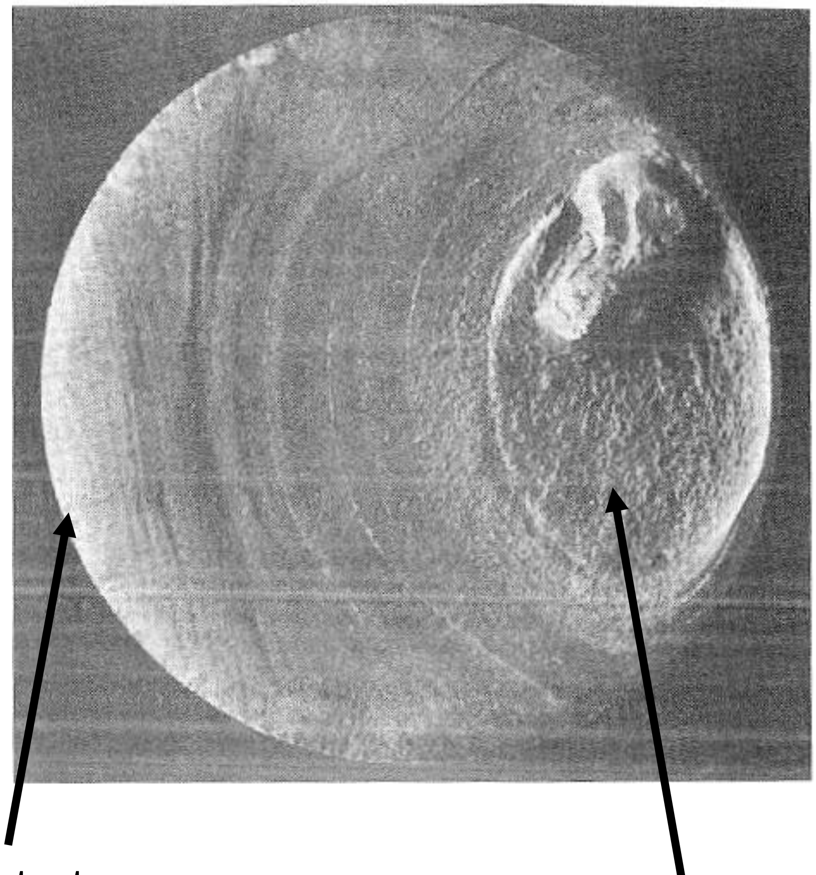


Crankshaft: Rotating shaft

Aircraft fuselage at takeoff and landing

Surface Fractography

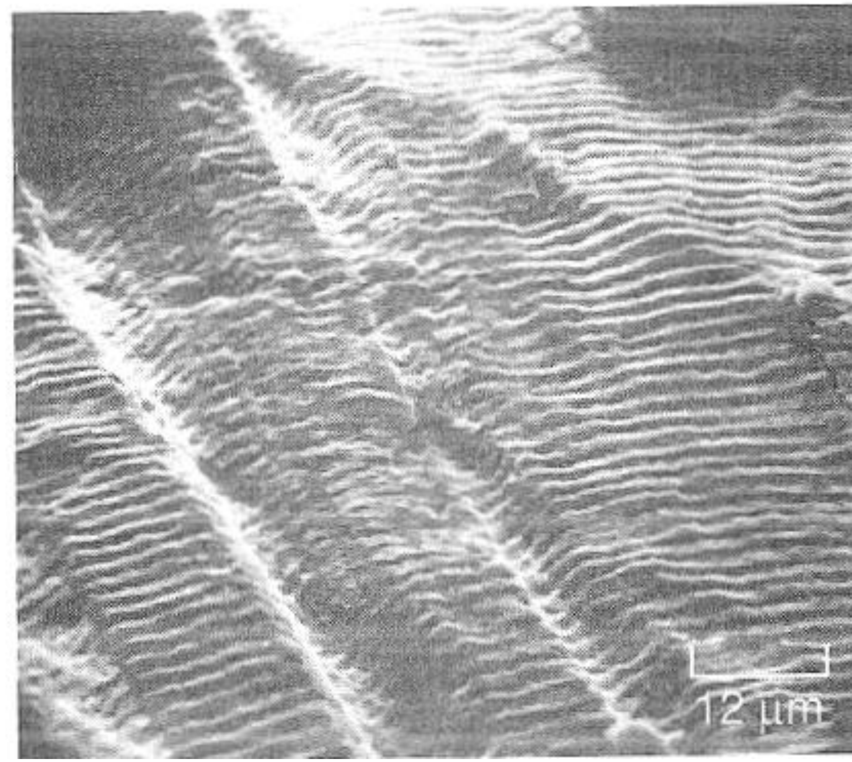
Typical clam shell markings



start

finish

Fatigue striations in 304 stainless steel



Courtesy of W.H. Durrant

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

Fatigue Phenomenon

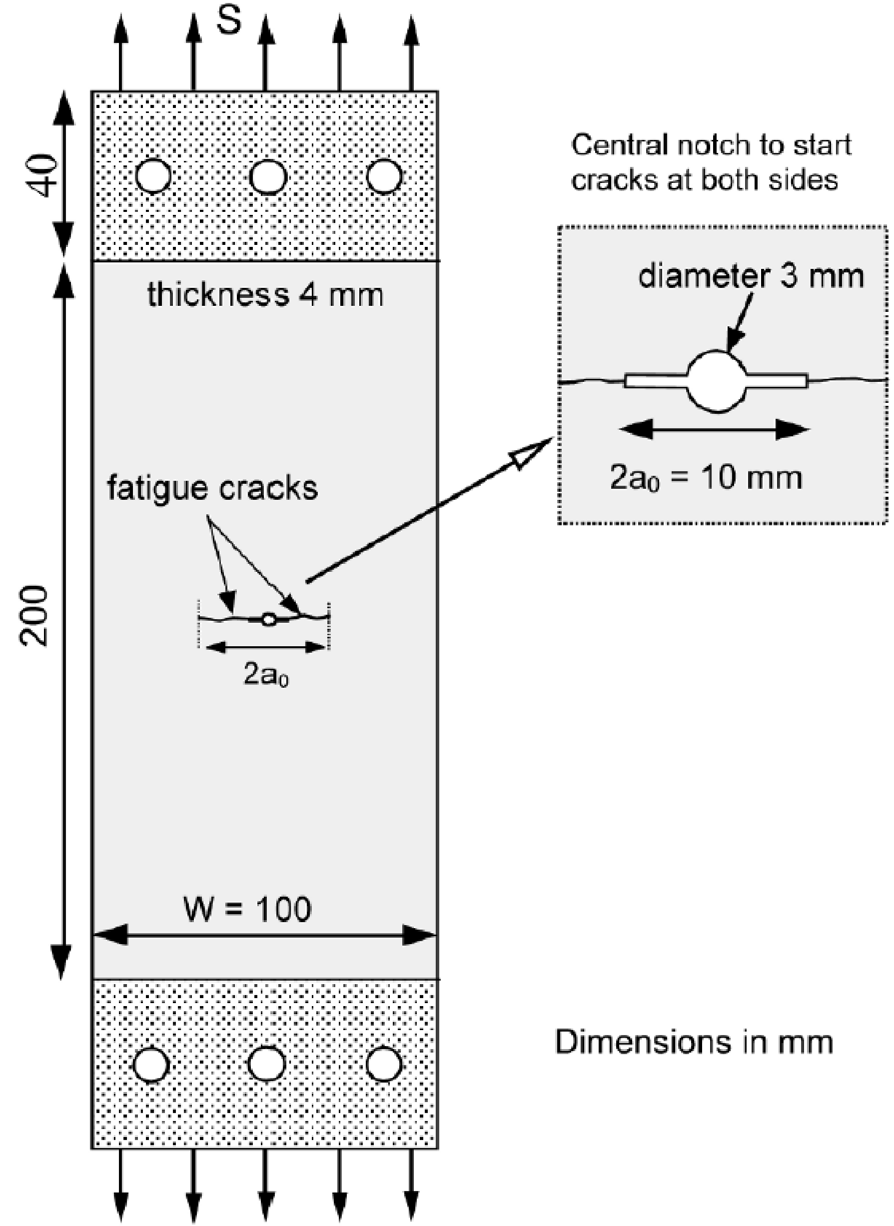
History of fatigue research

Fatigue failures in metallic structures are a well-known technical problem. In 1829 August Wöhler did the first laboratory investigations on fatigue. He recognized that a single load application, far below the static strength of a structure, did not do any damage to the structure. But if the same load was repeated many times it could induce a complete failure.

In a specimen subjected to a cyclic load, a fatigue crack nucleus can be initiated on a microscopically small scale, followed by crack grows to a macroscopic size, and finally to specimen failure in the last cycle of the fatigue life. Thus, the fatigue phenomenon will be considered in metallic materials, firstly occurring on a microscale and later on a macroscale.

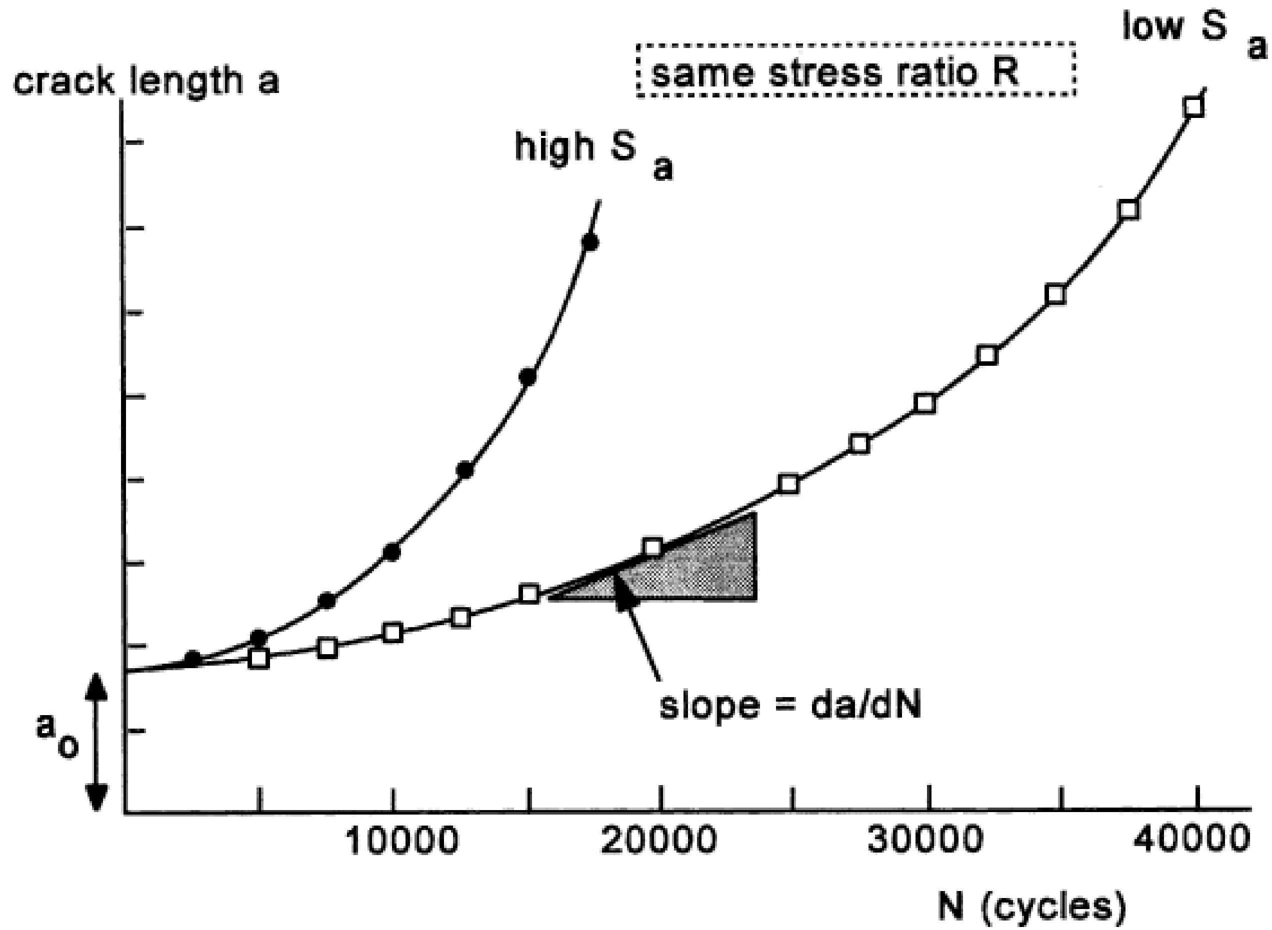
Crack propagation test

A crack propagation test can be carried out on a simple sheet or plate specimen with a central crack as shown in figure. The specimen is provided with a sharp central notch for rapid crack initiation. The crack starter notch in figure consists of a small hole with two saw cuts at both sides of the hole. Two fatigue cracks grow from either side of the starter notch.



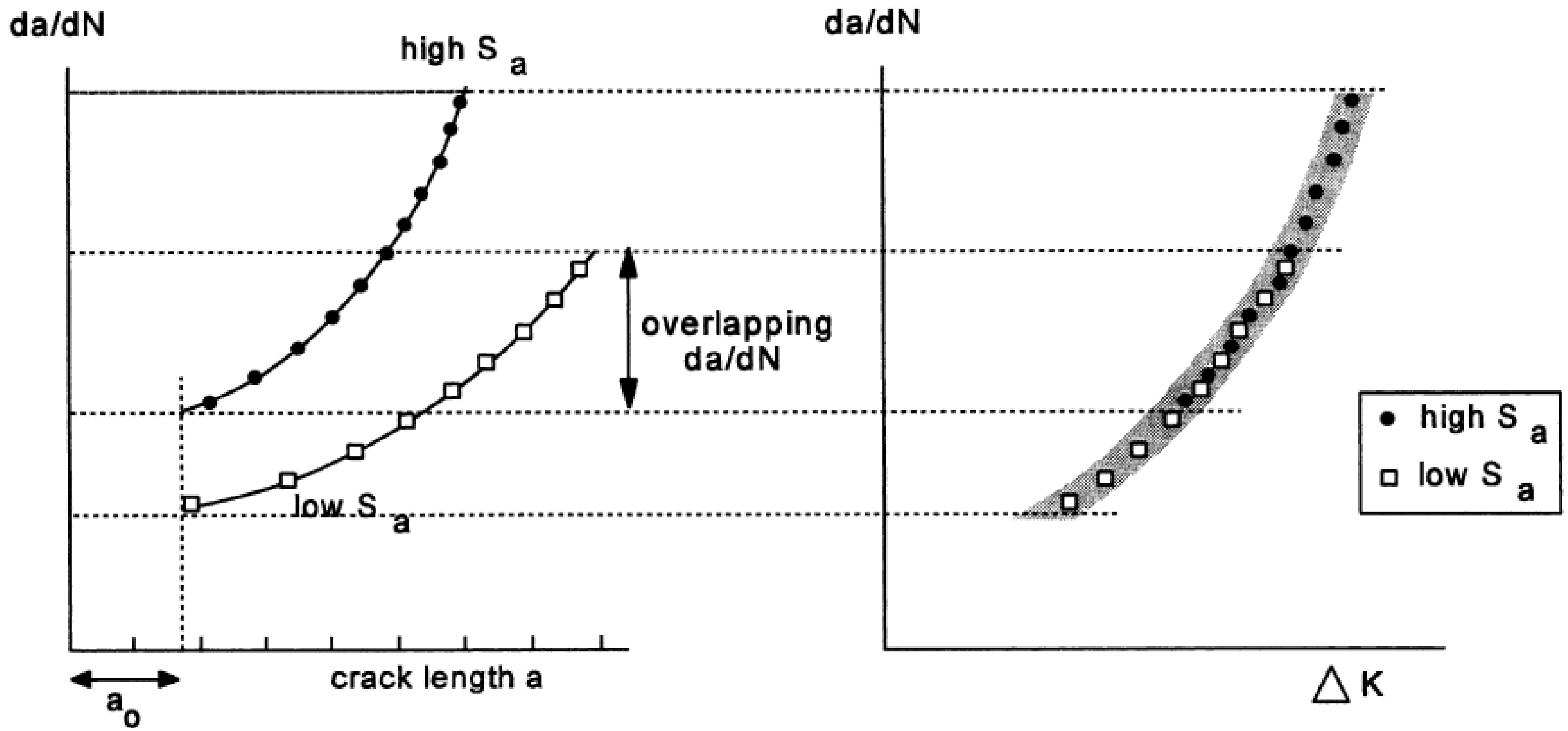
Fatigue crack growth curve

The most simple representation of crack growth records is a graph with the crack length data plotted as a function of the number of cycles, for a low and a high stress level. Both curves start at the same initial crack length, a_0.



Fatigue crack growth rate

The most simple representation of crack growth records is a graph with the crack length data plotted as a function of the number of cycles.



(b) da/dN-a (c) da/dN-ΔK

Concept of Derivation of Paris law for fatigue crack growth

Considering crack-propagation laws, in general, we treat cracks in infinite sheets subjected to a uniform stress perpendicular to the crack and relate the crack length ($2a$) to the number of cycles of load applied (N) with the stress range (σ) and material constants (C_i). Thus, the form in which all crack propagation laws may be given by

$$\frac{da}{dN} = f(a, \sigma, C_i)$$

Paris law for fatigue crack growth

Paris proposed a crack propagation theory at about the same time. It is based on the following argument: Irwin's stress-intensity-factor *K* reflects the effect of external load and configuration on the intensity of the whole stress field around a crack tip.

$$\frac{da}{dN} = f(K) = f(\sigma a^{1/2}) \qquad K = \sigma\sqrt{a}$$

The laws of Head, Frost and Dugdale, and Liu can all be approximated by the form

$$\frac{da}{dN} = C\sigma_a^n a^m \qquad n = m/2$$

General equation by Paris for fatigue crack growth

However, replotting these data on a log ΔK versus log (da/dN) graph reveals a linear relationship.

$$\frac{da}{dN} = C\sigma_a^n a^m \qquad \frac{da}{dN} = C(\Delta K)^m$$

ΔK_{th} fatigue crack growth threshold

$$K_{\max} = \sigma_{\max}\sqrt{a}$$

$$K_{\min} = \sigma_{\min}\sqrt{a}$$

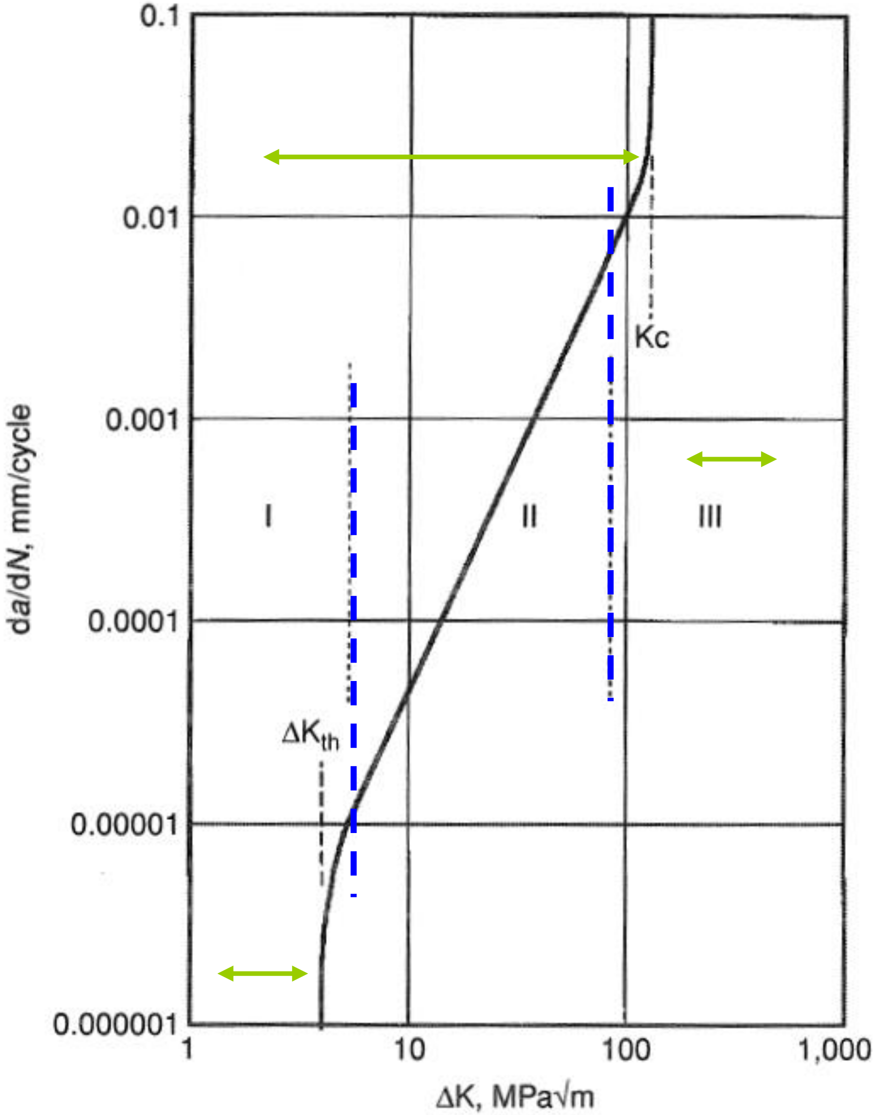
$$\Delta K = K_{\max} - K_{\min}$$

$$\Delta K = \Delta\sigma\sqrt{a}$$

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

Maximum stress intensity: K_{max}
Minimum stress intensity: K_{min}
Stress intensity range: ΔK
Stress ratio (R-ratio): K_{mim}/K_{max}

Paris law for fatigue crack growth



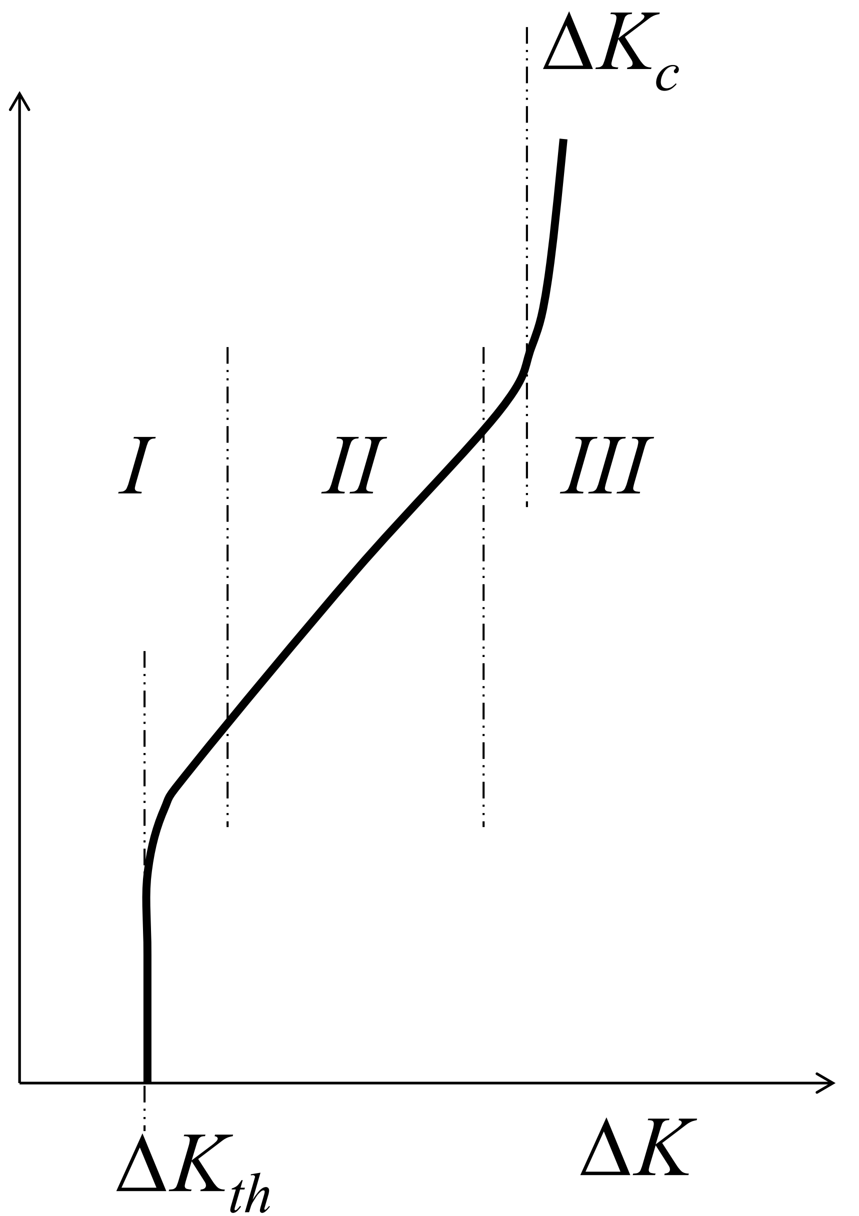
$$\frac{da}{dN} = C(\Delta K)^m$$

ΔK_{th} fatigue crack growth threshold

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

Fatigue crack growth

- 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 Mechanism

Prediction of fatigue life

Fatigue prediction methods can only be evaluated if fatigue is understood as a crack initiation process followed by a crack growth period.

The fatigue life is usually split into a **crack initiation** period and a **crack growth** period.

(i) The initiation period is supposed to include some micro-crack growth, but the fatigue cracks are still too small to be visible.

(ii) In the second period, the crack is growing until complete failure. It is technically significant to consider the crack initiation and crack growth periods separately because several practical conditions have a large influence on the crack initiation period.

Prediction of fatigue life-conti.

Two important conclusions:

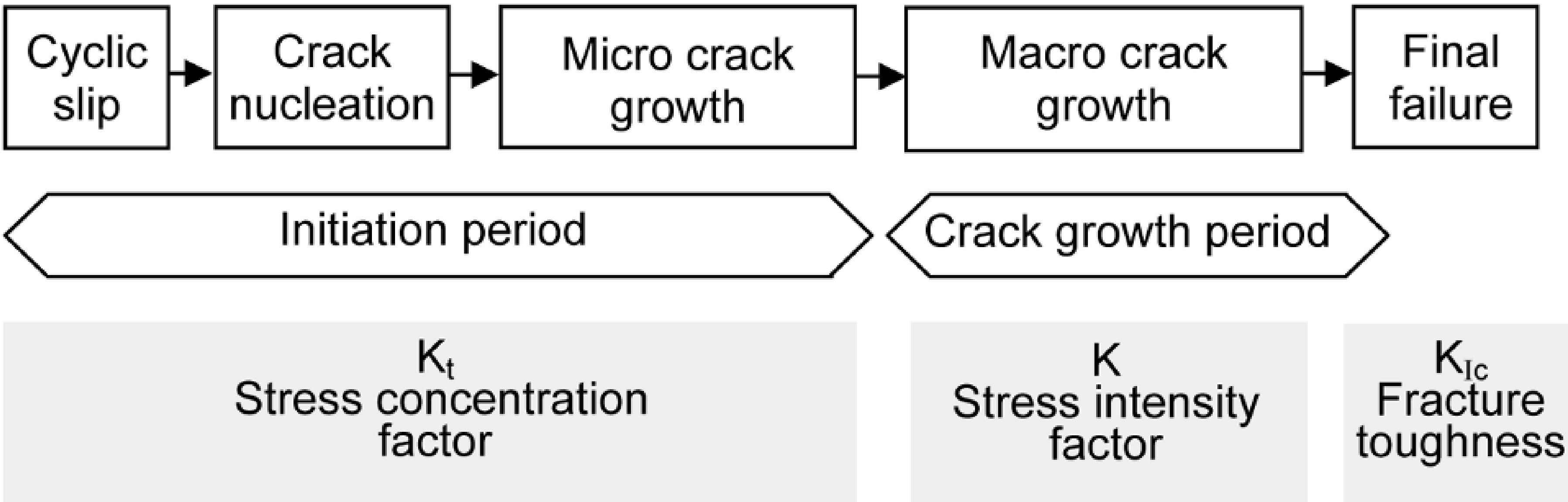
(i) In the crack initiation period, fatigue is a material surface phenomenon.

(ii) Crack growth resistance when the crack penetrates into the material depends on the material as a bulk property. Crack growth is no longer a surface phenomenon.

Different phases of the fatigue

Microscopic investigations in the beginning of the 20th century have shown that fatigue crack nuclei start as invisible microcracks in slip bands. In spite of early crack nucleation, microcracks remain invisible for a considerable part of the total fatigue life.
After a microcrack has been nucleated, crack growth can still be a slow and erratic process, due to effects of the microstructures, e.g. grain boundaries. However, after some microcrack growth has occurred away from the nucleation site, a more regular growth is observed. This is the beginning of the real crack growth period. Various steps in the fatigue life are indicated in the following figure.

Different phases of the fatigue



Fatigue Crack initiation

Fatigue crack initiation is due to cyclic slip, that is, cyclic plastic deformation, or in other words dislocation activities. Fatigue occurs at stress amplitudes below the yield stress. At such a low stress, plastic deformation is limited to a small number of grains of the material. This microplasticity preferably occurs at the free surface of grains because of the lower constraint on slip, and it is present at one side only.

Cyclic slip requires a cyclic shear stress, and on a microscale the shear stress is not homogeneously distributed. The shear stress on crystallographic slip planes differs from grain to grain, depending on the size and shape of the grains, crystallographic orientation of the grains, and elastic anisotropy of the material.

Fatigue Crack initiation-conti.

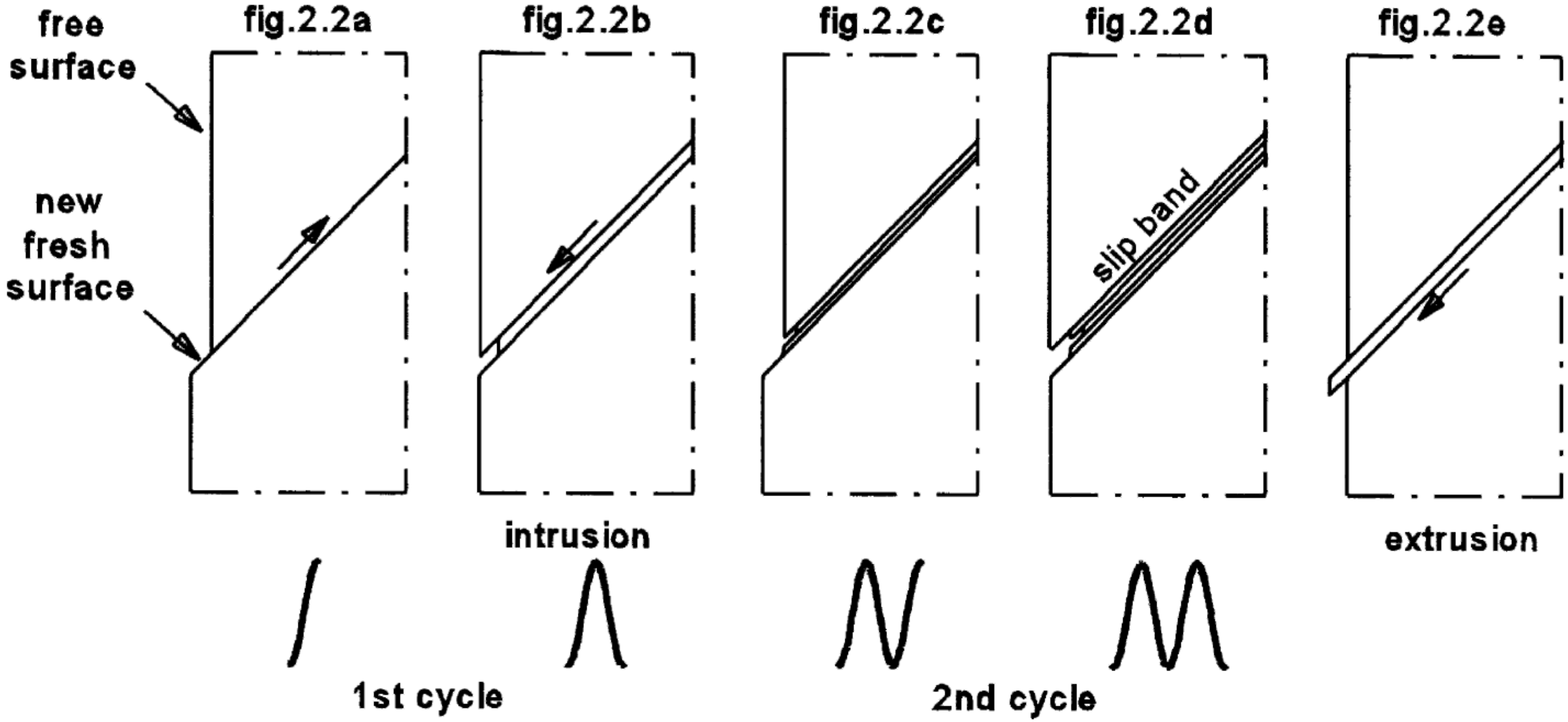
Figure 2.2(a): If slip occurs in a grain, a slip step will be created at the free surface, that is, a rim of new material will be exposed to the environment.

Figure 2.2(b): During the increase of the load, strain hardening, a larger shear stress will be needed on the same slip band in the reversed direction. Reversed slip will thus preferably occur in the same slip band on adjacent parallel slip planes. Here a microscopical intrusion is a microcrack.

Figures 2.2(c) and (d): The same sequence of events can occur in the second cycle.

Figure 2.2(e): The small shift of the slip planes during loading and unloading results in an intrusion. However, an extrusion is obtained, if the reversed slip would occur at the lower side of the slip band.

Fatigue Crack initiation-conti.

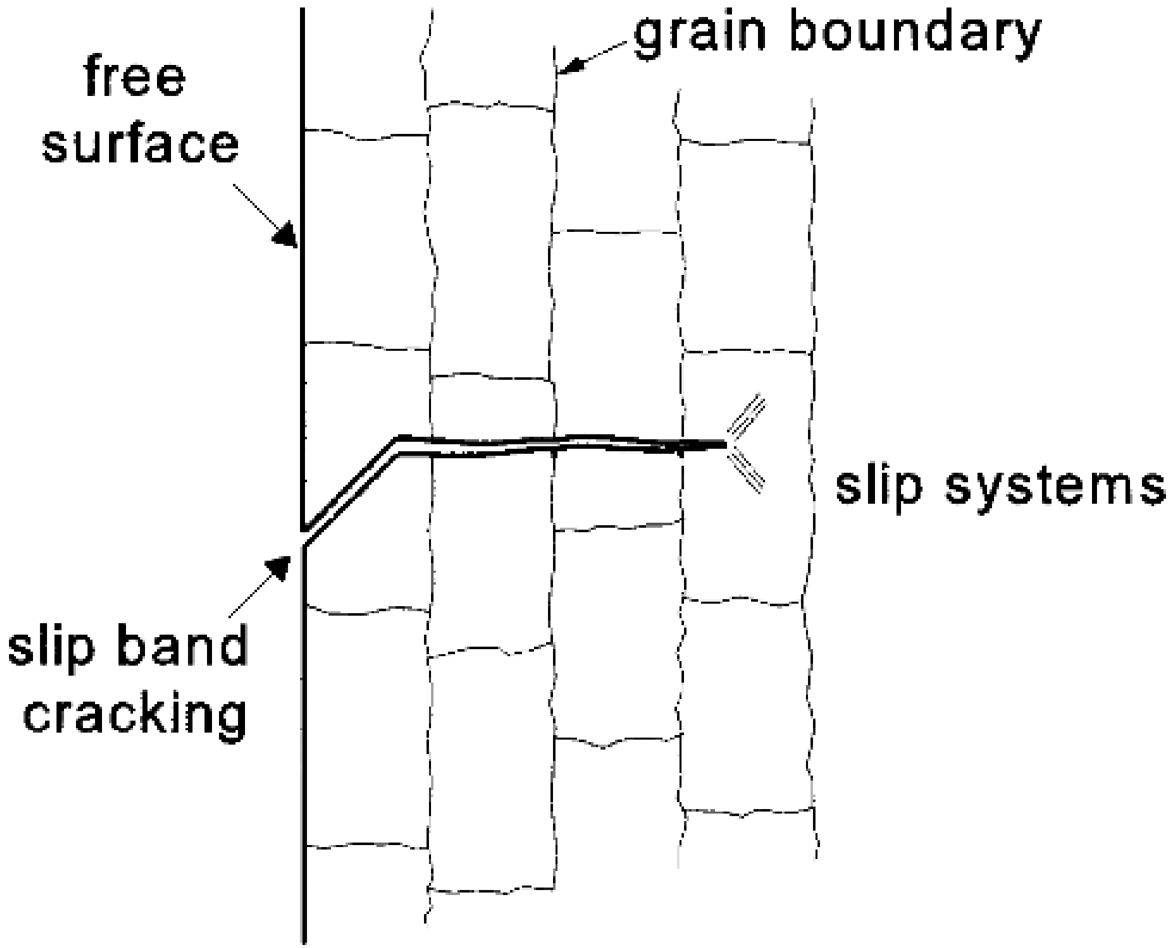


Fatigue Crack growth

As long as the size of the microcrack is still in the order of a single grain, the microcrack is obviously present in an elastically anisotropic material with a crystalline structure and a number of different slip systems. The microcrack contributes to a **stress concentration** at the tip of the microcrack on a microlevel.

Moreover, the constraint of the neighbouring grains will lead more slip systems activated. Thus, the microcrack growth direction will then deviate from the initial slip band direction. In general, there is a tendency to grow perpendicular to the loading direction in the following figure.

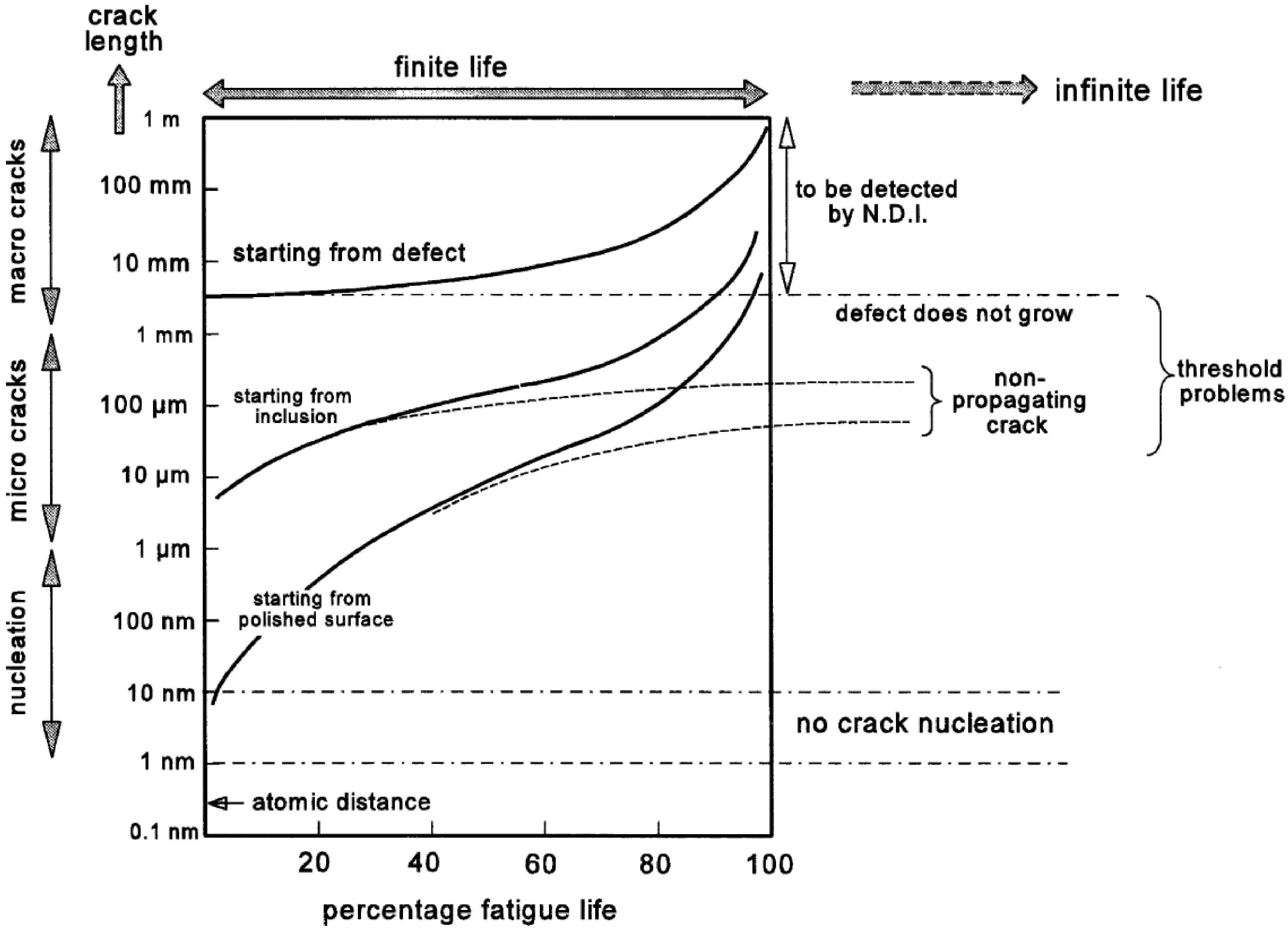
Cross section of microcrack



Transition from initiation period to crack growth

The transition from the initiation period to the crack growth period has not yet been defined. In a qualitative way the following definition will be used:
"The initiation period is supposed to be completed when microcrack growth is no longer depending on the material surface conditions."

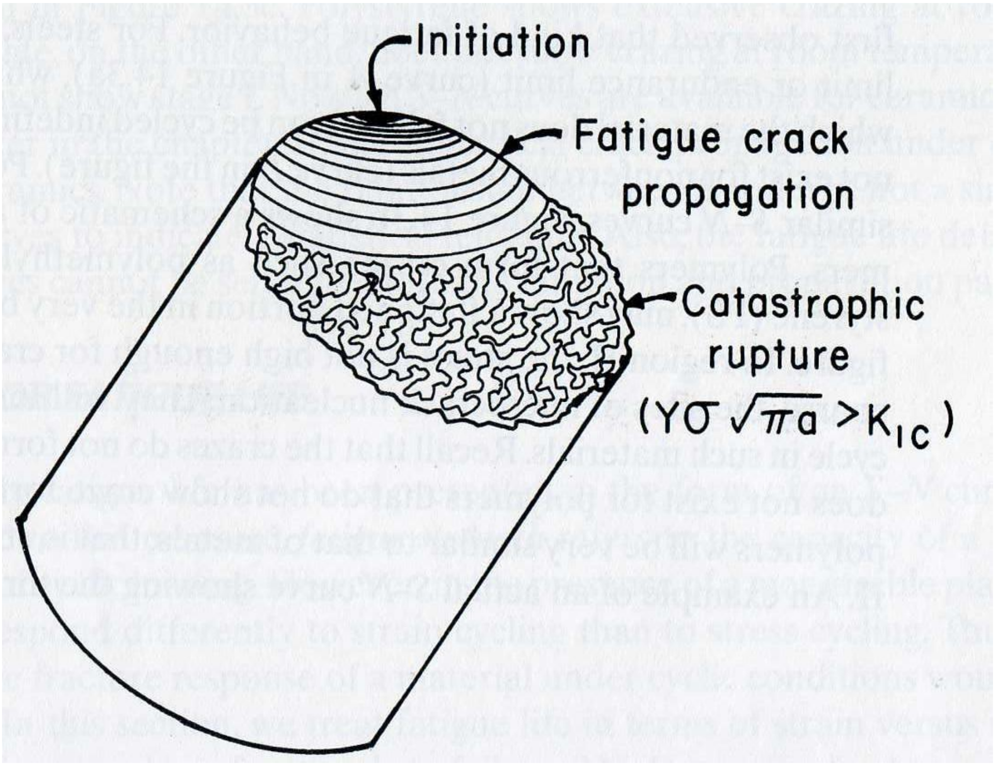
Microcracks starting from a perfect free surface can have a sub-micron crack length (<1 μm). However, cracks nucleated at an inclusion will start with a size similar to the size of the inclusion. The size can still be in the sub-millimeter range. Only cracks starting from macrodefects can have a detectable macrocrack length immediately. A crack size below 1 mm is practically invisible (or undectable).



crack
length
finite life
infinite life
1 m
100 mm
10 mm
1 mm
100 µm
10 µm
1 µm
100 nm
10 nm
1 nm
0.1 nm
macro cracks
micro cracks
nucleation
starting from defect
starting from
inclusion
starting from
polished surface
to be detected
by N.D.I.
defect does not grow
non-
propagating
crack
threshold
problems
no crack nucleation
atomic distance
20
40
60
80
100
percentage fatigue life

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

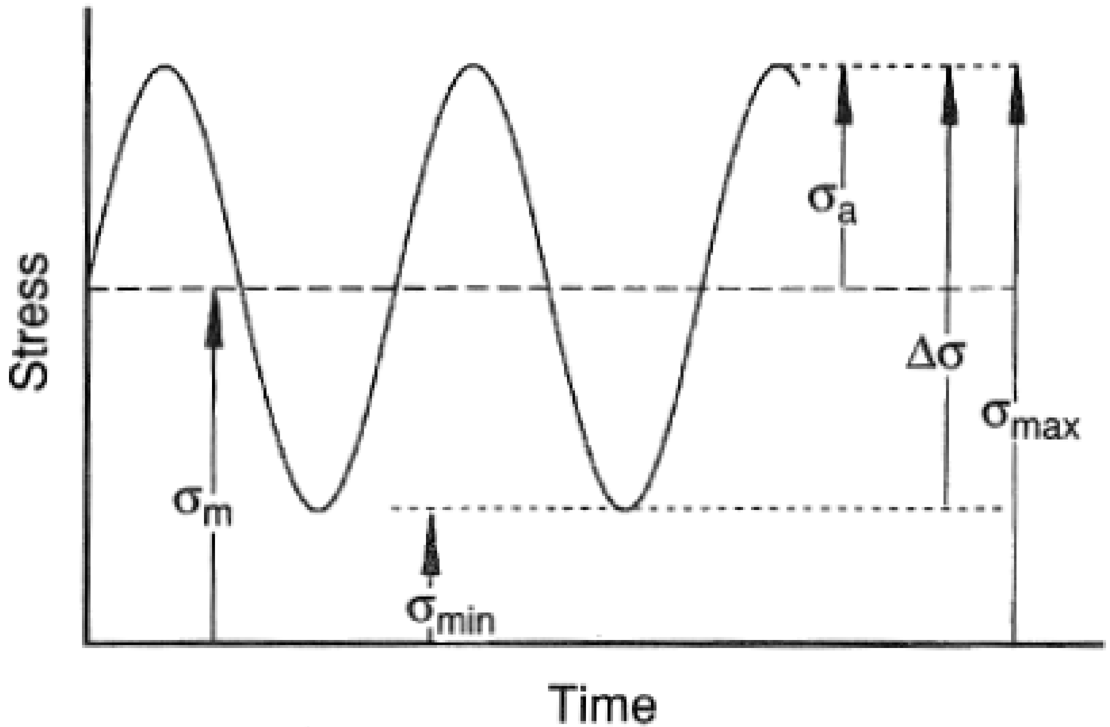


It is estimated that 90% of service failures of metallic components that undergo movement of one form or another can be attributed to fatigue.

Fatigue test

Nomenclature of cyclic stress-controlled fatigue

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



cyclic stress range

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

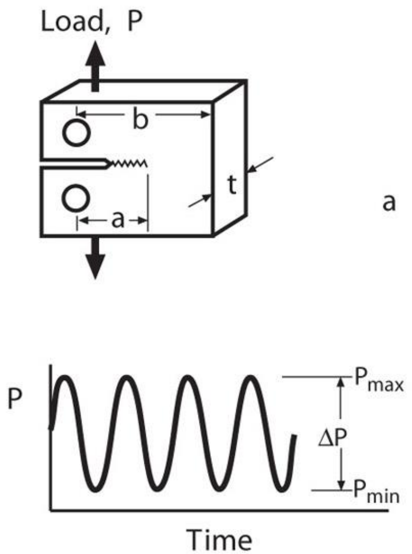
Mean stress

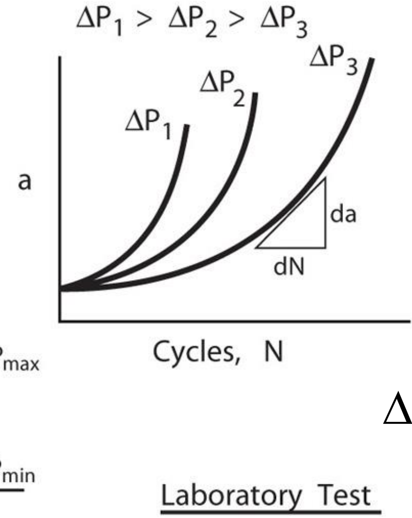
$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2}$$

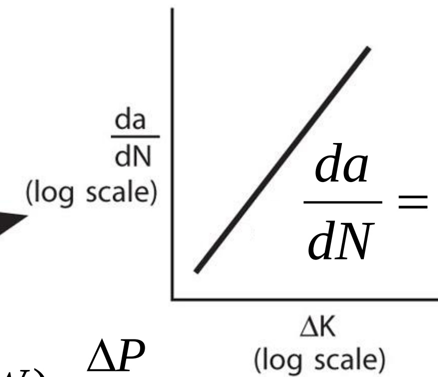
Stress ratio

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

Fatigue-crack growth rate

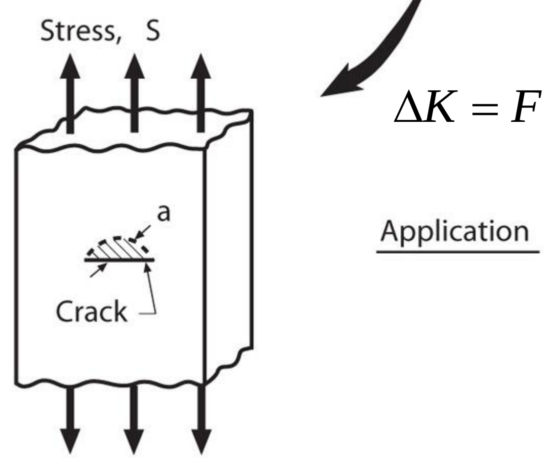






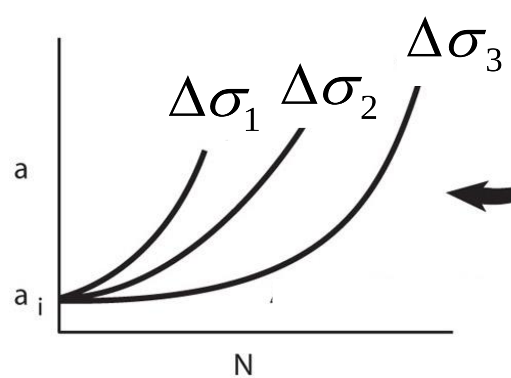
$$\frac{da}{dN} = C\left(\Delta K\right)^m$$

$$\Delta K = F(a/W)\frac{\Delta P}{B\sqrt{W}}$$

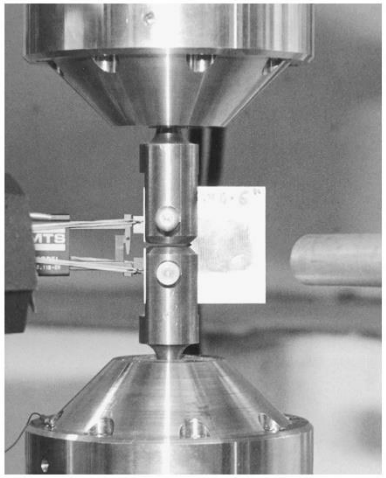


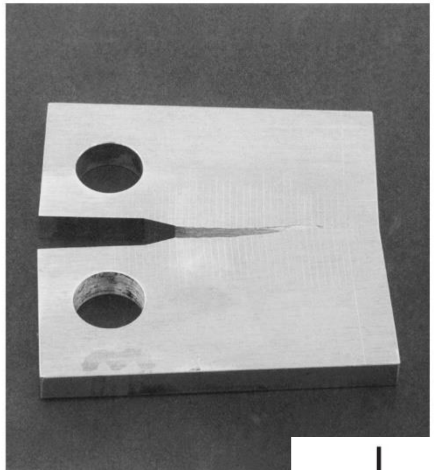
$$\Delta K = F(a/W)\Delta\sigma\sqrt{\pi a}$$

$$\Delta\sigma_1 > \Delta\sigma_2 > \Delta\sigma_3$$



Fatigue crack growth rate testing





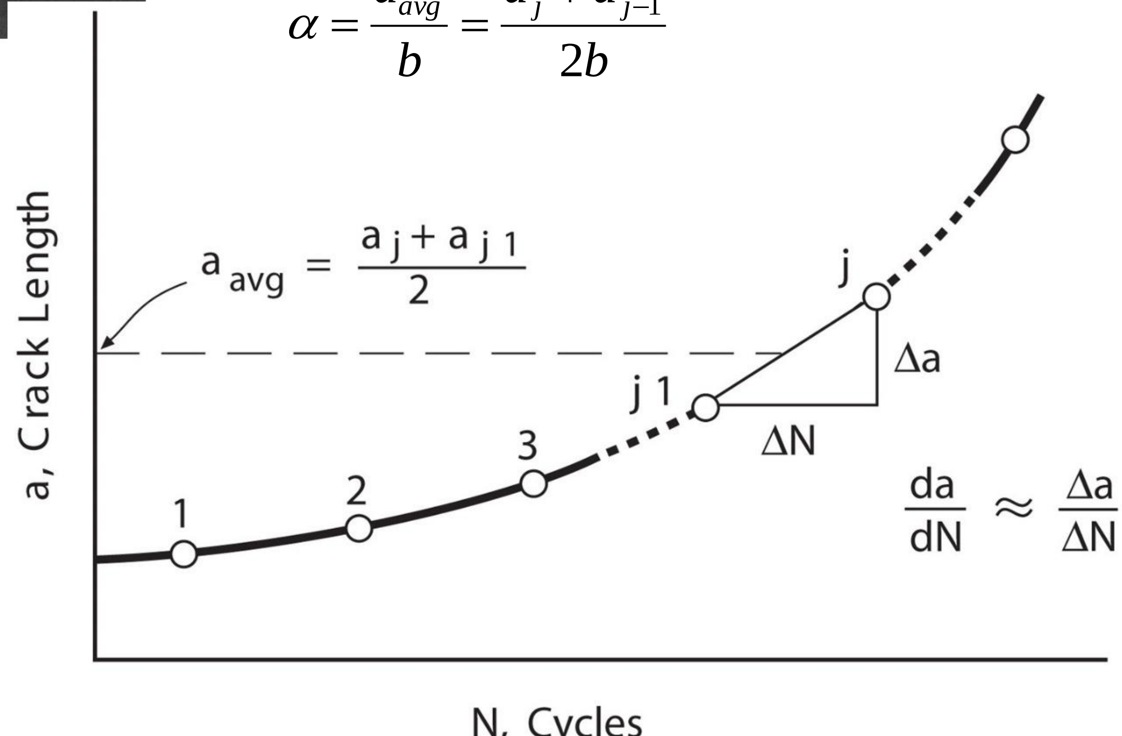
$$\left(\frac{da}{dN}\right)_j \approx \left(\frac{\Delta a}{\Delta N}\right)_j = \frac{a_j - a_{j-1}}{N_j - N_{j-1}}$$

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

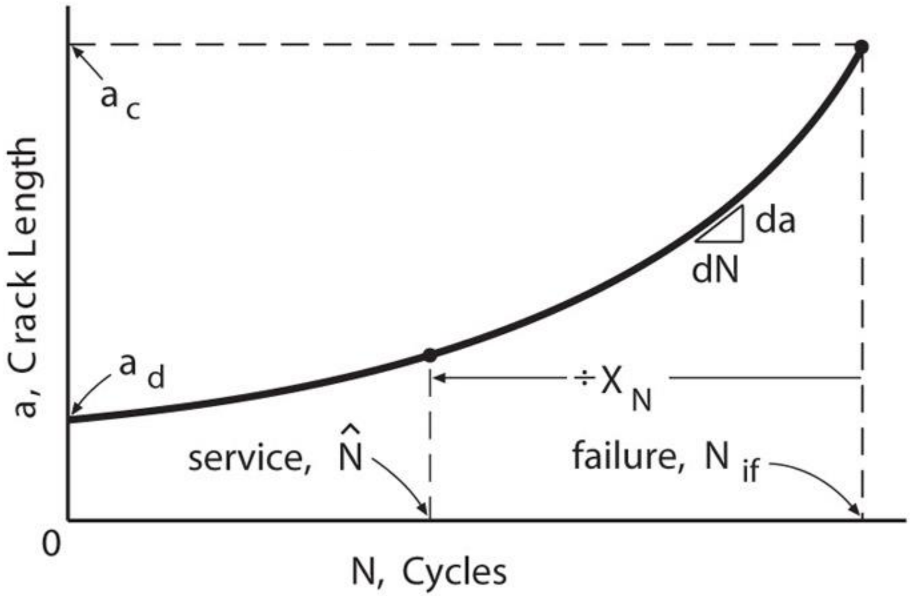
$$\alpha = \frac{a_{avg}}{b} = \frac{a_j + a_{j-1}}{2b}$$

$$K = F(a/W)\frac{P}{B\sqrt{W}}$$

$$\Delta K = F(a/W)\Delta\sigma\sqrt{\pi a}$$



Determination for Fatigue Crack Growth



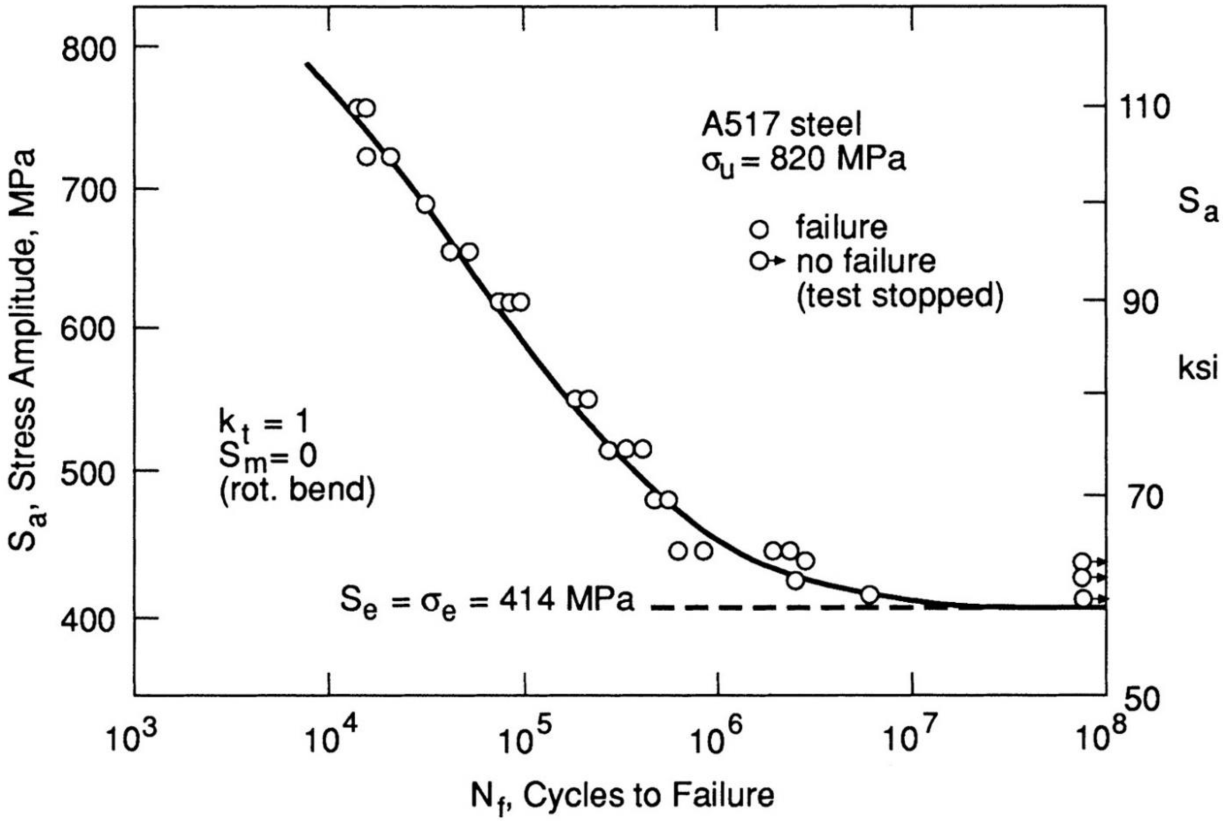
Fatigue growth rate, da/dN

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

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

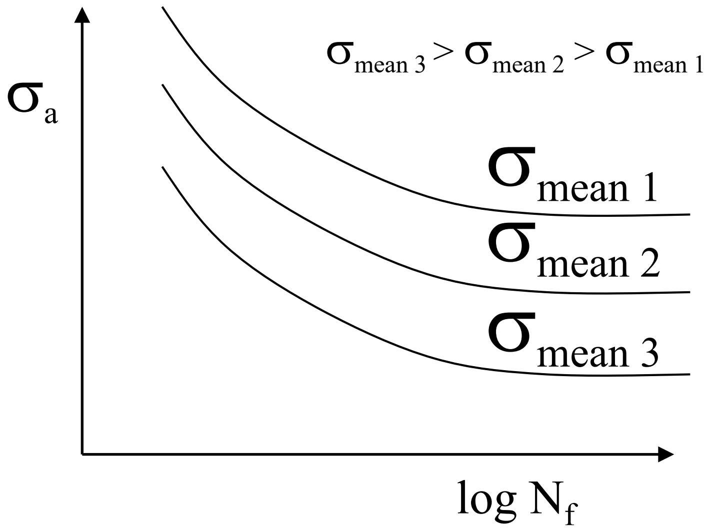
$$\Delta K = K_{max} - K_{min}$$

S-N curve: Fatigue resistance



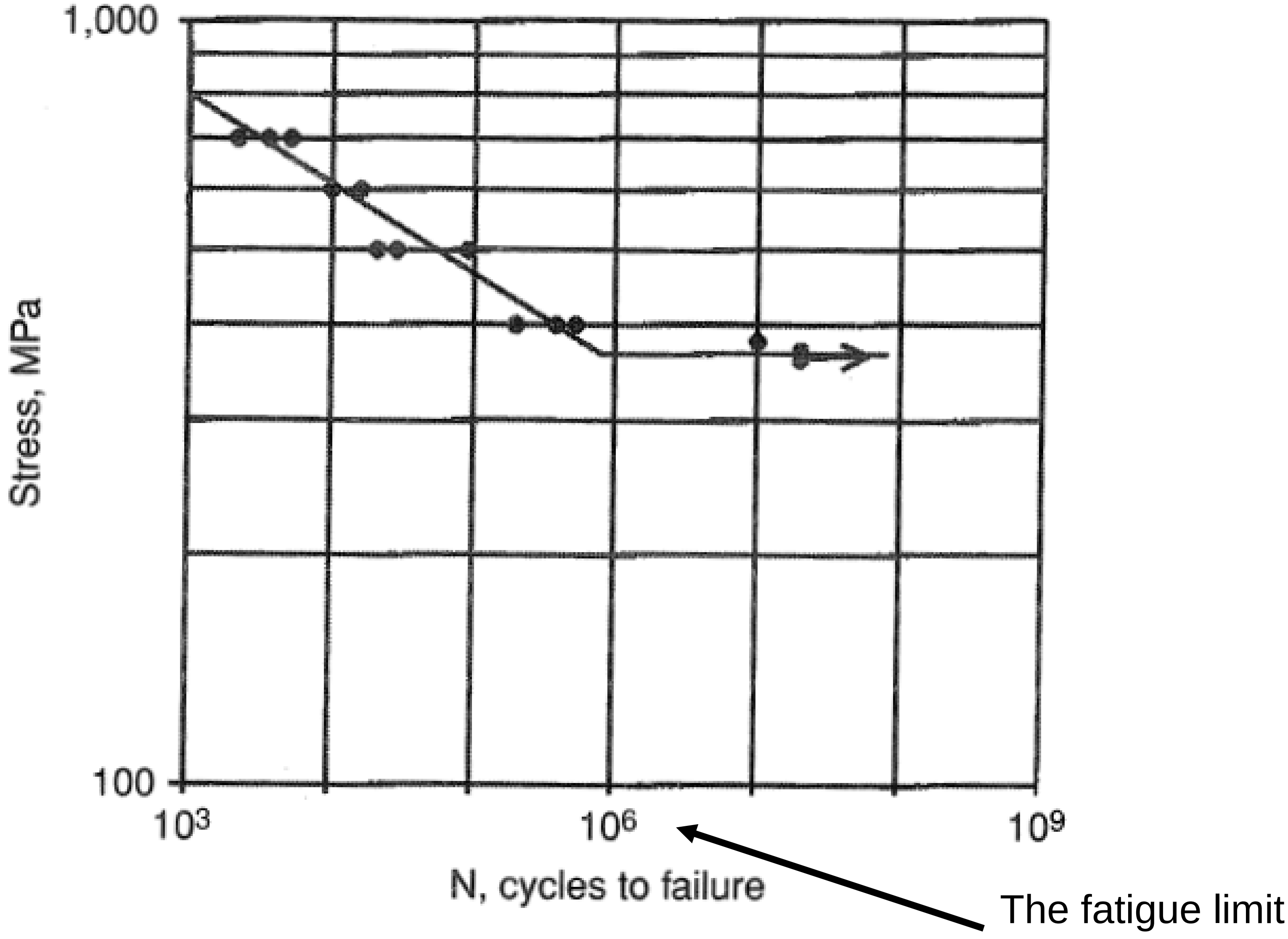
- Traditionally, the behavior of a material under fatigue is described by the S-N (σ-N) curves, where S (σ) is the stress and N is the number of cycles to failure. The S-N –curve is called a Woehler curve.

Effect of mean stress on fatigue life



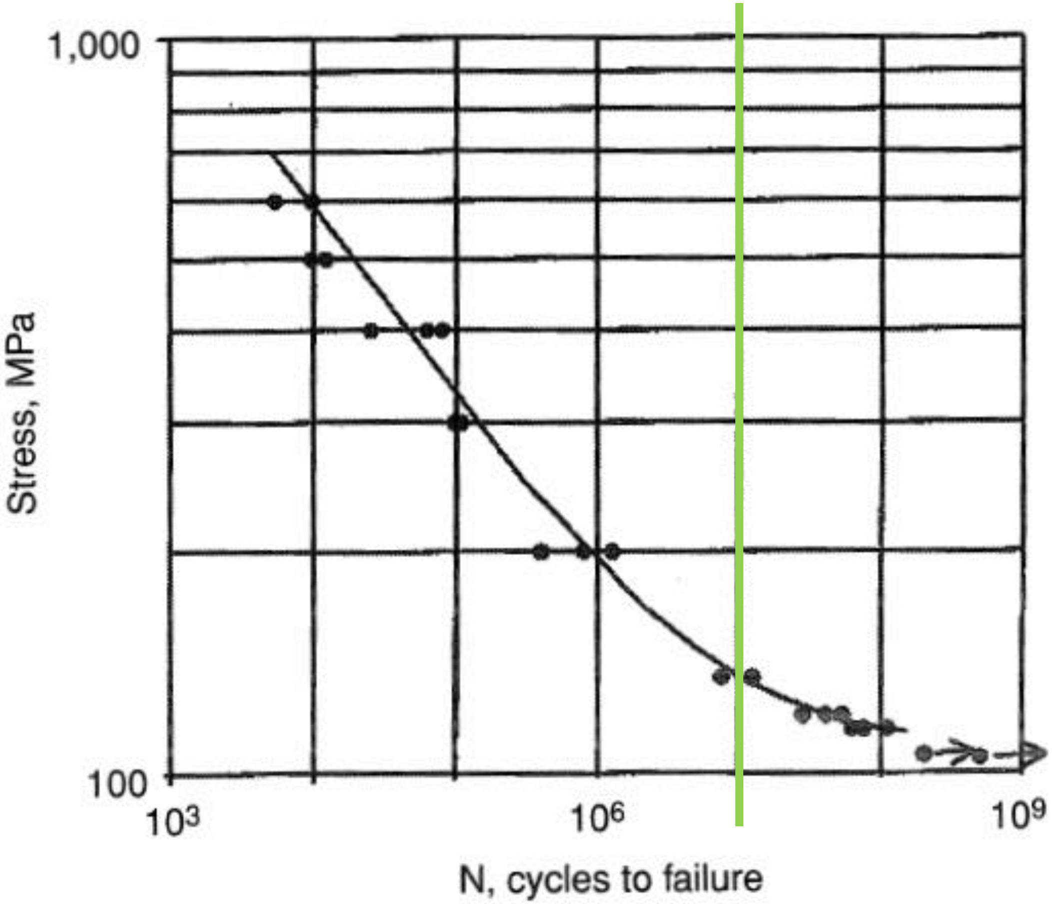
The greater the number of cycles in the loading history, the smaller the stress that the material can withstand without failure.

Example of S-N curve for annealed 4340 steel



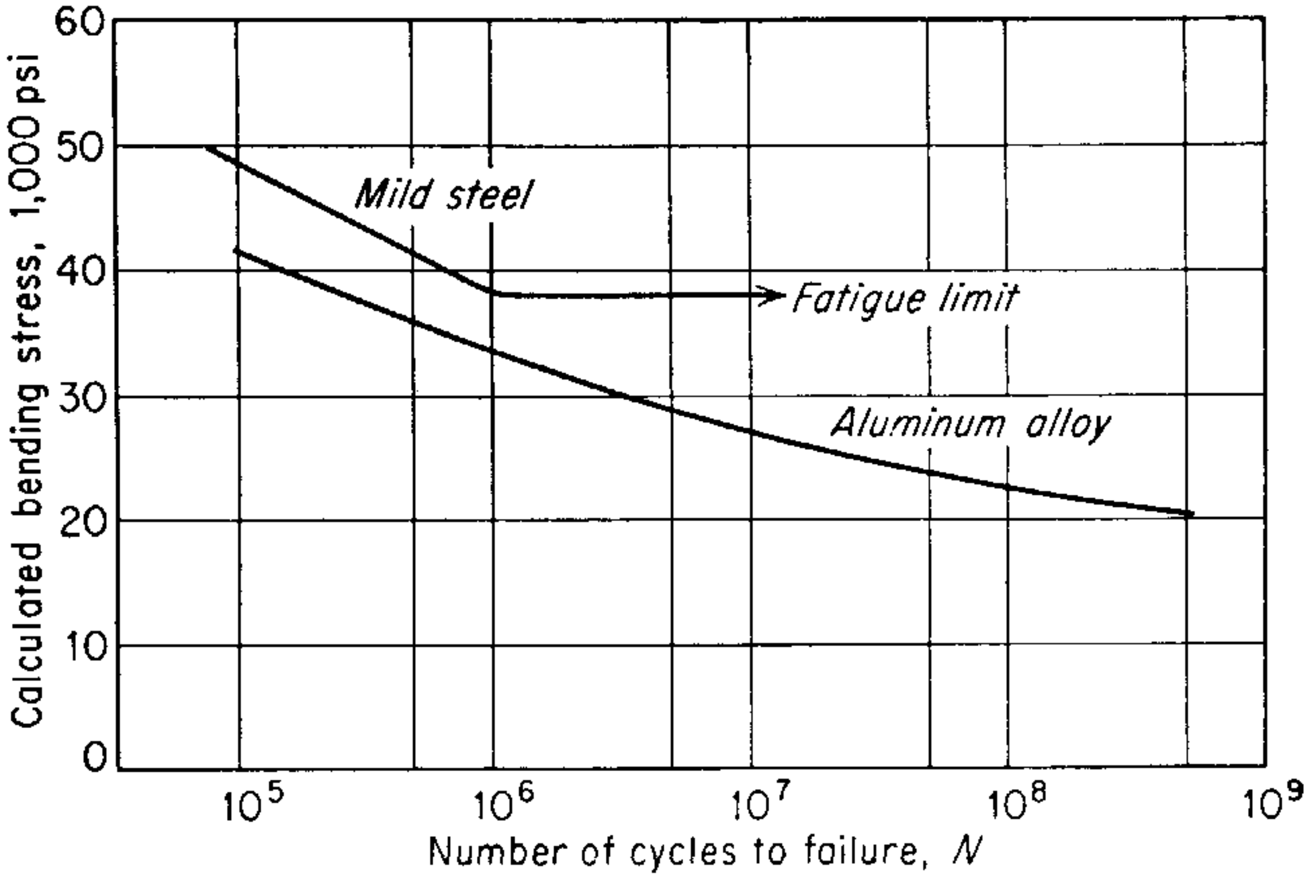
Example of S-N curve for Al alloy 7075 T6

$N_f=10^7$



No true fatigue limit

S-N curve between steels and aluminum alloys



[Dieter]