

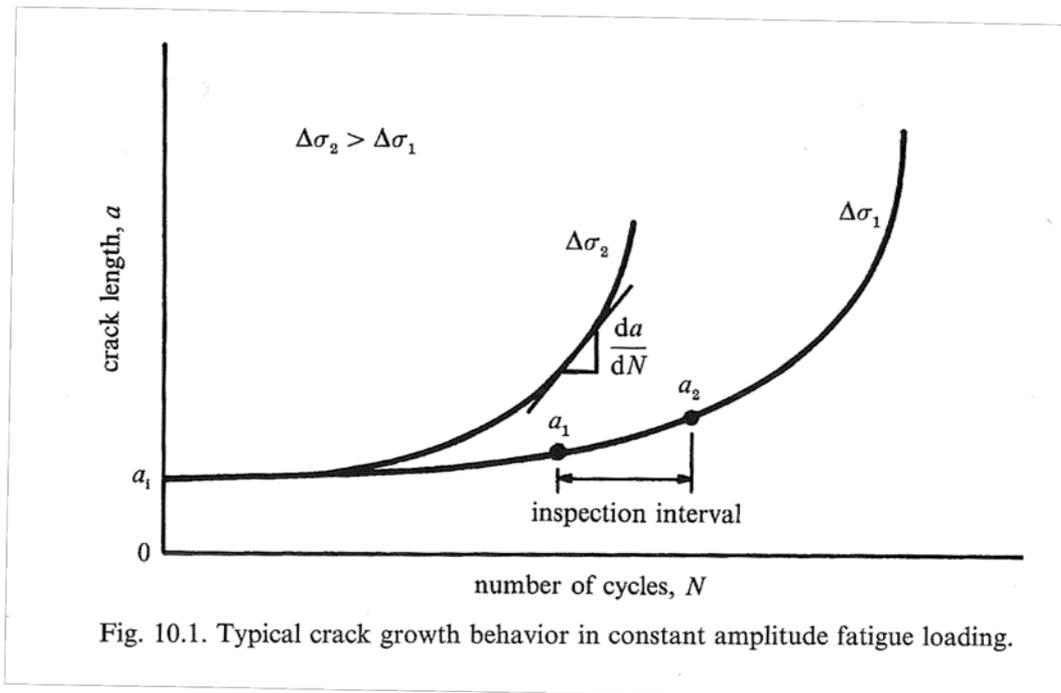
Chapter 10 Fatigue crack growth in ductile solids

- As discussed in earlier chapter the total life consists of both crack initiation and crack propagation. Modern defect-tolerant approaches are based on the premise that the structure is inherently flawed. The useful fatigue life is the number of cycles to propagate the dominant flaw to a critical dimension.
- In this chapter mechanics and micromechanics of stable crack propagation for ductile solids subjected to cyclic loads of fixed amplitude. In this chapter the cracks are assumed to be ‘long’ cracks, typically several mm long, for which the growth rate is independent of crack length.



Chapter 10.1 Characterization of crack growth

- The growth rate of a fatigue crack subjected to a constant amplitude is expressed in terms of crack length increment per cycle, da/dN .
- When the applied stress range, $\Delta\sigma$, is constant, da/dN generally increases with number of fatigue cycles.



Chapter 10.1 Characterization of crack growth (2)

- Important to be able to in a reliable way calculate the crack growth rate. When the applied load is so small that the plastic zone ahead of the crack is small, linear elastic fracture mechanics (LEFM) gives a appropriate continuum description for fatigue fracture.
- Paris, Gomez and Andersson suggested a empirical equation linking where fatigue crack growth rate is based on stress intensity range, $\Delta K = K_{max} - K_{min}$ (Paris law).

$$\frac{da}{dN} = C(\Delta K)^m, \quad m=2-4 \text{ for ductile metals}$$

- C and m are scaling constants. Depends on microstructure, environment, temperature and load ratio, R .

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



Chapter 10.1 Characterization of crack growth (3)

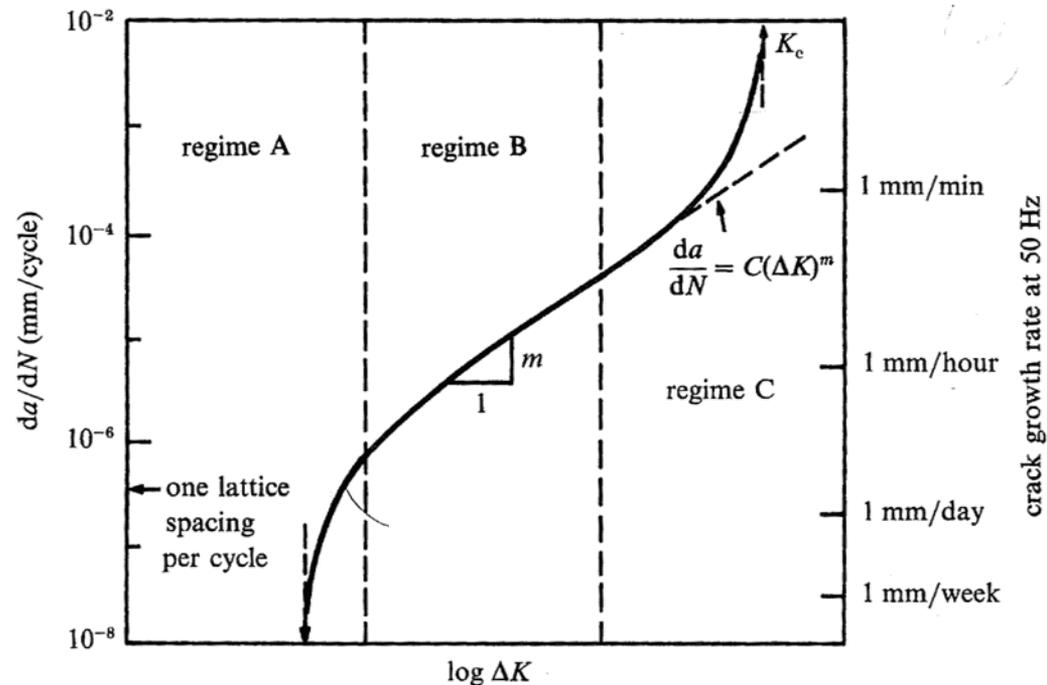


Fig. 10.8. Schematic illustration of the different regimes of stable fatigue crack propagation.



Chapter 10.1 Characterization of crack growth (2)

- Stable crack growth occurs at stress intensity levels K_{max} well below the quasi static fracture toughness K_{Ic} . Can be as low as 1/100 of K_{Ic} for very ductile metallic materials.
- The estimated remaining fatigue life can easily be calculated by integrating Paris law if the initial and critical crack lengths are known.



Chapter 10.2 Microscopic stages of fatigue crack growth

- The microscopic mode of fatigue crack growth is strongly affected by the slip characteristics of the material, microstructural dimensions, applied stress level and near tip plasticity.
- In ductile solids crack growth is a process of localized deformation on slip bands near the crack tip.
- Three different stages depending on crack length, stage I, stage II and stage III.



Chapter 10.2 Microscopic stages of fatigue crack growth

Stage I fatigue crack growth

- When the crack and the plastic zone around the crack is limited within a few grain diameters, crack growth predominantly by *single shear* in the direction of the primary slip system.
- Results in a zigzag crack path and serrated or faceted fracture surfaces.
- Can be observed also for longer cracks if the plastic zone at the tip is smaller than the grain dimensions.

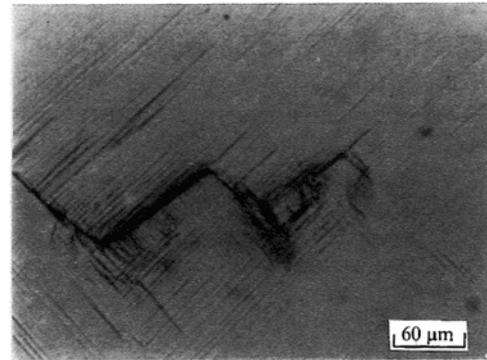
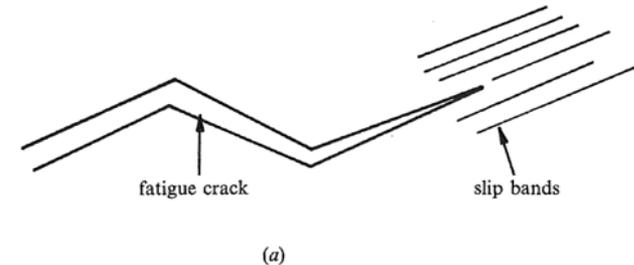


Fig. 10.2. (a) A schematic of stage I fatigue crack growth. (b) An example of stage I fatigue crack growth in a single crystal of Mar M-200 nickel-base superalloy. The tensile axis is vertical. The {100} plane is normal to the tensile axis. (Photograph from P.B. Aswath & S. Suresh.)



Chapter 10.2 Microscopic stages of fatigue crack growth

Stage II fatigue crack growth

- At higher stress intensity values the plastic zone at the tip encompasses several grains. The crack growth process involves simultaneous or alternating flow along two slip planes, called *duplex slip*.
- This results in a planar mode I crack path normal to the tensile axis.

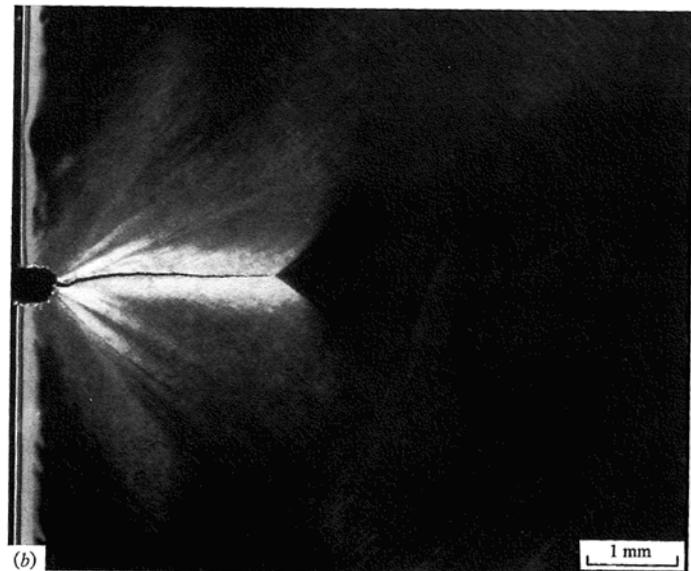
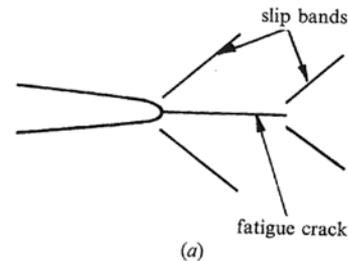


Fig. 10.3. (a) An idealization of stage II fatigue crack growth. (b) An example of stage II crack growth in a Cu single crystal. Two sets of {111} slip planes (white areas) are seen. The tensile axis is vertical. (From Neumann, 1969. Copyright Pergamon Press plc. Reprinted with permission.)

Chapter 10.2 Microscopic stages of fatigue crack growth

Stage II fatigue crack growth (2)

- In stage II fatigue striations are formed which can be seen as ripples on the fracture surface.
- In the Paris regime it has been found that the spacing between adjacent striations correlate to measured average crack growth rate per cycle.
- Can also be used to see the direction of the crack advance, were final failure occurred and if the failure was due to fatigue or not.

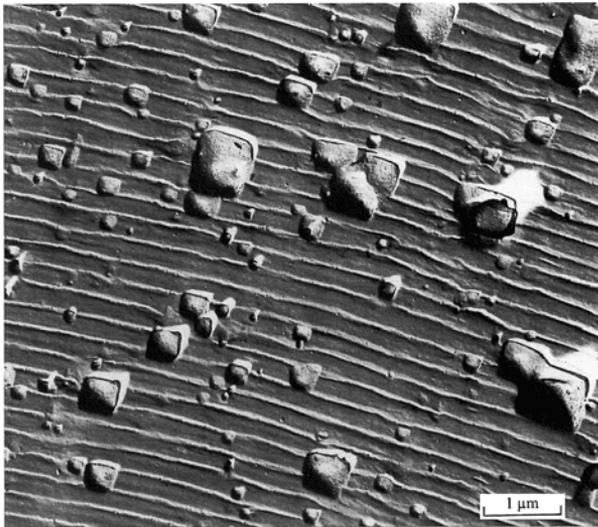
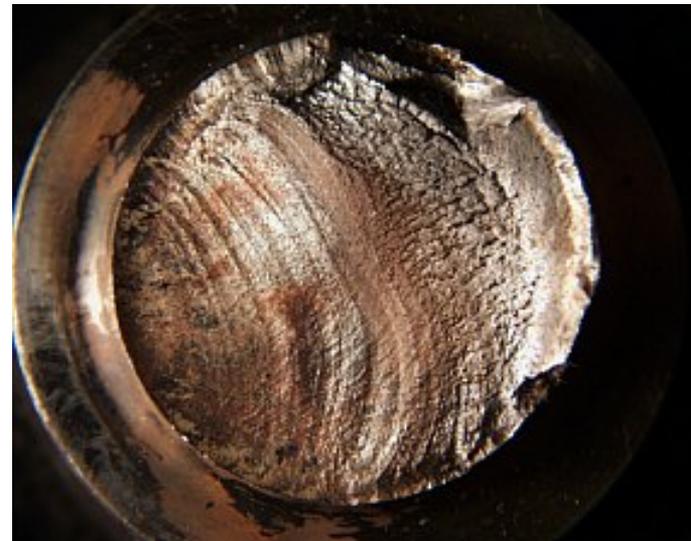


Fig. 10.4. Fatigue striations on the etched failure surface in 2024-T3 aluminum alloy. The arrow indicates crack growth direction. (From Pelloux, 1969. Copyright American Society for Metals. Reprinted with permission.)



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Chapter 10.2 Microscopic stages of fatigue crack growth

Stage II fatigue crack growth (3)

- Not all engineering materials form striations. Is often seen in pure metals and many ductile alloys. In steel they occur infrequently and are barely visible in cold-worked alloys.
- Development of striations is also influenced by stress state, ΔK , alloy content and environment.
- Several conceptual models exists to rationalize the formation of fatigue striations and planar growth of stage II fatigue cracks.
 - Plastic blunting
 - Alternating slip model
 - Environmental effects



Chapter 10.2 Microscopic stages of fatigue crack growth

Stage III fatigue crack growth (4)

- Plastic blunting. An appealing physical concept by Laird (1967).
- Applies to a wide variety of ductile materials.

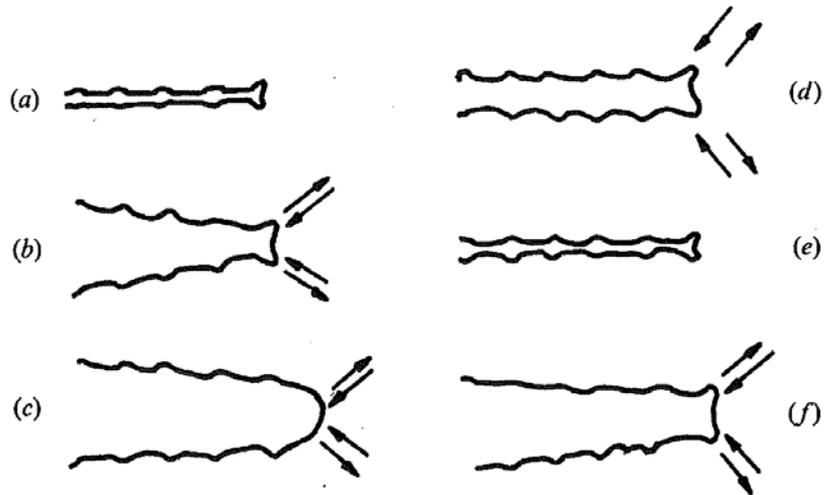


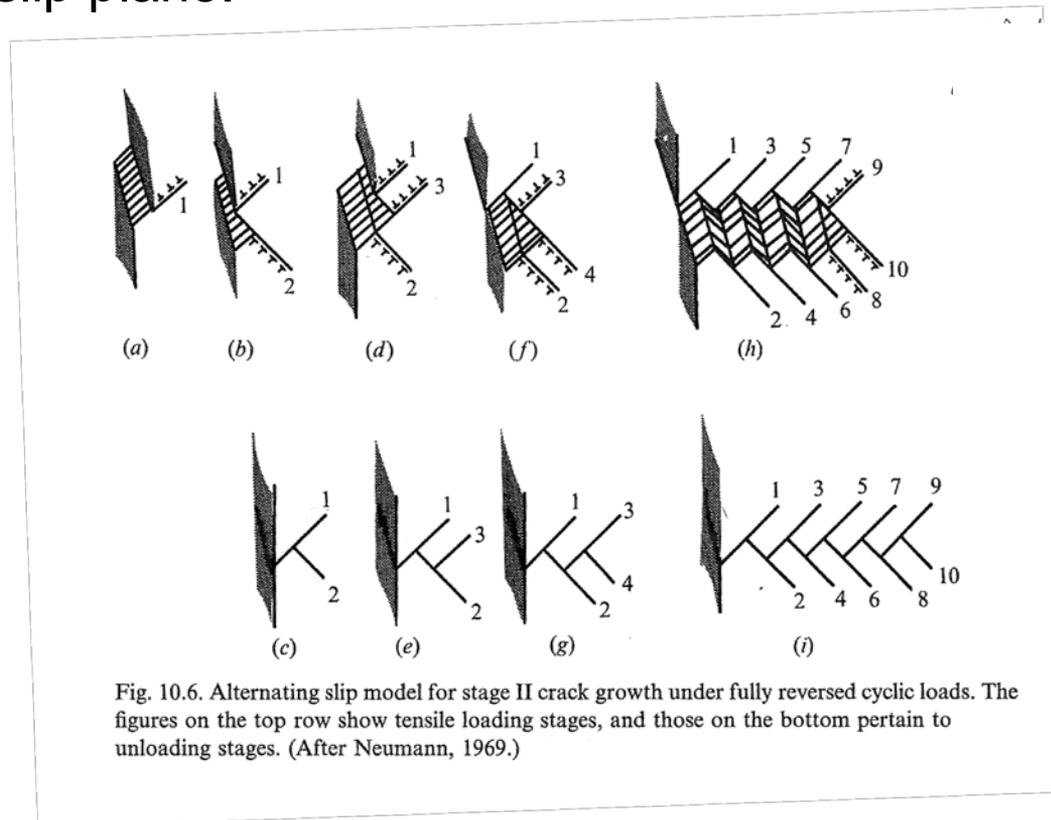
Fig. 10.5. An idealization of plastic blunting and re-sharpening which leads to stage II fatigue crack growth in fully-reversed fatigue. (a) Zero load, (b) small tensile load, (c) peak tensile load, (d) onset of load reversal, (e) peak compressive load, and (f) small tensile load in the subsequent tensile cycle. Arrows indicate slip direction. (After Laird, 1967.)



Chapter 10.2 Microscopic stages of fatigue crack growth

Stage II fatigue crack growth (5)

- Alternating slip model. For ductile metal single crystals were work hardening of the primary slip plane leads to alternating shear on another slip plane.



Chapter 10.2 Microscopic stages of fatigue crack growth

Stage III fatigue crack growth (6)

- Some environmental effects on the formation of striations can be incorporated in the blunting model.
- Seen that the formation of striations may be suppressed in vacuum in aluminum alloys which form striations in moist air. This is the case for several other alloys forming striations in air. Also the fatigue crack growth rate was more than a magnitude slower that in air.
- The mechanism behind this is due to irreversible slip.

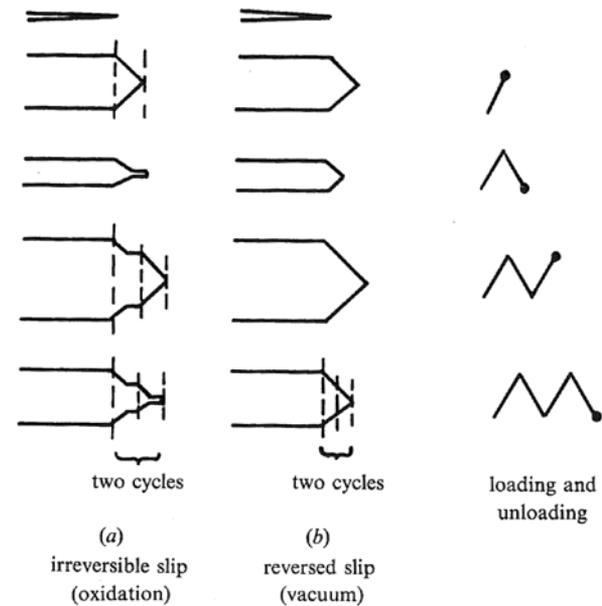


Fig. 10.7. Effects of environment on fatigue crack growth by alternating slip. See text for details. (After Pelloux, 1969.)



Chapter 10.3 Different regimes of fatigue crack growth

- The Paris law relationship, with a linear relationship between $\log(da/dN)$ and $\log(\Delta K)$ is only valid for a portion of the total crack growth curve.
- At extreme values of ΔK , both higher and below the Paris regime, higher growth rates are obtained.

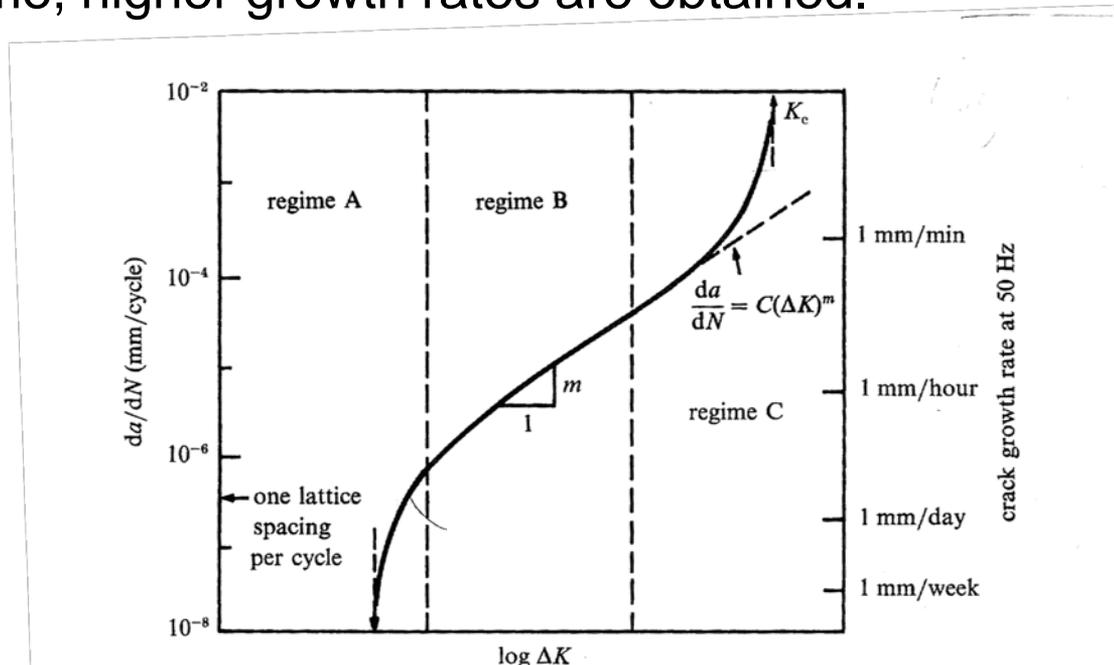


Fig. 10.8. Schematic illustration of the different regimes of stable fatigue crack propagation.



Chapter 10.3 Different regimes of fatigue crack growth (2)

Three different regions A, B and C can be identified:

A: The average da/dN is smaller than the lattice spacing.
There exists a threshold stress intensity factor ΔK_0 below which the crack remains dormant or too slow to be detected.

B: Paris regime, linear variation of $\log(da/dN)$ vs. $\log(\Delta K)$

C: High ΔK values, the crack growth rate increases rapidly causing catastrophic failure.



Chapter 10.3 Different regimes of fatigue crack growth (3)

Table 10.1. *Characteristics of the three regimes of fatigue crack growth.*

Regime	A	B	C
Terminology	Slow-growth rate (near-threshold)	Mid-growth rate (Paris regime)	High-growth rate
Microscopic failure mode	Stage I, single shear	Stage II, (striations) and duplex slip	Additional static modes
Fracture surface features	Faceted or serrated	Planar, with ripples	Additional cleavage or microvoid coalescence
Crack closure levels	High	Low	—
Microstructural effects	Large	Small	Large
Load ratio effects	Large	Small	Large
Environmental effects	Large	*	Small
Stress state effects	—	Large	Large
Near-tip plasticity [†]	$r_c \leq d_g$	$r_c \geq d_g$	$r_c \gg d_g$

*Large influence on crack growth for certain combinations of environment, load ratio and frequency.

[†] r_c and d_g refer to the cyclic plastic zone size given in Eq. 9.85, and the grain size, respectively.



Chapter 10.4 Near-threshold fatigue crack growth

- Low growth rates of about 10^{-6} mm/cycle. In this region ΔK approaches ΔK_0 . A common definition of ΔK_0 is when da/dN is about 10^{-8} mm/cycle due to difficulties in the crack monitoring system and number of elapsed cycles.
- Fatigue design against ΔK_0 is often too conservative for ductile alloys. Can be used for instance for designing high speed turbine rotors which are subjected to many load cycles.
- ΔK_0 values depend on factors such as microstructure, R -value, environment and crack length.
- The range of $\Delta K_0(R)$ can be seen in Fig. 10.9 for different alloys



Chapter 10.4 Near-threshold fatigue crack growth (2)

- Large variations in ΔK_0 for low R-values.
- Less variation for different microstructure and alloys for higher R-values.

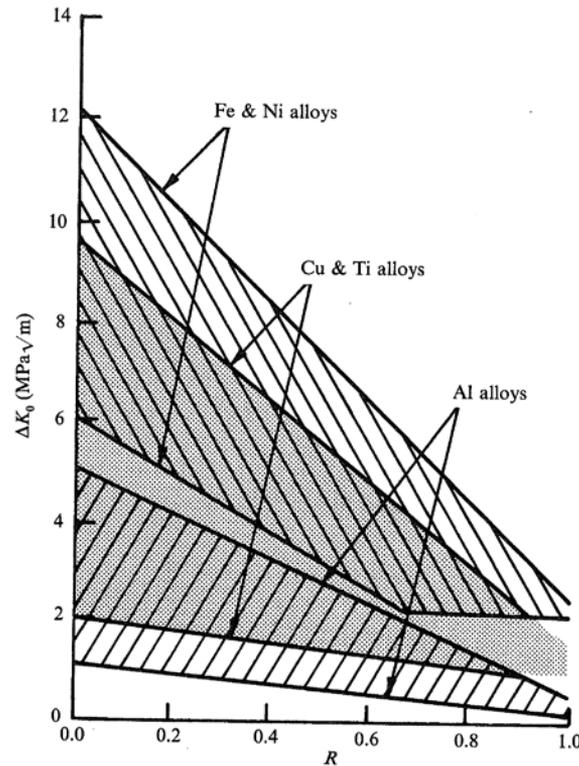


Fig. 10.9. Typical range of threshold ΔK_0 values measured in room temperature air and plotted as a function of the load ratio, R , for a variety of engineering alloys. (After Liaw, Leax & Logsdon, 1983.)



Chapter 10.4 Near-threshold fatigue crack growth (3)

Effects of microstructural size scale.

- The transition from near ΔK_0 regime to intermediate region is accompanied by a change from microstructure-sensitive to a microstructure-insensitive fracture behavior.
- Typically occurs when the size of the cyclic plastic zone r_c becomes comparable to an characteristic microstructural dimension l^* e.g. the grain size.

$$r_c = \alpha \left(\frac{\Delta K_T}{\sigma'_y} \right)^2 \approx l^*. \quad (10.12)$$

Where ΔK_T is the stress intensity factor term corresponding to this transition. Compare with eq. 9.85. Rearrangement of the equation results in:

$$\Delta K_T \propto \sigma'_y \sqrt{l^*}. \quad (10.13)$$



Chapter 10.4 Near-threshold fatigue crack growth (4)

Effect of slip characteristics

Different microstructure results in different ΔK_0 although they have the same size of the cyclic plastic zone and grain size because of differences in slip characteristics.

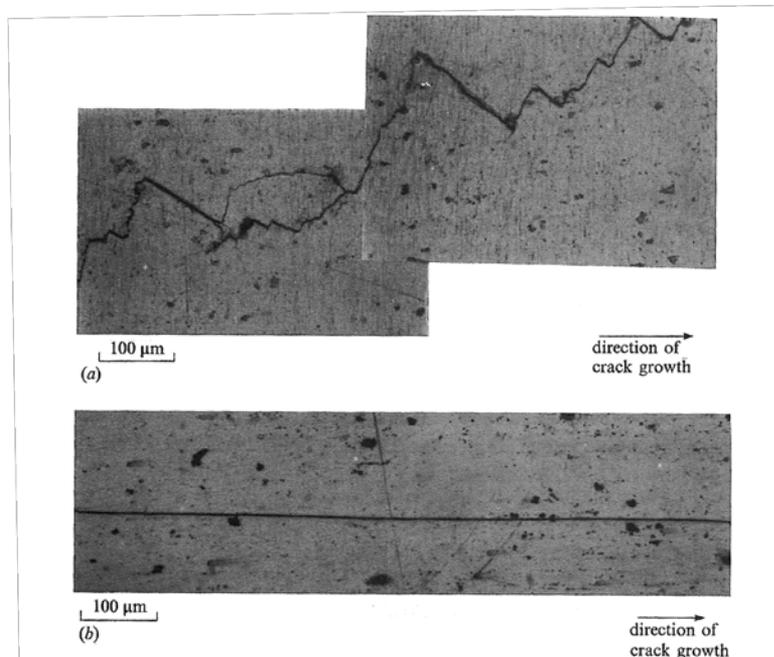


Fig. 10.11. Profiles of near-threshold fatigue cracks observed in (a) an under-aged condition (T3 temper) and (b) an over-aged condition (T8 temper) of an Al-Cu-Li alloy in laboratory air at a high load ratio, R . (From Blankenship & Starke, 1991. Copyright Pergamon Press plc. Reprinted with permission.)

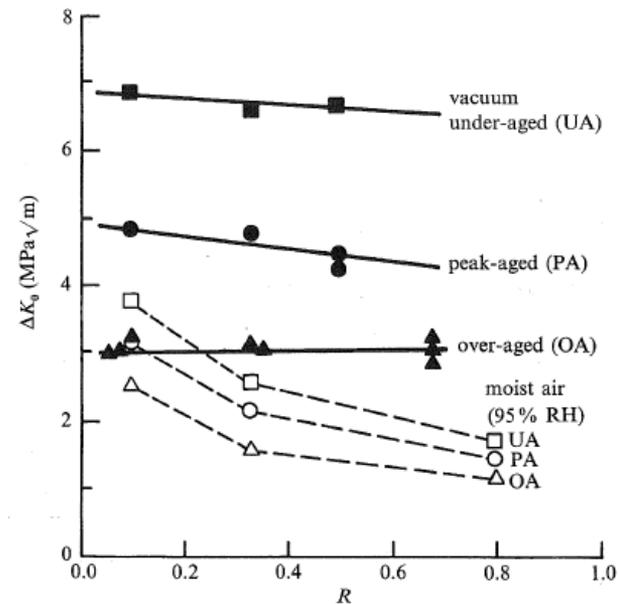


Fig. 10.12. Variation of the threshold ΔK_0 as a function of the load ratio, R , for under-aged and over-aged conditions of a 7075 aluminum alloy. Both microstructures have the same yield strength, $\sigma_y = 450$ MPa and an average grain size of $90 \mu\text{m}$. (After Suresh, Vasudevan & Bretz, 1984. Results for ΔK_0 at $R = 0.33$ in vacuum are courtesy of A.K. Vasudevan.)

Chapter 10.4 Near-threshold fatigue crack growth (5)

On the determination of ΔK_0

- Experimental determination of ΔK_0 is strongly influenced by artifacts in the test methods.
- The most common is the load-shedding technique.
 - A fatigue pre-crack is initiated of a starter notch at ΔK values in the Paris regime of crack growth.
 - ΔK is reduced in stages (max 10%) with constant cyclic frequency and R-ratio. In each step the crack propagates of the order of a mm (at least $4r_c$).
 - This step is repeated until ΔK_0 , for no crack growth or da/dN is smaller than 10^{-8} mm/cycle is reached.



Chapter 10.5 Intermediate region of crack growth

- The intermediate region has been subjected of most extensive research.
- The microscopic mechanism for crack growth involves duplex slip and blunting and re-sharpening of the crack.
- The growth rate is influenced such as: microstructure, loading, environment and crack closure.
- No single theory can predict crack propagation for a wide variety test conditions even for a single alloy system.
- Several attempts have been made to predict the growth rate from physical principles, divided into:
 - Geometrical models, based on crack tip displacement. Only good for a small segment of the Paris regime.
 - Damage accumulation models, based on the critical value of accumulated strains or plastic work at the crack tip.



Chapter 10.6 High growth rate regime

- At high ΔK values the growth rates are significantly higher than in the Paris regime.
- Crack growth is sensitive to microstructure, load ratio and stress state but relative insensitive to test environment.
- Different critical ΔK for different R - values.

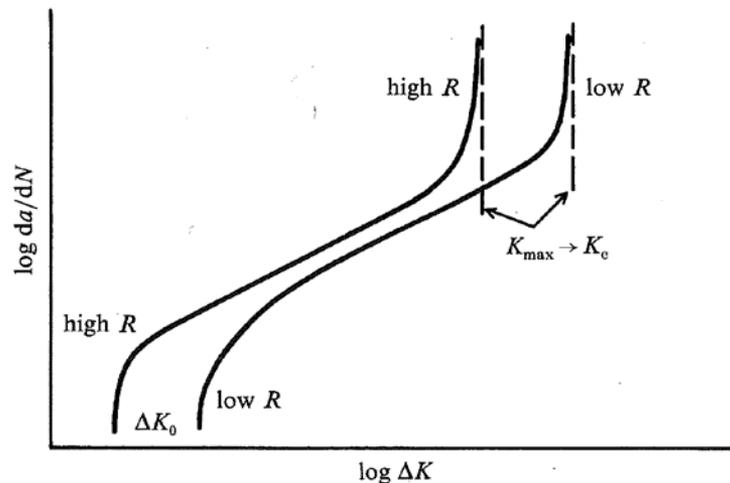


Fig. 10.13. A schematic representation of the effect of load ratio, R , on fatigue crack growth behavior.



Chapter 10.6 High growth rate regime (2)

- At high ΔK values when the fast fatigue fracture is approached static fracture modes such as cleavage and intergranular separation occurs in addition to striation growth. Cause an increase in sensitivity to microstructure.
- At high ΔK values the plastic zone becomes large which makes linear elastic fracture mechanics invalid as $K_{max} \rightarrow K_{IC}$.
- Many semi-empirical and empirical models have been proposed to account for the near threshold and final failure regime from that described of Paris law. Does not all account for any microstructural or environmental effects. Often not the most interesting part since only a very small portion of the total life remains at this stage.

