Chapter 4. Fatigue crack initiation in ductile solids

- Definition of initiation of fatigue cracks is strongly linked to the size scale of observation:

  -Engineer: resolution of crack detection

  -Material scientist: nucleation of flaws at PSBs

- Many different failure mechanisms behind crack initiation: flaws at grain boundaries, twin boundaries, inclusions, inhomogeneity's and stress concentrations.
- In this chapter mechanisms of fatigue crack initiation in nominally defect free pure metals and alloys is discussed.
- Continuum aspects are discussed in chapters 7 and 8.

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Chapter 4.1 Surface roughness and fatigue crack initiation

- In materials of high purity, cyclic straining of the material leads to different amount of net slip on different glide planes. The irreversibility of the shear displacement results in 'roughening' of the surface seen as microscopic hills and valleys called extrusions and intrusions .

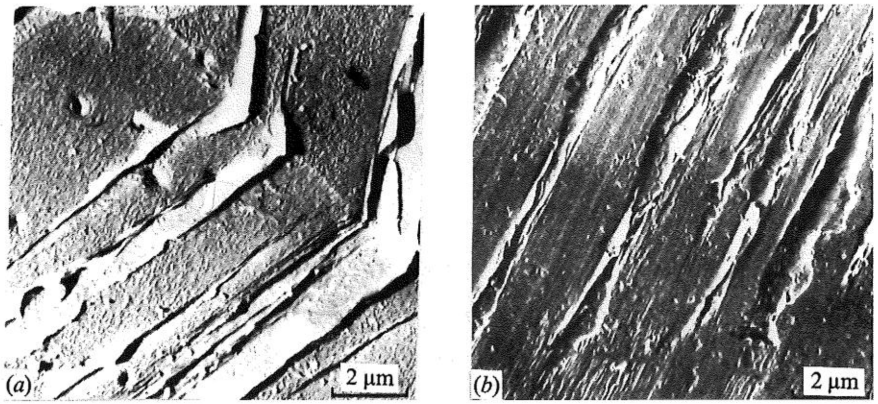

Fig. 4.1. (*a*) Intrusions and (*b*) extrusions along slip bands in polycrystalline Cu fatigued at −183 °C. (From Cottrell & Hull, 1957. Copyright The Royal Society, London. Reprinted with permission.)

- The valleys function as micronothches and the effect of the stress concentration promotes additional slip and fatigue crack nucleation.

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Chapter 4.1 Surface roughness and fatigue crack initiation (2)

- In experiments showed that surface slip steps form in proportion to applied plastic strain.
- Individual steps undergo irreversible slip.
- Crack nucleation occurs preferentially at PSBs with the highest slip offset and largest strain localization.
- General trends:

  -The surface of a fatigued crystal is covered with PSB extrusions, intrusions and protrusions. A protrusion is a surface uplift containing tens of matrix/PSB lamellae, consists of several intrusions and extrusions.

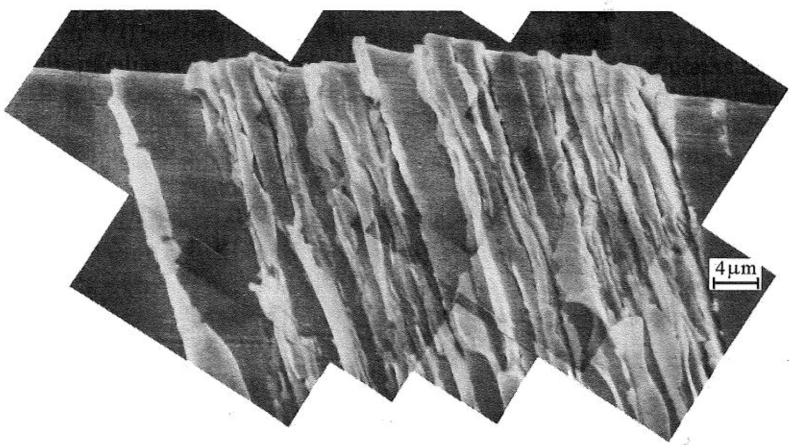

Fig. 4.2. Protrusions with extrusions and intrusions on the surface of a Cu crystal fatigued at room temperature for 120 000 cycles at $\gamma_{pl} = 0.002$. (From Ma & Laird, 1989a. Copyright Pergamon Press plc. Reprinted with permission.)

Chapter 4.1 Surface roughness and fatigue crack initiation (2)

- General trends:
  - -Protrusions grow slower than extrusions
  - -The height of the protrusion increases in proportion to the width.
  - -Large local strains in the PSB-matrix interface.

The contour of a PSB

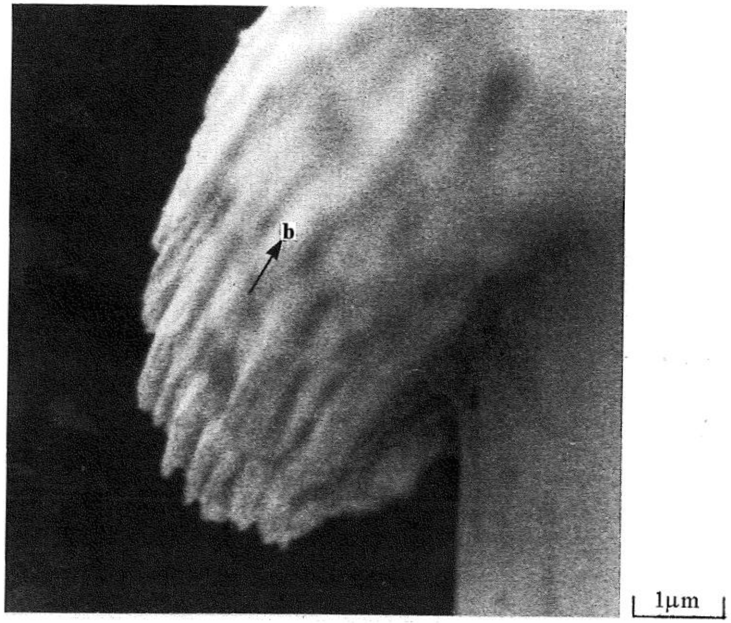

Fig. 4.3. The contour of a PSB profile created in a Cu crystal. (From Differt, Essmann & Mughrabi, 1986. Copyright Taylor & Francis, Ltd. Reprinted with permission.)

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Chapter 4.2 Vacancy-dipole models

- At the beginning stages of cyclic saturation PSBs are formed accompanied of extrusions. Has to do with dislocations distances in the matrix approaches the annihilation distance, below which annihilation is favored.
- Screw dislocations of opposite sign annihilates through cross slip whereas edge dislocations form dipoles. If close enough (1.6mm) they annihilate and form a vacancy or an interstitial.
- Seen in microscope that the majority of dipoles are of vacancy type. The vacancy generation is responsible for the swelling of the material which produces protrusions and extrusions in fatigue.

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Chapter 4.2 Vacancy-dipole models (2)

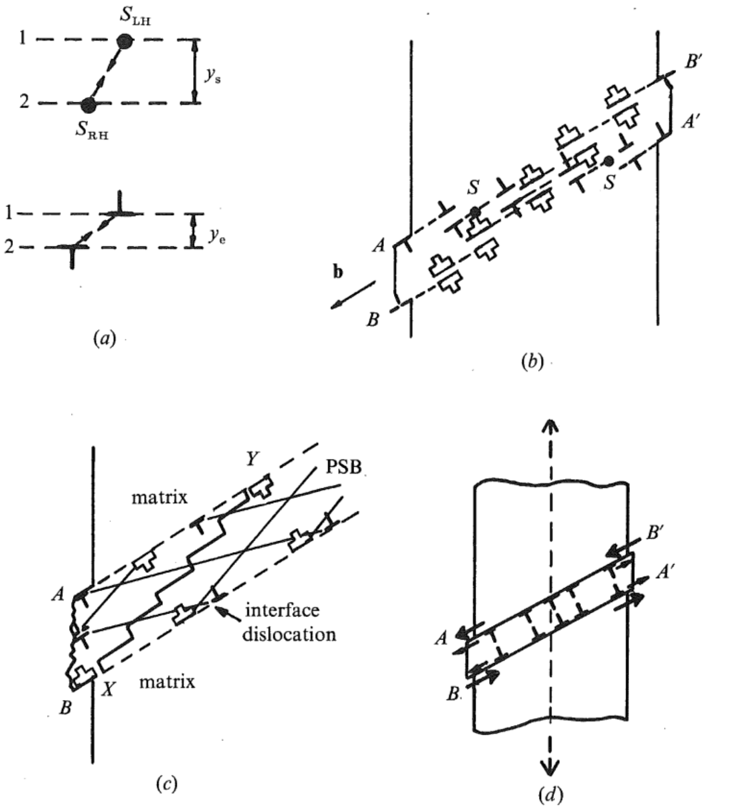

Fig. 4.4. (*a*) The critical annihilation distance for screw and edge dislocations. (*b*) Mechanism of extrusion formation by combined glide and dislocation annihilation. (*c*) Irreversible slip in the PSB creating effective interfacial dislocations which put the slip band in a state of compression. (*d*) The combined effects of applied stresses and internal stresses. Bigger arrows indicate repulsive forces on interfacial dislocations and smaller arrows denote forces caused by the applied load. (After Essmann, Gösele & Mughrabi, 1981.)

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Chapter 4.3 Crack initiation along PSBs

- In the PSB/matrix interface there are abrupt gradients in density and distribution of dislocations. Preferable site for fatigue crack nucleation.
- The strains within the PSBs are highly inhomogeneous and localized at the PSB/matrix interface.
- In materials that form PSBs crack nucleation and early growth appear in the PSB.

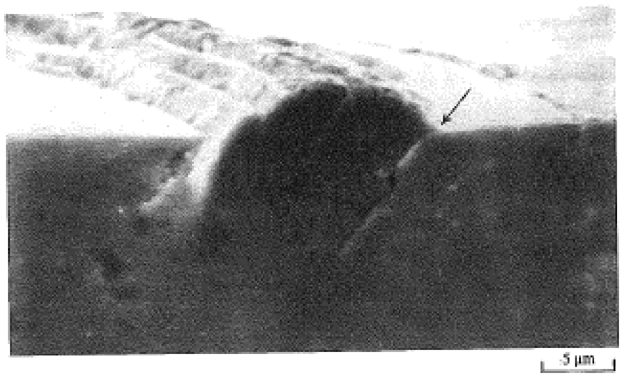

Fig. 4.5. Fatigue crack initiation (denoted by an arrow) at a PSB–matrix interface in a Cu crystal fatigued for 60 000 cycles at $\gamma_{pl} = 0.002$ at 20 °C. (From Ma & Laird, 1989b. Copyright Pergamon Press plc. Reprinted with permission.)

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Chapter 4.3 Crack initiation along PSBs (2)

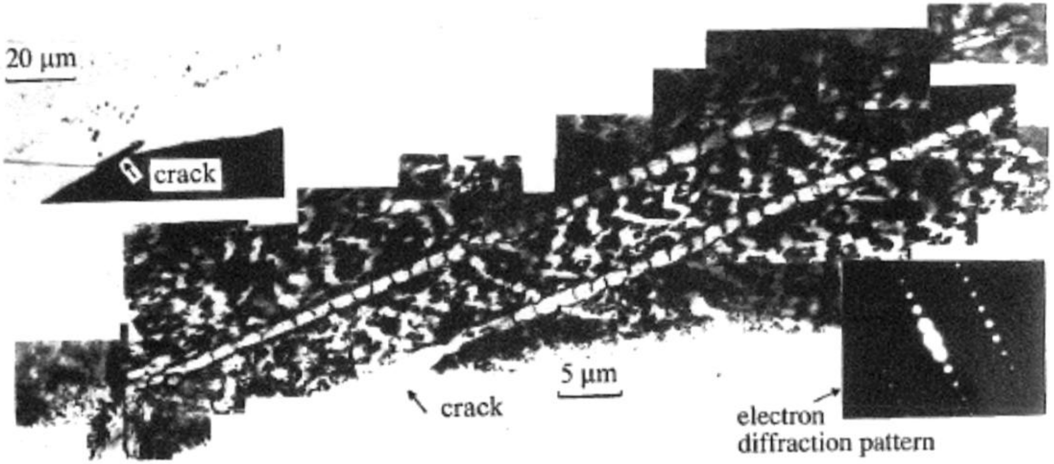

Fig. 4.6. A nascent fatigue crack along the ladder structure of a PSB in fatigued, polycrystalline copper. Inset at left is an optical micrograph showing the location of the crack with respect to the free surface. (From Katagiri *et al.*, 1977. Copyright *Metallurgical Transactions*. Reprinted with permission.)

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Chapter 4.4 Role of surfaces in crack initiation

- It is well known that a single PSB can extend through the cross section.
- Interesting to know if it is the surface topography alone which is responsible for crack nucleation or internal dislocation structures plays an equally important role.
- Experiments have shown that removing the extrusions and intrusions increased the fatigue life both for single crystals and polycristalls.

Chapter 4.6 Environmental effects on crack initiation

- The test environment plays an important role in nucleation of fatigue cracks. It effects the extent of slip irreversibility . The fatigue life is improved in vacuum.
- Oxides that are formed at the slip steps in air or chemically aggressive medium makes reverse slip difficult on the same plane upon load reversal. Also a transport of embrittling species to the bulk of the material can occur. This facilitates crack nucleation.

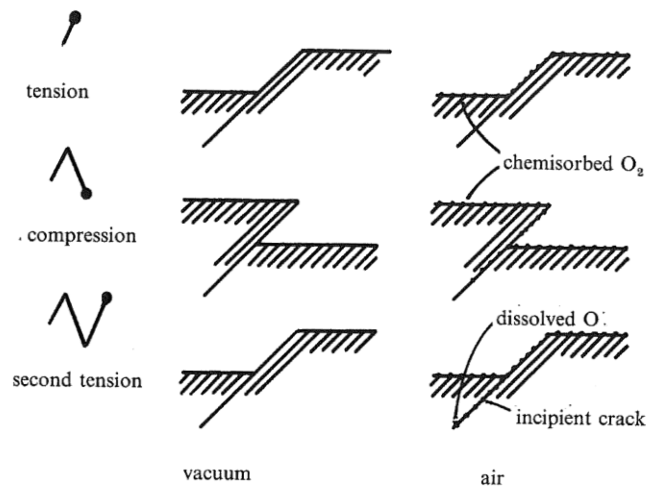

Fig. 4.8. A model for fatigue crack nucleation near a free surface by the synergistic effect of single slip and environmental interactions. (After Thompson, Wadsworth & Louat, 1956, and Neumann, 1983.)

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Chapter 4.7 Kinematic irreversibility of cyclic slip

It is the cyclic slip irreversibility that introduce and accumulate damage in the material. Several different mechanisms:

-Cross slip of screw dislocations.

-The extrusions grow at rates 1-10 nm/cycle and the protrusions a magnitude smaller.

-Random distribution of slip with progressive deepening of valleys at surfaces.

-Dislocation-dislocation interaction leading to formation of nodes, jogs or locks impending motion.

-Production of point defects during saturation.

-Irreversibility due to shape changes and difference in dislocation back stress.

-Reduction in slip displacement during unloading due to absorption of embrittling species or oxidation of slip steps.

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Chapter 4.8 Crack initiation along grain and twin boundaries

- The nucleation of fatigue cracks at GB occurs in embrittling environments and elevated temperatures.
- Intergranular failure is common in brittle solids due to thermal contraction mismatch or presence of grain boundary glass phases.
- Occurrence of GB fatigue crack nucleation is in ductile solids in absence of GB particles, creep or environmental influence is less common.
- In general, GB cracking may arise from two mechanisms:

  -At low plastic strain amplitude the impingement of PSBs at GBs cause cracking.

  - At high plastic strain amplitude GB cracking due to surface steps at the boundary

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Chapter 4.8 Crack initiation along grain and twin boundaries

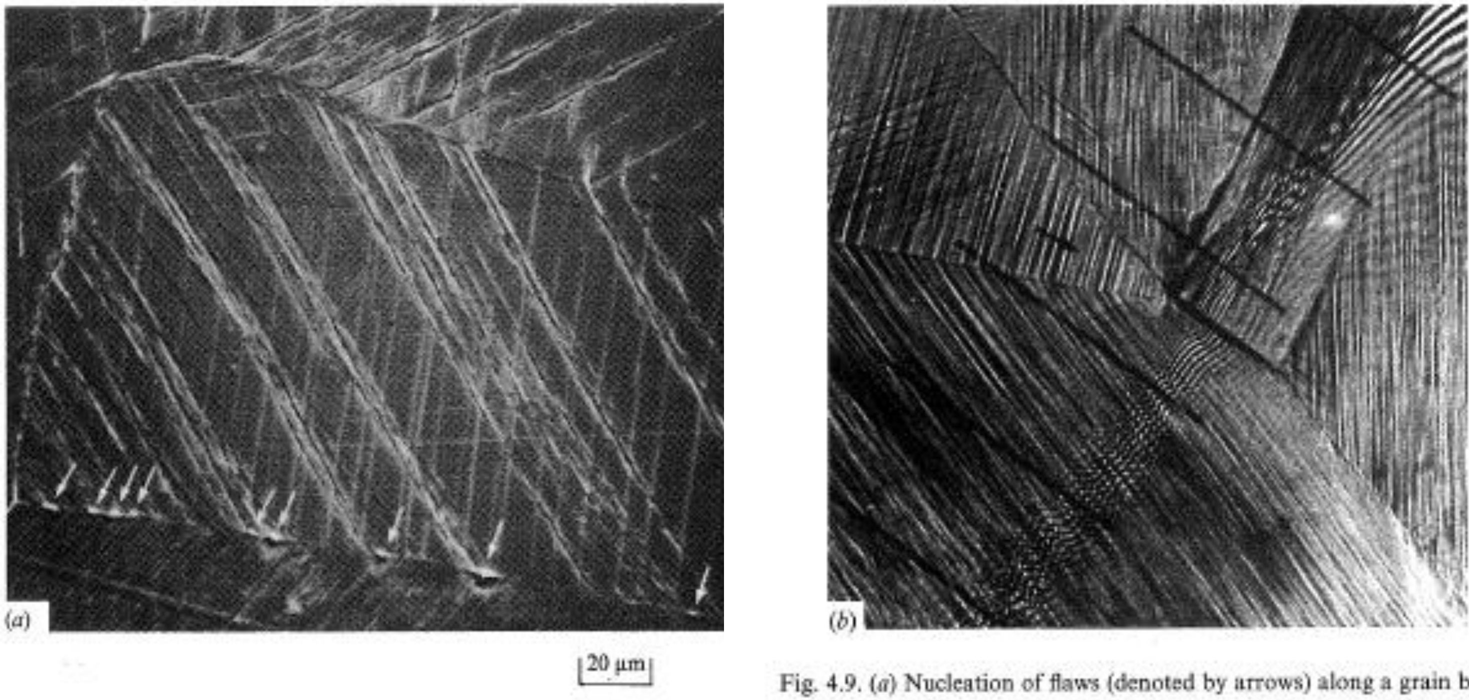

Fig. 4.9. (a) Nucleation of flaws (denoted by arrows) along a grain boundary. (From Figueroa & Laird, 1983. Copyright Elsevier Sequoia, S.A. Reprinted with permission.) (b) White light interferograms showing slip-step formation at grain boundary in fatigued Cu. (From Kim & Laird, 1978. Copyright Pergamon Press plc. Reprinted with permission.) The dark diagonal lines parallel to the arrow are fiducial markers whose separation is 100 µm.

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Chapter 4.9 Crack initiation in commercial alloys

- Many different possible sites for crack nucleation: voids, slag or gas entrapments, inclusions, dents, scratches, forging laps and folds, macroscopic stress concentrations, regions of chemical nonuniformity.
- In metals and alloys of high purity surface grains are the most likely location for crack initiation. In commercial alloys also interior locations are feasible
- Different sites most important for different alloys, see examples in the book.

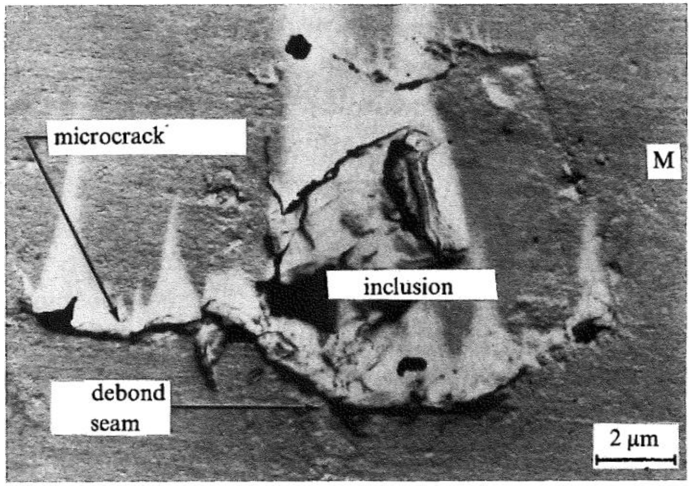

Fig. 4.11. Scanning electron micrograph showing the nucleation of a fatigue crack normal to the tensile axis (vertical direction) at the site of an $MnO–SiO_2–Al_2O_3$ inclusion which is partially debonded from the 4340 steel matrix denoted M. (From Lankford & Kusenberger, 1973. Copyright *Metallurgical Transactions*. Reprinted with permission.)

Chapter 4.10 Environmental effects in commercial alloys

- If a component is exposed to a chemically aggressive medium preferential attack at selected points at the surface may provide nucleation sites for fatigue cracks, called 'corrosion pits'. Can be locations where:

  -Slip steps or intrusions

  -Grain boundaries

  -The oxide layer is broken

  -Inclusions

  -One of the phases

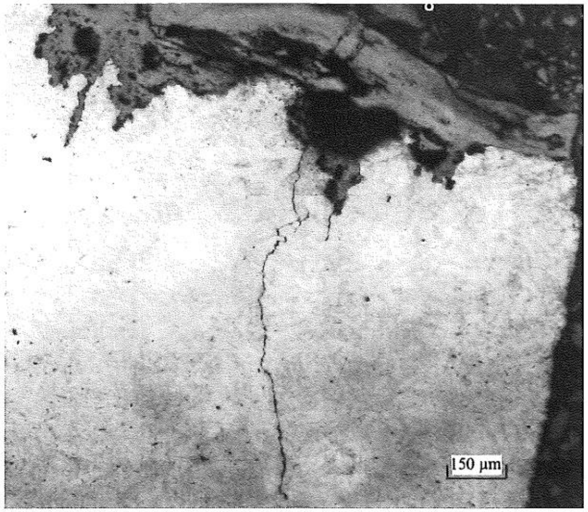

Fig. 4.14. A fatigue crack initiated at corrosion pits in stress relief groove in a low pressure turbine rotor made of Ni–Cr–Mo–V steel. (From Lindley, 1982. Reprinted with permission from T.C. Lindley.)

- Typically smaller than a millimeter in depth and serve as a micro notch.

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Chapter 4.11 Crack initiation at stress concentrations

- Initiation of fatigue cracks at stress concentrations is an important topic. Dealt with in chapters 7-9 for cyclic tension or cyclic tension-compression in the context of stress-life, strain-life and fracture mechanics approach.
- Fatigue cracks can also initiate ahead of a stress concentration under fully compressive cyclic loads. Can appear in many real applications: landing gears, railways etc.
- The cracks grow in a direction normal to the loading direction. The growth rate decreases as the distance to the notch increases until arrest appears at a certair crack length a*.

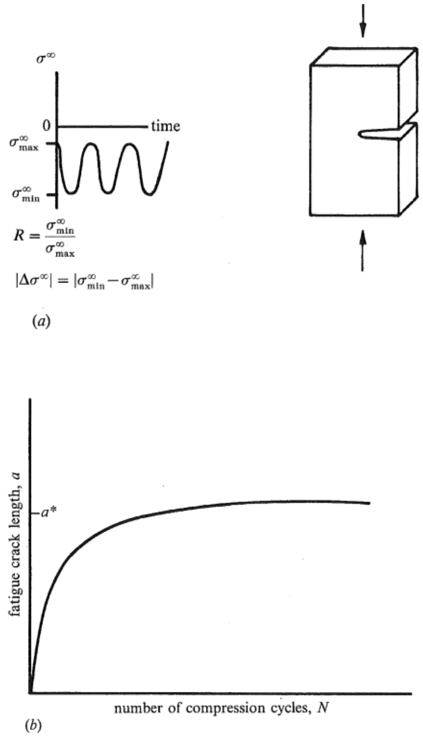

Fig. 4.15. Schematic showing (a) the loading of a notched specimen in cyclic compression and (b) typical variation of crack length, measured from the notch tip, as a function of the number of compression cycles.

Chapter 4.11 Crack initiation at stress concentrations

- Examples of cracks initiated ahead of a stress concentration in composites under fully compressive loads.

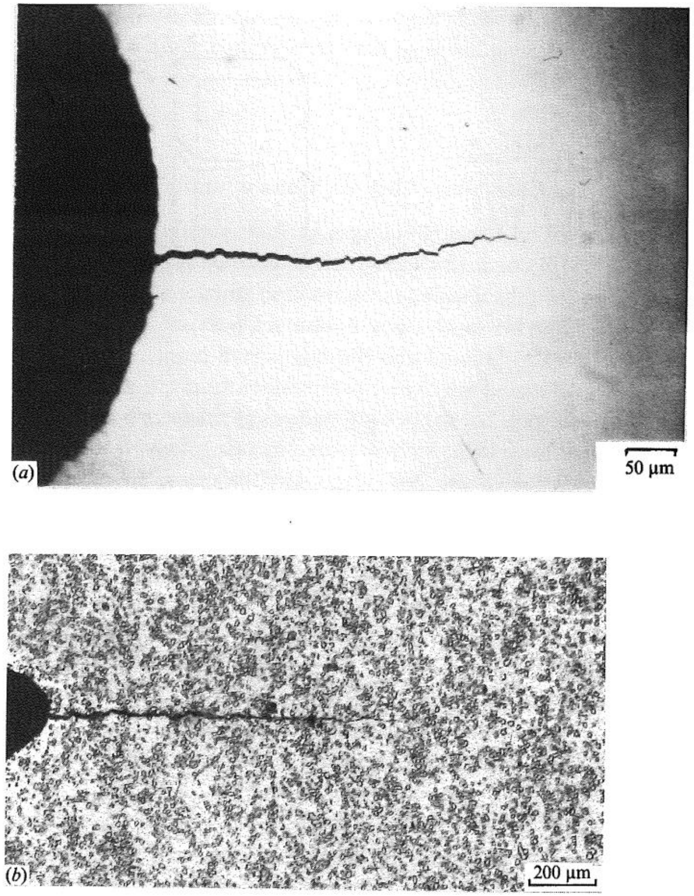

Fig. 4.16. Examples of mode I fatigue cracks initiated at stress concentrations under far-field cyclic compression:(*a*) Ti–48 Al intermetallic with a predominantly γ-phase microstructure. (*b*) Al–3.5 Cu alloy reinforced with 20 volume% of SiC particles. The cyclic compression loading axis is vertical in both cases. (Photographs courtesy of P.B. Aswath and Y. Sugimura, respectively.)

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Chapter 4.11 Crack initiation at stress concentrations

- The mechanism behind is dictated by the development of the cyclic plastic zone ahead of the notch tip.
- Residual stresses are induced ahead of the notched tip. Closest to the tip tensile stresses exists and further away compressive stresses exist. Results in that the crack can only grow a certain distance a*.
- When the crack grows the crack surfaces come in more contact resulting in lower residual stresses and lower growth rate (fig 4.15).

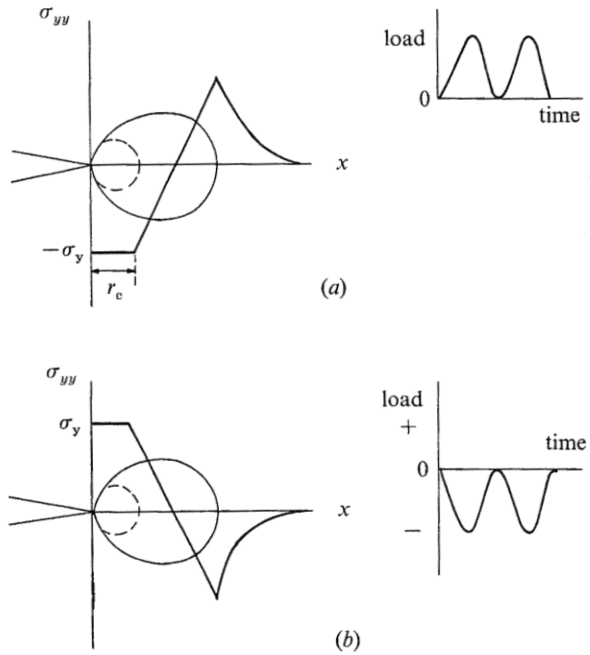

Fig. 4.17. (*a*) A schematic of a zone of residual compression ahead of a sharp notch (with a small included angle at the notch tip) subjected to cyclic tension in an elastic–perfectly plastic solid. r_c is the cyclic plastic zone defined in Eq. 9.74. (*b*) A zone of residual tension for the nonclosing notch subjected to cyclic compression.

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