Chapter 14. Retardation and transients in fatigue crack growth

- In chapters 9-12 ΔK has uniquely determined the crack growth rate. There are, however, some situations where the local ΔK, responsible for crack growth can be markedly different from the nominal value.
- These differences in driving force can come from:
  - Premature closure of the crack faces
  - Periodic deflection of the crack path
  - Shielding of the crack tip e.g. residual stresses, phase transformations
  - Bridging of the crack faces by fibers, particles or corrosion products

LUND UNIVERSITY

Chapter 14. Retardation and transients in fatigue crack growth (2)

- These processes can lead to a retardation in the crack growth and enhance the resistance against fatigue.
- It is important to understand these mechanism in order to develop accurate life prediction models and for improving microstructural design for enhanced damage tolerance.
- First various mechanisms for constant amplitude cyclic loading and then variable amplitude fatigue and load sequences are discussed.

Chapter 14.1 Fatigue crack closure

- When a fatigue crack closes at a far-field tensile load.
- The first observed mechanism for crack closure was due to remaining residual stresses left in the wake behind the crack tip by Elber (1970, 1071). Theses stresses is responsible for earlier contact between the crack faces, reducing the driving force for fatigue crack advance.
- Since then additional sources for closure have been identified:
  - Oxide-induced crack closure
  - Microscopic crack closure
  - Viscous fluid-induced crack closure
  - Transformation-induced crack closure

Chapter 14.1 Fatigue crack closure (2)

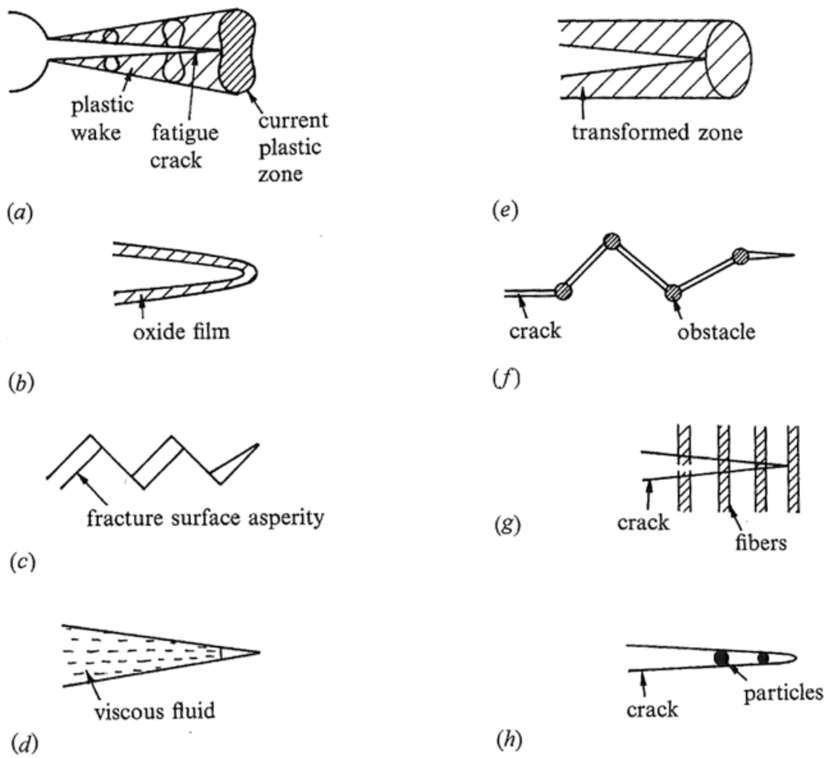

Fig. 14.1. A schematic illustration of the mechanisms which promote retardation of fatigue crack growth in constant amplitude fatigue. (*a*) plasticity-induced crack closure; (*b*) oxide-induced crack closure; (*c*) roughness-induced crack closure; (*d*) fluid-induced crack closure; (*e*) transformation-induced crack closure; (*f*) crack deflection; (*g*) crack-bridging by fibers; (*h*) crack-bridging (trapping) by particles.

LUND UNIVERSITY

Chapter 14.2 Plasticity-induced crack closure

- Seen from experiments that not only the conditions ahead of the crack tip is important, but also the nature of the crack face contact behind the crack tip.
- The conditions in the wake is a result of load history, length of the crack and stress state.
- **Mechanism**: An atomically sharp notch or saw-cut closes at zero compressive load. However, the propagation of a fatigue crack gives rise to a wake of previously plastically deformed material. This results in residual tensile strains left in the material behind the advancing crack, closing the crack.

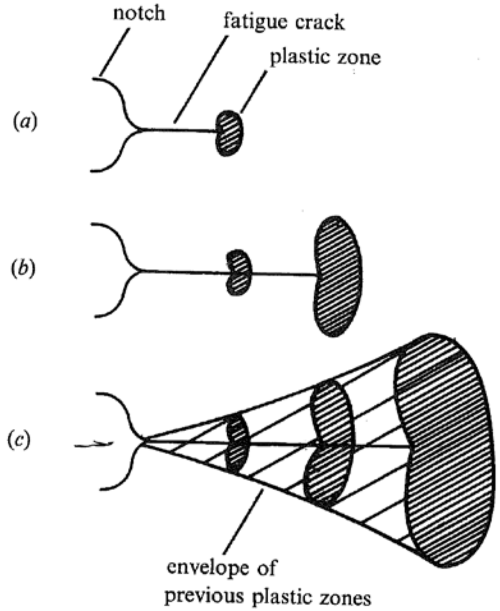

Fig. 14.2. The development of an envelope of prior plastic zones around an advancing fatigue crack. (After Elber, 1970, 1971.)

Chapter 14.2 Plasticity-induced crack closure (2)

- Elber also studied the closure behavior using strain gages above and below the crack. He measured the far-field tensile load at which the fracture surfaces opened completely during a fatigue cycle. Resulted in what is called a compliance plot.

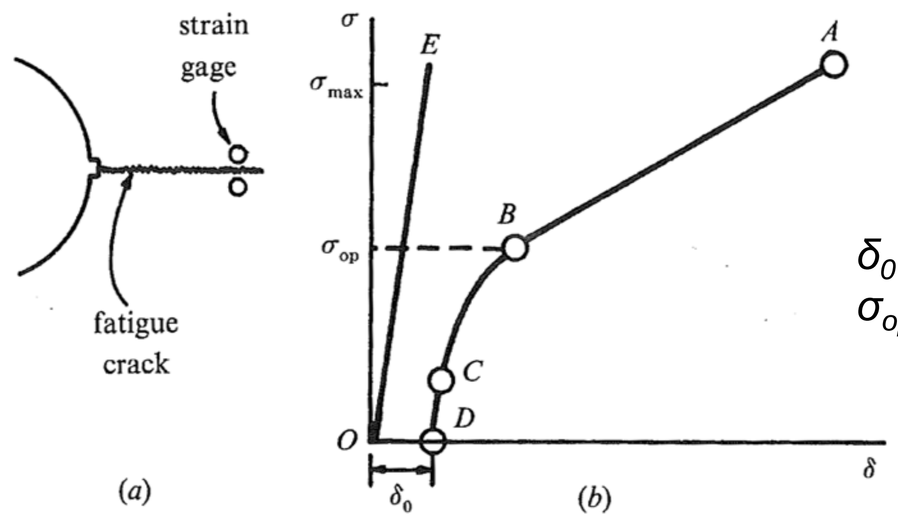

Fig. 14.3. A schematic of the relationship between the applied stress and the displacement measured by the strain gages. (After Elber, 1970.)

δ_0 residual crack opening displacement

σ_{op} stress when fully open

Chapter 14.2 Plasticity-induced crack closure (3)

- The compliance curve can also be presented in terms of stress intensity factor. Figure below shows a typical curve for many alloys showing both the loading and unloading part $K(\delta)$.
- The curves are used to calculate the stress intensity factor when the crack is fully open K_{op} and fully closed K_{cl}.

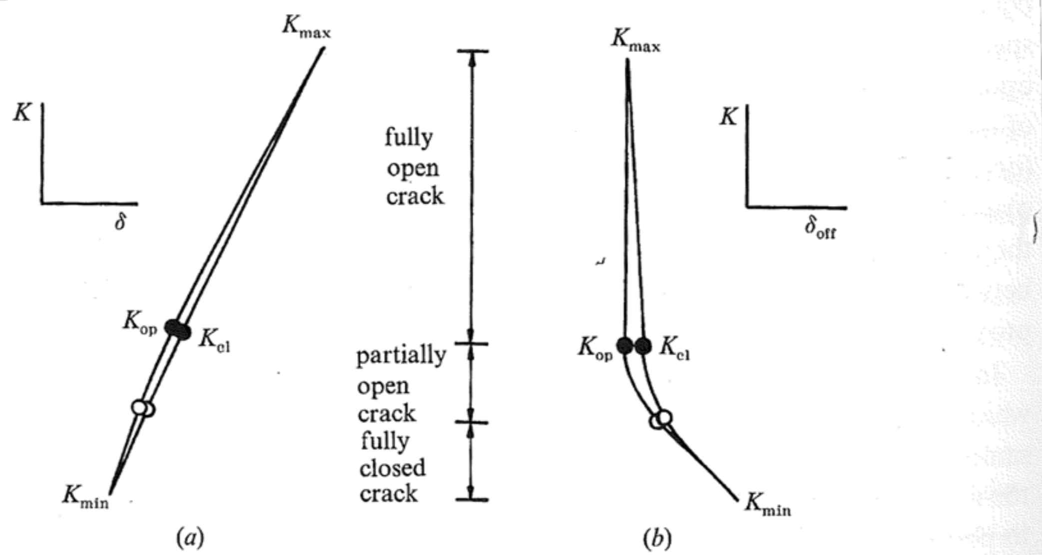

Fig. 14.4. (*a*) A plot of the stress intensity factor K as a function of the crack opening displacement during a complete fatigue cycle. (*b*) Modification of the compliance plot using the offset procedure.

Chapter 14.2 Plasticity-induced crack closure (4)

- No unique definition for K_{cl} since the crack closes gradually.
- Elber argued that the crack can propagate only during the part of the load cycle where the crack is open.
- The effective stress range $\Delta\sigma_{eff}$ and effective stress intensity range ΔK_{eff} is responsible for crack growth.

$$\Delta\sigma_{\text{eff}} = \sigma_{\max} - \sigma_{\text{op}} = U\Delta\sigma, \qquad \Delta K_{\text{eff}} = K_{\max} - K_{\text{op}} = U\Delta K, \qquad (14.1)$$

- The corresponding characterization of fatigue crack growth becomes:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C(\Delta K_{\text{eff}})^m = C(U\Delta K)^m. \qquad (14.2)$$

- This equations takes the effects of R-value into account. The U-value is also dependent of specimen geometry, stress state, stress intensity factor range and environment.
- Ex: Al alloy 2024-T3: $\frac{K_{\text{op}}}{K_{\max}} = 0.5 + 0.1R + 0.4R^2.$

LUND UNIVERSITY

Chapter 14.3 Oxide-induced crack closure

- The mechanism evolved as a consequence ro rationalize anomalies in the effects on environment on near ΔK_0 fatigue crack growth.
- From experiments seen that the thickness of oxide layers on fracture surfaces can be in the same size as the crack tip opening displacement (CTOD) near the threshold. Oxide-induced crack closure can have a decisive effect on the crack growth rate near ΔK_0.
- **Mechanism**: During propagation the presence of moist air leads to oxidation on freshly formed crack surfaces. At low CTODs near ΔK_0 and low R-ratios the possibility for repeated crack face contact is enhanced. Leads continual breaking and reforming of the oxide. Can in some cases lead to complete wedging.
- At high R-ratios (little contact) or high ΔK (high *da/dN no time for oxidation*) oxidation does not play a significant role.

LUND UNIVERSITY

Chapter 14.3 Oxide-induced crack closure (2)

- The degree of oxidation depends on microstructure, environment, *R*-ratio and *ΔK.*
- Therefore hard to formulate predictive models for its effects on crack growth rates. One simple estimation is to consider a rigid wedge inside I linear elastic fatigue crack.
- Oxide-induced crack closure is enhanced by moist environment, high temperature, low *R*-ratios, low *ΔK* values, high cyclic frequencies, lower strength and coarser-grained microstructures*.* Also ageing treatments (variation in precipitation) can have a decisive effect.
- Example of effects due to environment and R-ratio.

LUND UNIVERSITY

Chapter 14.3 Oxide-induced crack closure (3)

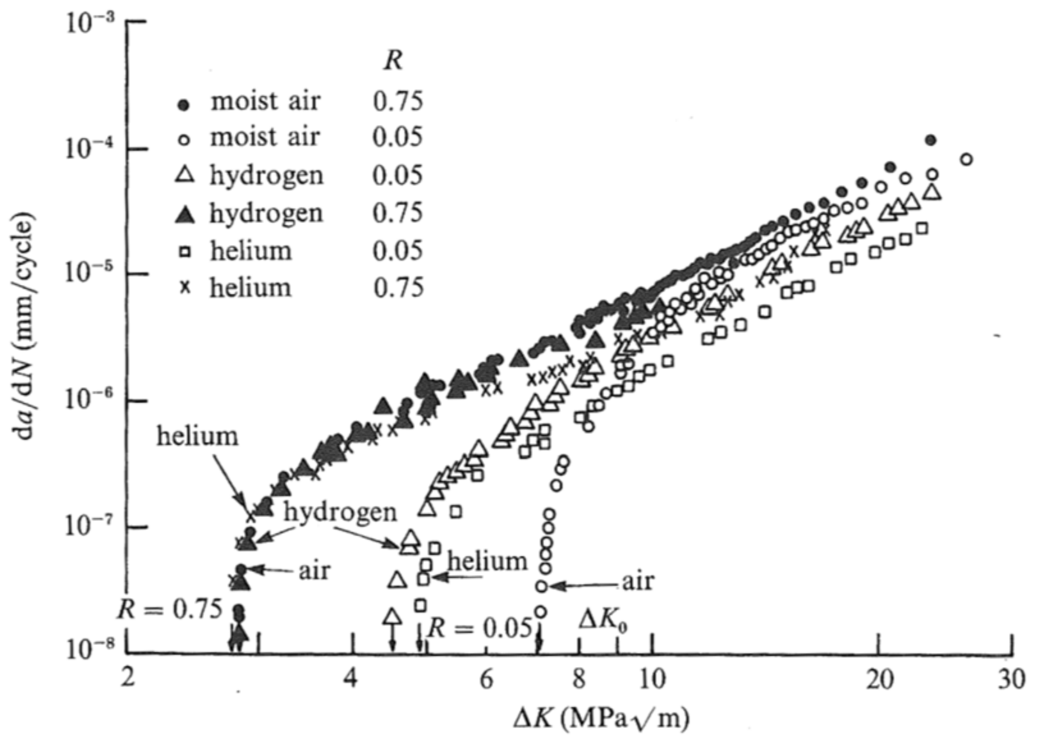

Fig. 14.8. Effects of dry and moist environments on near-threshold fatigue crack growth in $2\frac{1}{4}$Cr–1Mo steel (AISI A542 Class 2, martensitic microstructure, monotonic tensile yield strength = 769 MPa) at low and high load ratios. (After Suresh, Zamiski & Ritchie, 1981.)

LUND UNIVERSITY

Chapter 14.4 Roughness-induced crack closure

- Experimental observations reveals that crack propagation near ΔK_0 occurs in a single slip mechanism, stage I growth, leading to a highly serrated or faceted crack shape.
- Plastic deformation ahead of the crack tip and slip irreversibility leads to mis-match between the two fracture surfaces. In-situ studies have shown that there exists a strong mode II component and occurrence of premature contact between crack faces.
- Larger grains results in rougher surfaces and lower da/dN near ΔK_0, especially for low R-ratios.
- The effect of crack closure is enhanced by: Low ΔK values, small CTOD, large grains, shearable and coherent particles, periodic deflections in crack path and enhanced slip irreversibility

LUND UNIVERSITY

Chapter 14.4 Roughness-induced crack closure (2)

- The effect of grain size

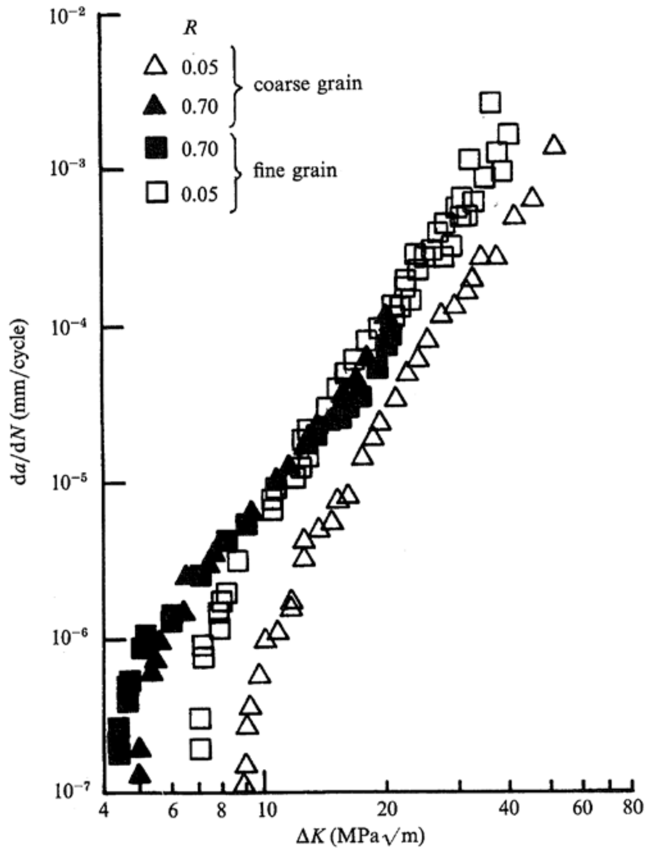

Fig. 14.9. The effect of prior austenite grain size on fatigue crack growth in a pearlitic eutectoid steel at $R = 0.1$ and 0.7. (After Gray, Williams & Thompson, 1983.)

LUND UNIVERSITY

Chapter 14.5-6 Additional mechanisms of fatigue crack closure

- There exists additional mechanisms for crack closure, not included in the course.
  - Crack closure due to viscous fluid
  - Crack closure due to phase transformation (change in volume)

Chapter 14.7 Some basic features of fatigue crack closure

- Generally more dominant at lower ΔK and R due to smaller minimum crack opening displacement.
- There is a characteristic size scale associated with each process: Size of wake, oxide thickness, height of surface asperities. When in the same size as the crack opening displacement it has marked effect on fatigue crack growth.
- The extent of crack closure increases with increasing crack length up to a saturation crack length.
- The mechanisms for closure acts both at the tip and the wake.
- No unique conclusion about effect of stress state. Generally more crack closure in plane stress in cyclic tension and plane strain in cyclic compression.

Chapter 14.12 Retardation following tensile overloads

- A single tensile overload or high amplitude block loading sequence can result in the retardation or arrest in crack growth.

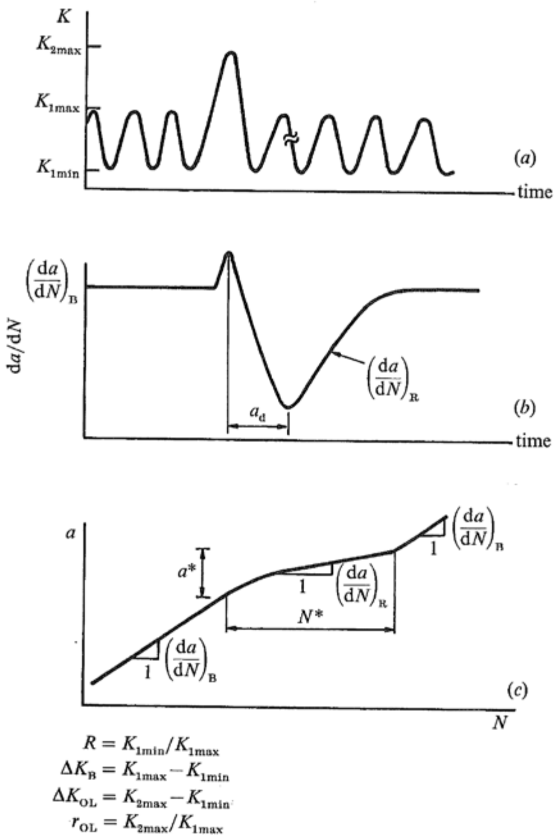

Fig. 14.17. Definitions of different parameters used to describe transient crack growth effects following single tensile overloads.

Chapter 14.12 Retardation following tensile overloads (2)

- First a small amount of temporally accelerated growth during the overload, can be seen as a *stretch zone* on the fracture surface.
- Followed by a longer period of decelerated crack growth. Continues for a certain growth distance called *delay distance* a_d.
- After reaching a minimum the growth rate increases reaching the pre-overload value.
- The overload produces a larger plastic zone, wake, resulting in plasticity induced crack closure.
- Other possible events are:
  - Increase in growth rate, breaking of particle, GB etc.
  - No effect at all except in the overload cycle itself.

Chapter 14.13 Transient effects following compressive overloads

- Application of fracture mechanics to the fatigue characterization is based on the premise that a crack grows during the portion of the cycle when the crack is open. However, it has been found that compressive overloads can increase the growth rate.
- The mechanism behind this effect is the development of tensile residual stresses in the material during unloading as discussed in chapters 4-6.
- Compressive overloads also lead to flattening of fracture surface asperities which reduces the effect of crack closure.
- Largest effect close to ΔK_0.

LUND UNIVERSITY

Chapter 14.13 Transient effects following compressive overloads (2)

Effect of compressive overloads

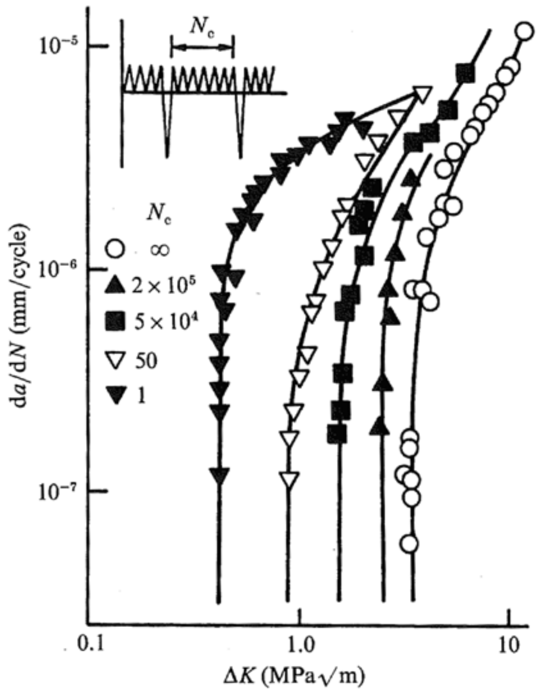

Fig. 14.20. Influence of compressive overloads on the rates of fatigue crack growth in a 2024-T351 aluminum alloy. (After Topper & Yu, 1985.) The growth rates are characterized in terms of the maximum stress intensity factor range. The inset shows the normalized stress intensity factor for the loading sequence as a function of time. N_c denotes the number of baseline tensile fatigue stress cycles in-between two overloads.

Chapter 14.13 Transient effects following compressive overloads (3)

Flattening of crack surfaces, abrasion marks.

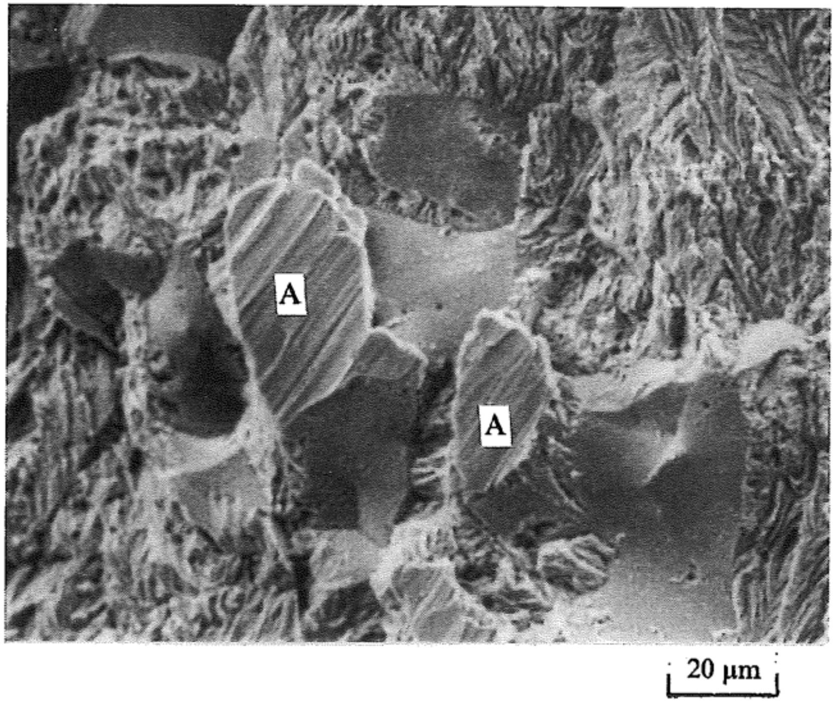

Fig. 14.21. Abrasion marks (denoted by *A*) on the fracture surface of an AISI A542 Class 3 subjected to compressive overloads. (From Aswath *et al.*, 1988.)

LUND UNIVERSITY

Chapter 14.13 Transient effects following compressive overloads (4)

Role of stress amplitude in the first load cycle of compression fatigue crack growth.

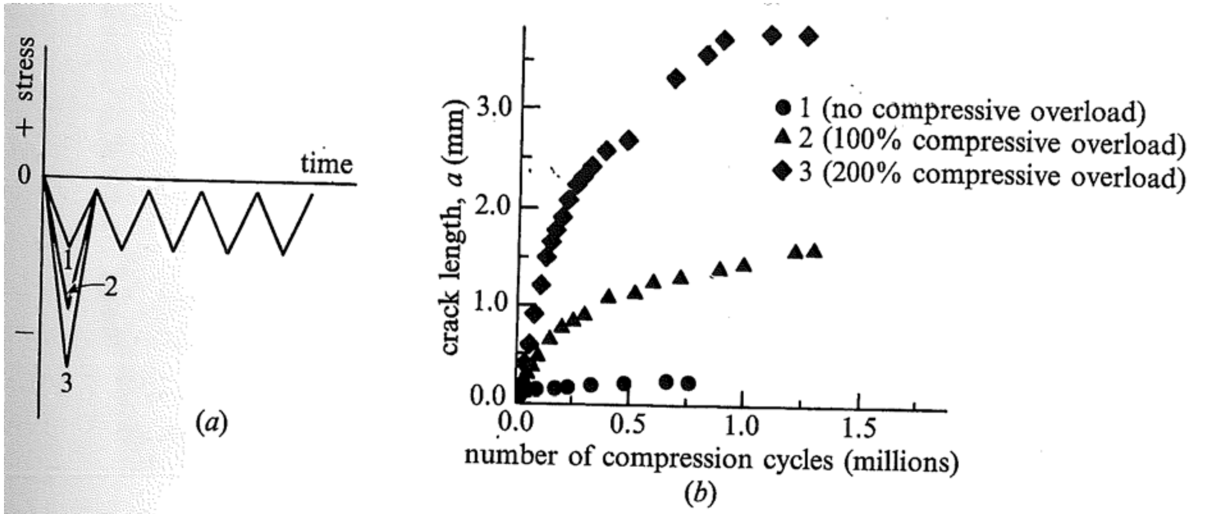

Fig. 14.22. (*a*) Schematic showing constant amplitude loading (test 1) and variable amplitude loading where a 100% (test 2) and 200% (test 3) overload was applied only in the first cycle. The applied stress amplitude of the remaining cycles was held fixed. (*b*) The effect of the stress amplitude of the very first compression cycle on crack growth behavior from a notch tip in an AISI A542-3 steel (tensile yield strength = 500 MPa) under plane stress. (After Aswath *et al.*, 1988.)

Chapter 14.14 Load sequence effects

- Different combinations of cyclic loads
- Block tensile load sequences.
  - Reduction in striation spacing during A.
  - S-stretch zone, in beginning of second block B

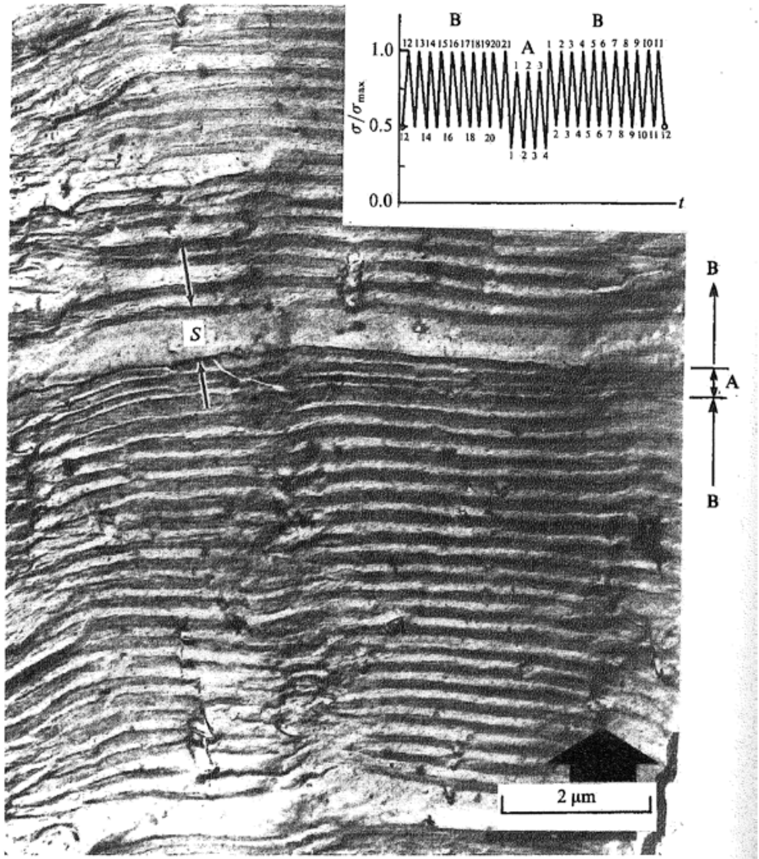

Fig. 14.23. Typical fractography resulting from a high–low–high block loading sequence applied to a 2024-T3 aluminum alloy. Crack growth corresponding to each block and the crack growth direction (large arrow) are indicated. The fatigue loading sequence is shown where the applied cyclic stress, normalized by its maximum value σ_{max}, is plotted as a function of time t. (From McMillan & Pelloux, 1967. Copyright American Society for Testing and Materials. Reprinted with permission.)

Chapter 14.14 Load sequence effects (2)

- Smaller striations in region B.
- No crack growth in region A.
- No stretch zone after A due to constant maximum stress intensity level.
- Not all materials show striations ant they do no always correlate with crack growth rates.

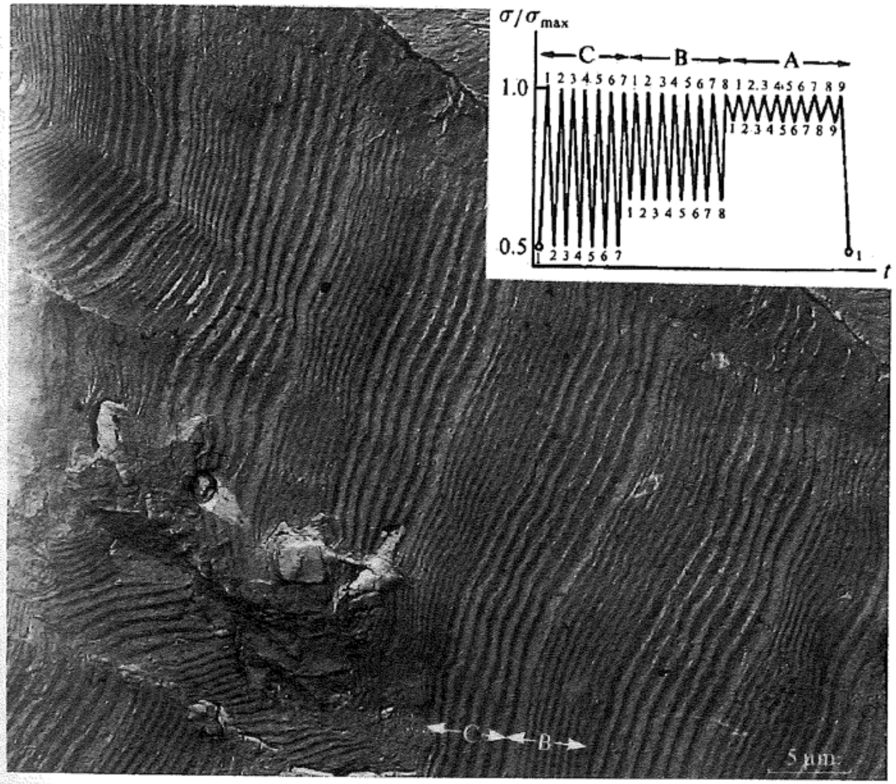

Fig. 14.24. Typical fracture surface due to block loading in a 2024-T3 aluminum alloy. Regions of crack growth corresponding to blocks B and C are marked. No crack growth occurred due to the application of block A. The fatigue loading sequence is shown in the inset where the applied cyclic stress, normalized by its maximum value σ_{max}, is plotted as a function of time t. (From McMillan & Pelloux, 1967. Copyright American Society for Testing and Materials. Reprinted with permission.)