Chapter 15. Small fatigue cracks

- In most investigations were continuum approaches have been used for small fatigue flaws it has been found that small flaws can grow significantly faster than long flaws for the same nominal driving force, *ΔK*.

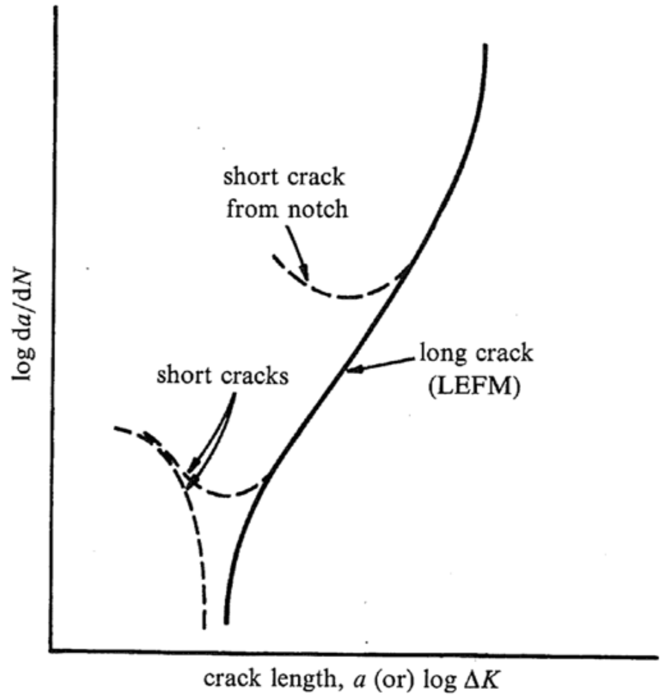

Fig. 15.1. A schematic of the typical fatigue crack growth behavior of long and short cracks at constant values of imposed cyclic range and load ratio.

Chapter 15. Small fatigue cracks (2)

- Can lead to overestimations of fatigue life for short flaws.

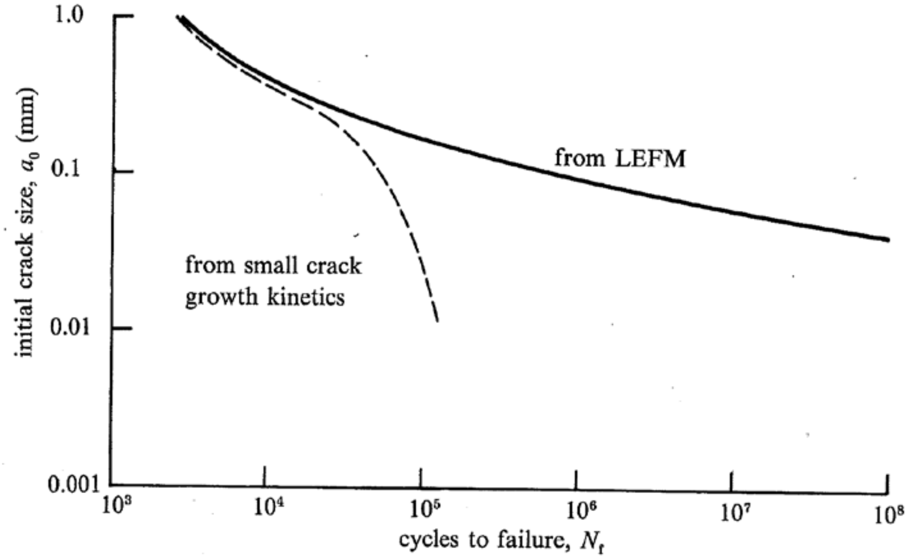

Fig. 15.2. The significance of the short crack problem is illustrated for an Astroloy. The plot shows the number of fatigue cycles to failure, estimated using LEFM and small crack growth kinetics, as a function of the initial flaw size. (After Hudak *et al.*, 1988.)

Chapter 15.1 Definition of small cracks

Different size scales below which *da/dN* exhibit a crack size dependence. Definitions of small cracks:

1. *Microstructurally small flaws*: Fatigue cracks for which the crack size is comparable to characteristic microstructurall dimension, grain size, particle spacing.
2. *Mechanically small* : When the plastic zone at the tip is comparable to the crack size.
3. *Physically small* : Larger than 1,2. Physically small around 1-2 mm.
4. *Chemically small* : Exhibit anomalies in *da/dN* below a certain crack size due to dependence of environmental effects on crack dimensions.

Chapter 15.2 Similitude

- The characterization of crack advance on the basis of LEFM is predicted upon the concept of similitude. Means that a specific material-environmental system with a certain history has identical near tip conditions for different geometries and crack lengths for the same *K* value.
- When the conditions at the tip is dependent of the crack length this concept breaks down.
- The small crack problem is the outcome that LEFM is incapable of uniquely characterize the growth of a fatigue crack independent of crack length.

Chapter 15.3 Microstructural aspects of small flaw growth

- The first report of accelerated crack growth for short fatigue cracks was presented by Pearson (1975). Found that short surface flaws could grow up to 100 times faster than long flaws at same ΔK. He also found the possibility for short flaws to grow below ΔK_{th} for long cracks.
- Initially *da/dN* decreases for a microstructurally short crack with increasing crack length.
- Subsequently increases until it merges with the behaviour of a long crack.
- The retardation of *da/dN* occurs when the crack tip reaches a GB.
- The crack grows through the GB when the plastic zone is established in the neighboring grain.
- Also full crack arrest is possible.

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Chapter 15.3 Microstructural aspects of small flaw growth

- Growth of small fatigue flaws.

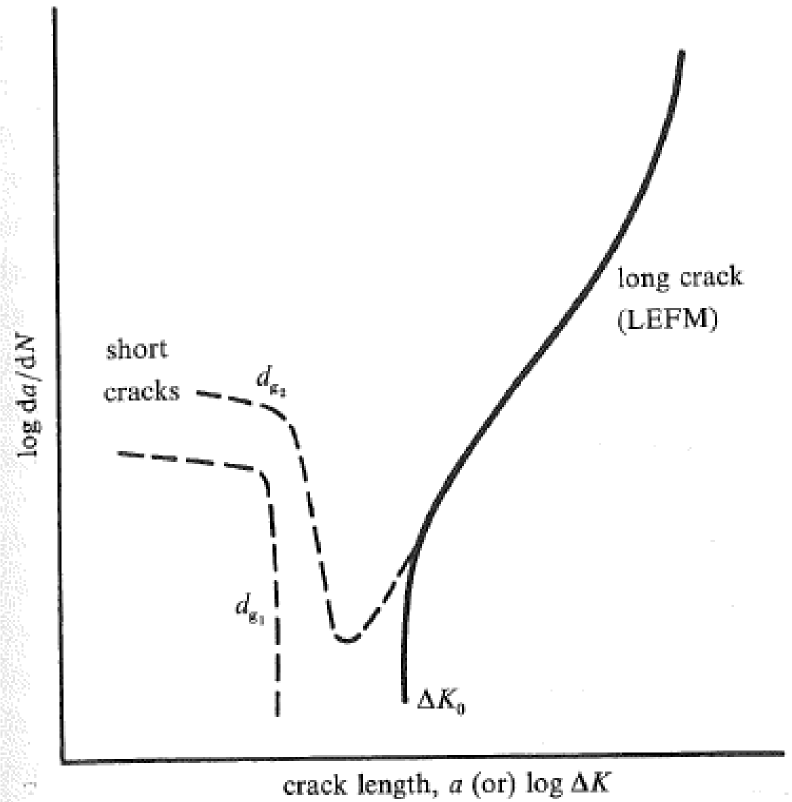

Fig. 15.3. A schematic of sub-threshold growth and transient retardation characteristics of a microstructurally small fatigue crack (dashed lines). $d_{g2} > d_{g1}$.

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Chapter 15.4 Threshold conditions for small flaws

- The stage I growth, retardation and arrest behavior indicate a different threshold value, ΔK_{th}, than for long cracks.
- For long cracks ΔK_{th} for should be crack size independent with $\Delta K_{th} = \Delta K_0$.
- Under a certain critical crack size a_0, ΔK_{th} is dependent of crack length.
- No unique definition. Low strength steels a_0≈100-1000μm, high strength steels a_0≈1-10μm

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Chapter 15.4 Threshold conditions for small flaws (2)

- Effect of crack size

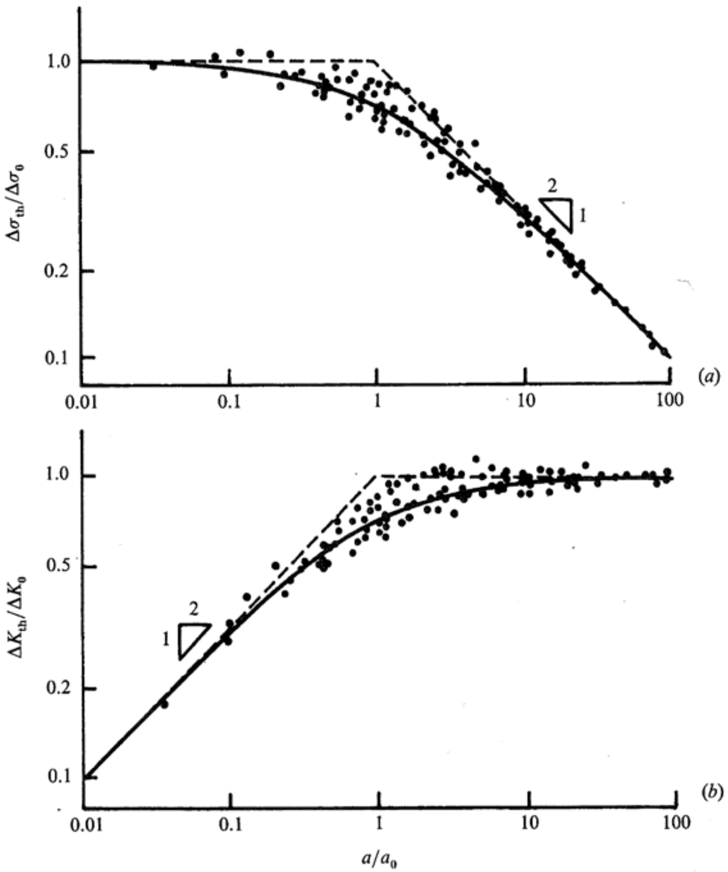

Fig. 15.4. The effect of crack size on (a) threshold stress and (b) threshold stress intensity factor range for a wide variety of engineering alloys with yield strength values ranging from 30 to 770 MPa. (After Tanaka, Nakai & Yamashita, 1981.)

Chapter 15.7 Effects of physical smallness of fatigue flaws

- Mechanical effects. Significantly longer, usually 0.5-2mm, than both the scale of the microstructure and size of near tip plastic zone. In principle LEFM could be used.
- However, it has been found that physically small flaws propagate faster than long cracks at the same *ΔK*.
- This effect is due to the limited wake existing for such short cracks, resulting in less crack closure and higher growth rates.

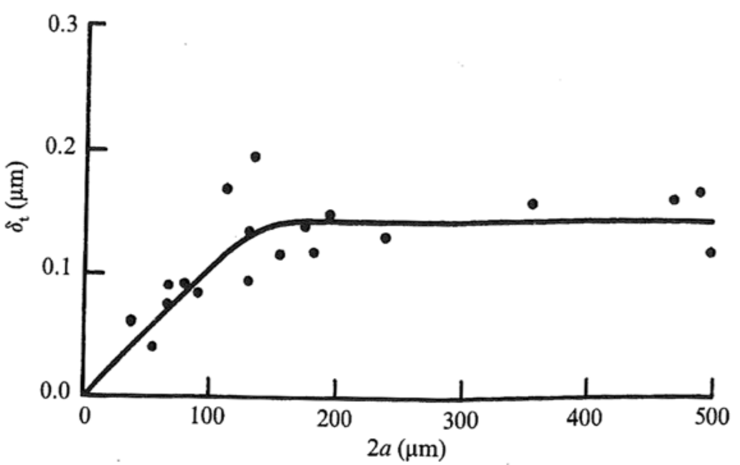

Fig. 15.12. The variation of the crack tip opening displacement δ_t at zero far-field load as a function of crack length 2*a* in a Ti–Al–Zn–Sn–Mo alloy. (After James & Morris, 1983.)

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Chapter 15.7 Effects of physical smallness of fatigue flaws (2)

- Environmental effects

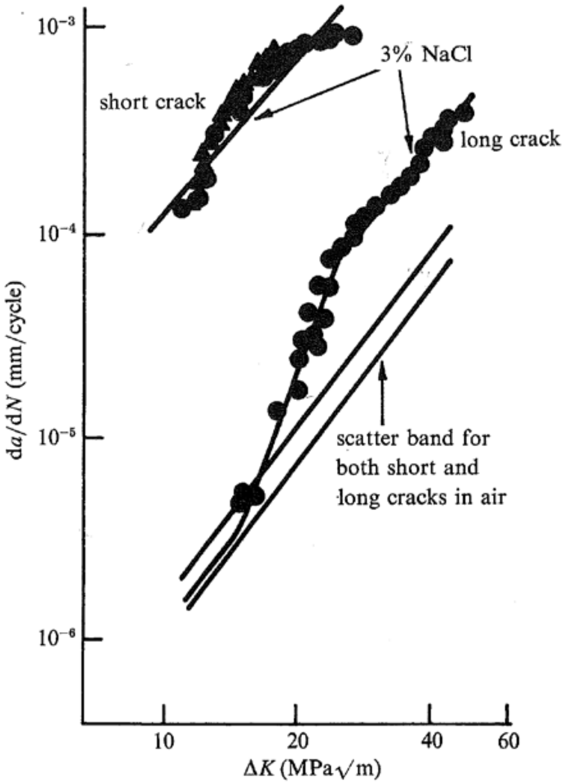

Fig. 15.13. The growth of long ($a \approx 50$ mm) and physically short ($a \approx 0.1 - 0.8$ mm) linear elastic fatigue cracks in laboratory air and 3% NaCl at room temperature. (After Gangloff, 1981.)

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Chapter 15.8 On the origins of ‘short crack problem’

- Local microscopic discrepancies i.e. GB, inclusions, precipitates can influence growth rate and crack path.
- The growth mechanisms are different to long cracks at identical ΔK due to difference in constraints by surrounding material. Stage I growth also gives rise to mixed mode loading at crack tip.
- The driving force for long and short cracks. The combined effect of crack deflection and crack tip plasticity is different to that of long cracks.
- Even when loading conditions and crack length satisfy LEFM a physical small crack grows faster due to less crack closure.
- In some corrosive media, the similitude concept is violated as a consequence of size-dependent corrosion fatigue mechanisms.
- No simple solution for engineers is available when developing design guidelines for components containing small flaws.

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Chapter 16. Environmental interactions: corrosion-fatigue and creep fatigue.

- The effect of the environments on the nucleation and growth of fatigue cracks have been discussed in chapters 4, 10, 14 and 15.
- Often the environment has an deleterious effect, although sometimes a beneficial effect on fatigue crack growth.
- Important part to be able to get a complete mechanistic theory or design methodology for fatigue fracture.
- In this chapter the effects of environment on fatigue behavior.
- In this course only the first part of corrosion fatigue, chapter 16.1-16.3, is included.

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Chapter 16.1 Mechanisms of corrosion fatigue

The deterioration of fatigue properties can be caused by an external medium in the form of a solid, liquid or gas.

- *Metal embrittlement*: weakening of a higher melting point metal in contact with certain lower melting point metals.
- *Liquid metal embrittlement*: metal embrittlement where the embritteling medium is a liquid metal.
- *Stress corrosion cracking (SCC)*: Embrittlement of alloys resulting from aqueous solutions.
- *Hydrogen embrittlement*: Hydrogen can be introduced (from hydrogenous gases) into the metal by dissociation of hydrogen molecules into atomic hydrogen or by release of hydrogen by metal dissulution.
- *Corrosion fatigue*: Damage and failure of a material under the combination of cyclic stresses and embrittling medium.

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Chapter 16.1 Mechanisms of corrosion fatigue (2)

Hydrogenous gases

- Metals exposed to hydrogenous gases. Key steps in inducement of hydrogen embrittlement:

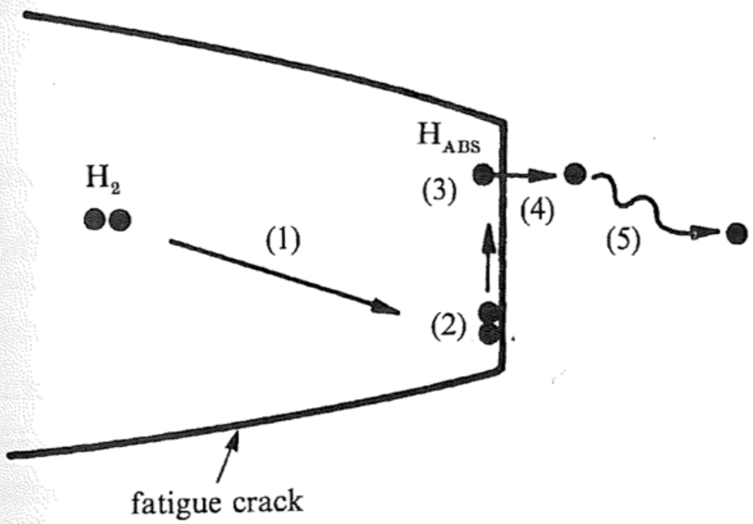

Fig. 16.1. An idealization of the critical steps involved in hydrogen embrittlement in hydrogenous gas media. (1) Transport of gaseous hydrogen. (2) Surface adsorption. (3) Dissociation into hydrogen atoms. (4) Hydrogen intake into the lattice. (5) Transport in material to regions of high tensile hydrostatic stresses.

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Chapter 16.1 Mechanisms of corrosion fatigue (2)

- Once atomic hydrogen is inside the material embrittlement occurs due to:
  - Decohesion of atomic bonds or interfaces.
  - Formation of molecular hydrogen at voids or defects.
  - Lowering of surface energy due to absorbed hydrogen.
  - Hydrogen precipitation.
- No single theory accounts for all effects.
- The fracture of a metal in the presence of hydrogen occurs in one of two ways:
  - Rate of failure is accelerated although no change in mode of fracture.
  - Transition from ductile to brittle mode of failure.

Chapter 16.1 Mechanisms of corrosion fatigue (3)

- Involve the mechanism of electrochemical reaction of freshly formed slip steps or at the crack tip. Includes two candidate mechanisms.
  - Anodic slip dissolution (Fig.16.2a)
  - Hydrogen embrittlement (Fig.16.2b)
- When a passivating oxide film is formed on the surfaces the reaction at the crack tip is controlled by: oxide rupture rate, solution renewal rate and passivation rate.
- Cyclic frequency and stress wave form has a strong influence on crack growth.

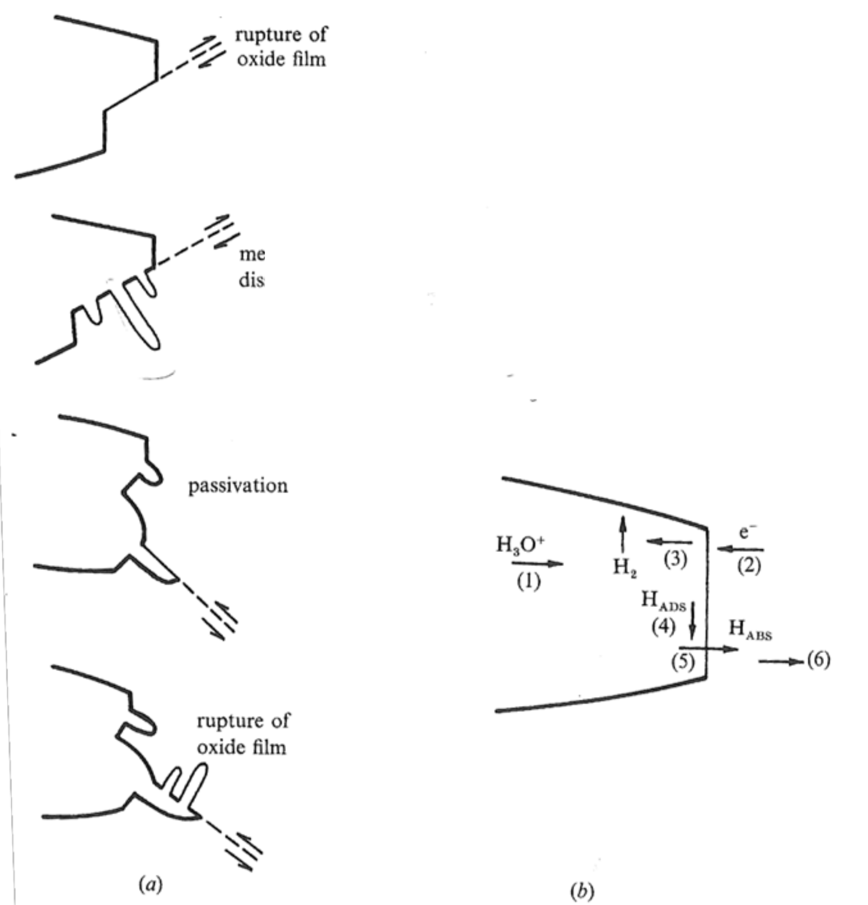

Fig. 16.2. A schematic illustration of (*a*) slip dissolution and (*b*) hydrogen embrittlement in aqueous media. (1) Liquid diffusion. (2) Discharge and reduction. (3) Hydrogen adatom recombination. (4) Adatom surface diffusion. (5) Hydrogen absorption in metal. (6) Diffusion of absorbed hydrogen. (After Ford & Silverman, 1979.)

Chapter 16.1 Mechanisms of corrosion fatigue (4)

Metal embrittlement (LME)

- Many materials exhibit a lower resistance to fatigue crack growth and initiation in an embrittling liquid metal (ex. Hg) than in aqueous and hydrogen environments.
- Is caused by absorption of the embrittling metal atom at slip steps and crack tips.
- Conventional models postulate that adsorption of the liquid metal lowers the stress necessary for the tensile separation of atoms.
- In an alternative model the mechanism behind LME is that the absorbed atom weakens the resistance of the material to plastic flow. Results in coalescence of cracks and voids in front of the crack tip.

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Chapter 16.1 Mechanisms of corrosion fatigue (5)

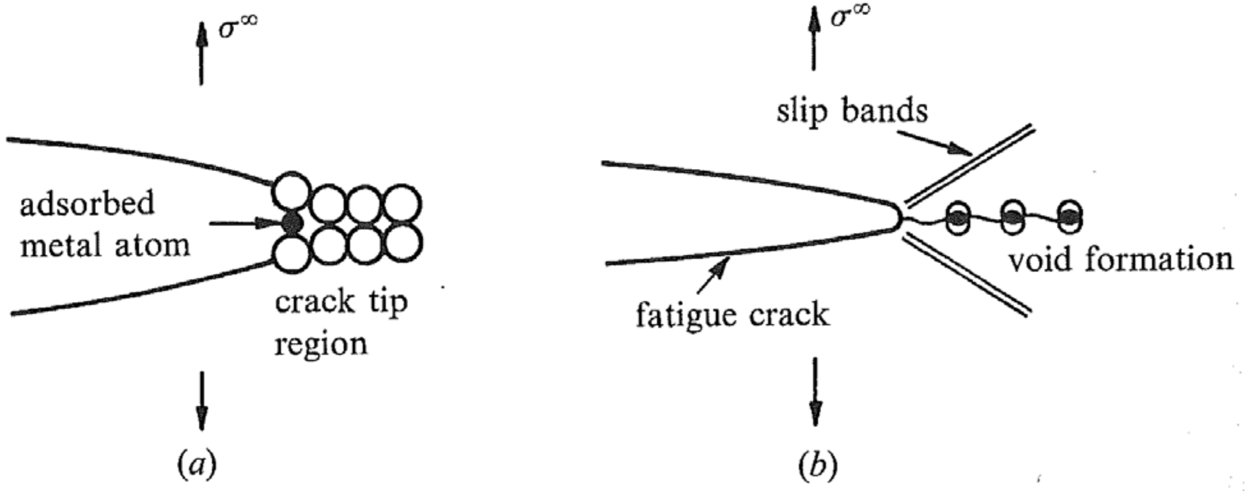

Fig. 16.3. Idealization of (*a*) solid or liquid metal embrittlement due to decohesion, and (*b*) liquid metal embrittlement due to increased local plastic flow and void growth.

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Chapter 16.2 Nucleation of corrosion-fatigue cracks

- Experimental work has shown that oxygen-containing media, moist and aqueous environments generally reduces fatigue life in ductile solids.
- Gaseous environments: Two mechanisms. 1. Oxidation of slip steps (Fig 4.8). 2. Surfaces of ductile alloys are strengthened with an oxide film. During cyclic load dislocations accumulate leading to cavities and voids, grow into cracks-
- Aqueous environments: No universal conclusions. Some mechanisms and conclusions listed in the book. The rate of the environmental impact and its influence on the fatigue life depends on the electrochemistry of the medium and loading conditions.

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Chapter 16.2 Nucleation of corrosion-fatigue cracks (2)

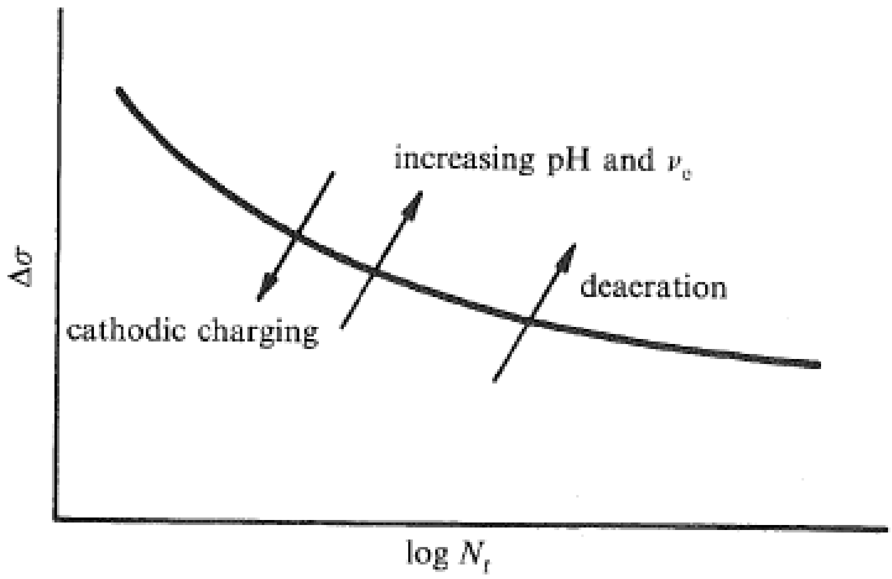

Fig. 16.4. A schematic of the effects of corrosive media on the number of cycles to failure, N_f, under a fixed cyclic stress range, $\Delta\sigma$.

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Chapter 16.3 Growth of corrosion fatigue

- Convenient to characterize the effect of environment on the fatigue crack growth by considering different combinations of growth rates measured under purely mechanical fatigue and stress corrosion conditions.
- Corrosion fatigue crack growth in metals can be represented in three ways (Fig. 16.5c-e)
  - True corrosion fatigue
  - Stress corrosion fatigue
  - Mixed corrosion behaviour

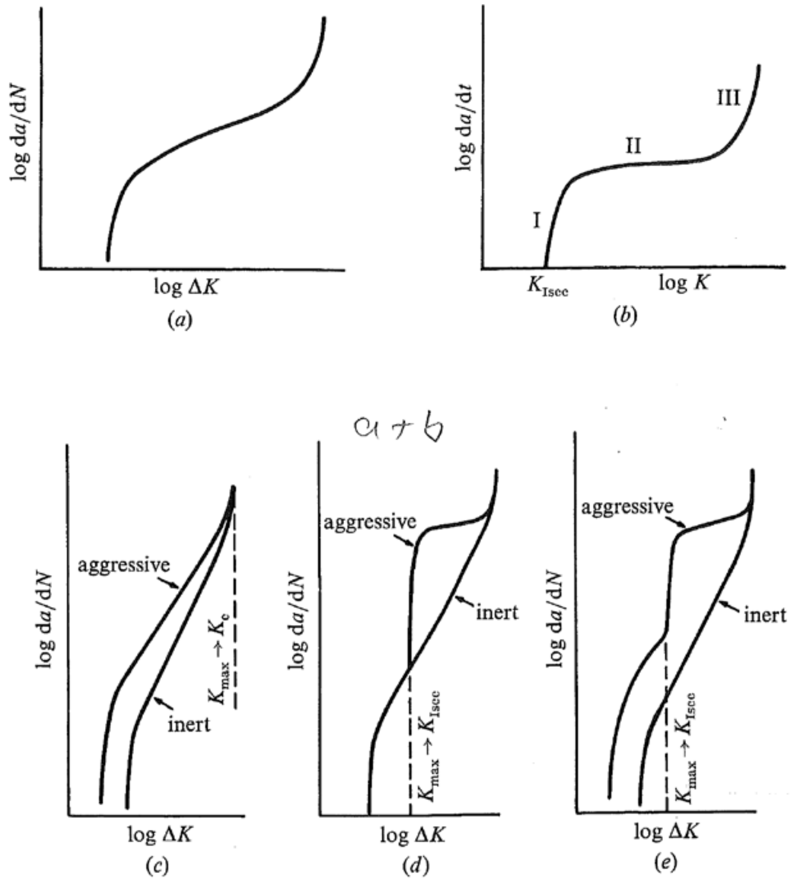

Fig. 16.5. Schematic representations of the combinations of mechanical fatigue and environmentally assisted crack growth. (*a*) Fatigue crack growth behavior in inert environments. (*b*) Stress corrosion crack growth under sustained loads. (*c*) True corrosion-fatigue arising from synergistic effects of cyclic loads and aggressive environment. (*d*) Stress corrosion-fatigue behavior obtained from a superposition of mechanical fatigue (*a*) and stress corrosion cracking (*b*). (*e*) Mixed corrosion behavior obtained from a combination of (*c*) and (*d*). (After McEvily & Wei, 1972.)

Chapter 16.3 Growth of corrosion fatigue (2)

- Typical fatigue crack growth characteristics of high strength steels.

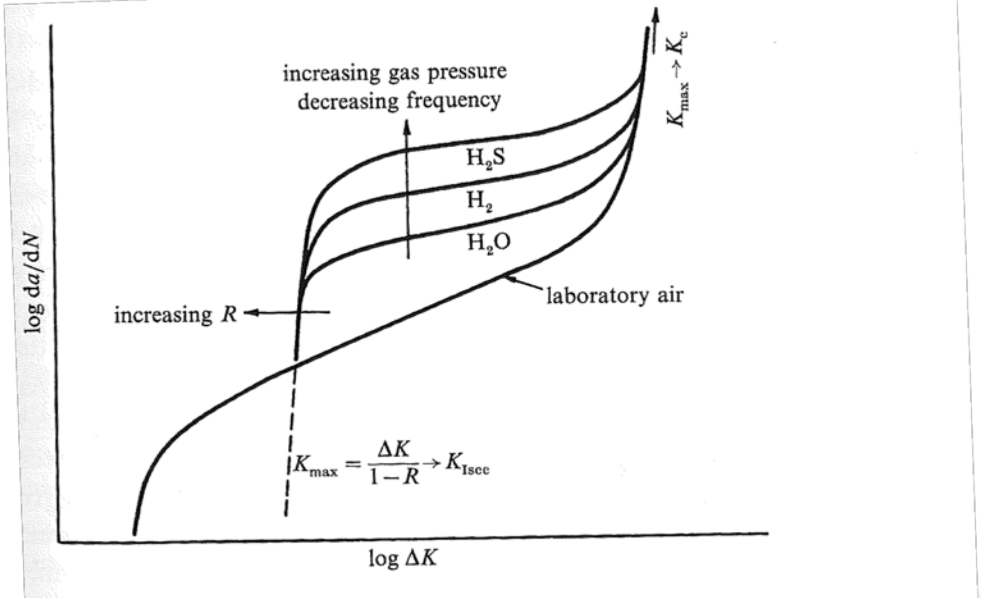

Fig. 16.6. Schematic illustration of the effects of environment, test frequency and R ratio on fatigue crack growth in high strength steels.

- Superposition of mechanical fatigue and stress corrosion cracking gives a reasonable accurate description in many high strength materials. Not the case for low strength materials.

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Chapter 16.3 Growth of corrosion fatigue (3)

Effect of mechanical variables:

Frequency

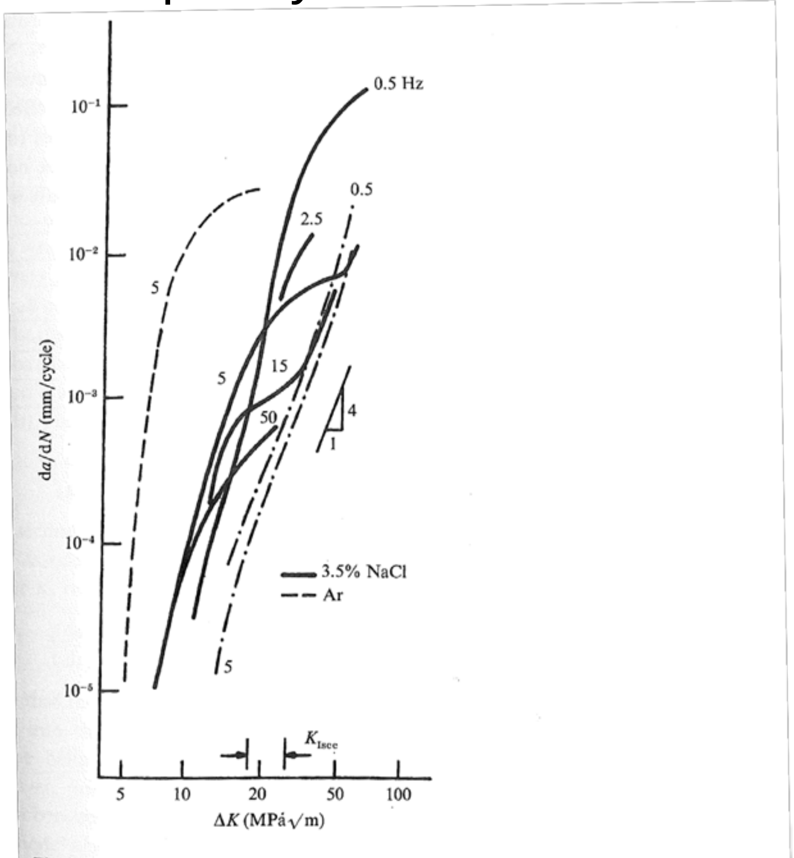

Fig. 16.9. Influence of frequency on the rate of fatigue crack growth in mill-annealed Ti–8Al–1Mo–1V alloy in 3.5% NaCl and in argon gas at $R = 0.05$ and sinusoidal cyclic load variation at room temperature. The dashed curve at left shows the fatigue crack propagation behavior in 3.5% NaCl at $R = 0.75$ and at 5 Hz frequency. (After Bucci, 1970.)

stress waveform

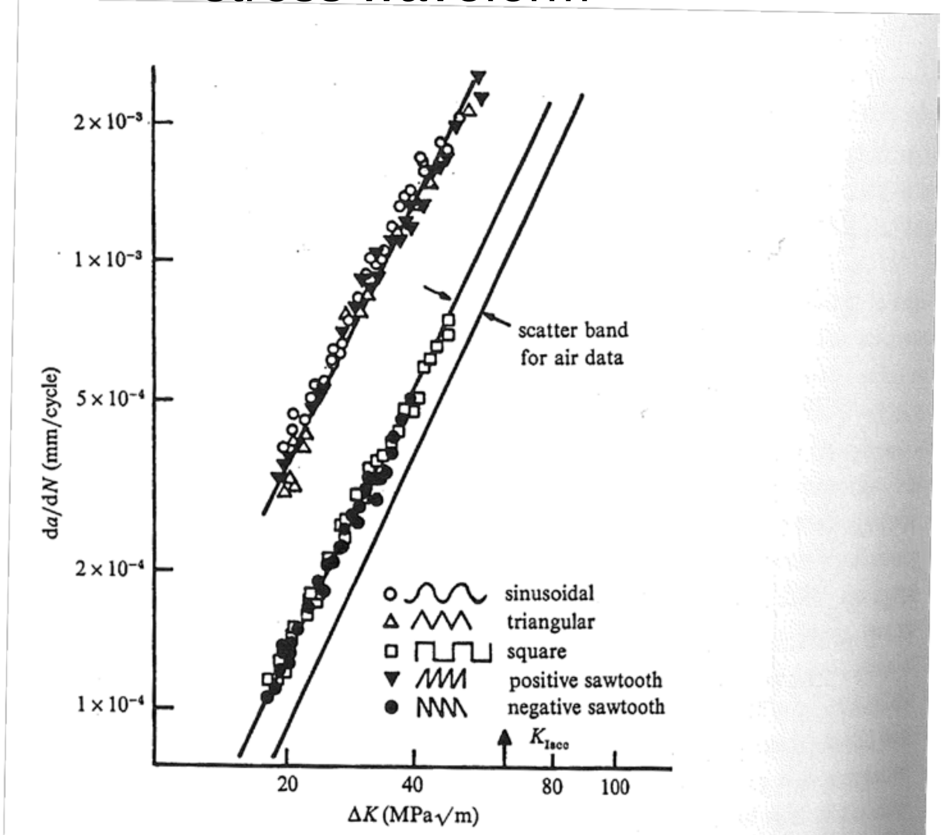

Fig. 16.10. The effect of stress waveform on fatigue crack growth in 12Ni–5Cr–3Mo steel in 3% NaCl solution at 0.1 Hz at room temperature. (After Barsom, 1972.)

Chapter 16.3 Growth of corrosion fatigue (3)

- There does not exist a single model capable of predicting the features of environmentally assisted fatigue for broad classes of materials and environments.
- Simple approaches uses superposition of crack growth rates for purely mechanical fatigue and stress corrosion crack growth rate:

$$\left(\frac{\mathrm{d}a}{\mathrm{d}t}\right) = \left(\frac{\mathrm{d}a}{\mathrm{d}t}\right)_{\mathrm{F}} + \left(\frac{\mathrm{d}a}{\mathrm{d}t}\right)_{\mathrm{SC}}. \tag{16.2}$$

$$\left(\frac{\mathrm{d}a}{\mathrm{d}t}\right)_{\mathrm{SC}} = \nu_{\mathrm{c}} \int_0^{1/\nu_{\mathrm{c}}} \frac{\mathrm{d}a}{\mathrm{d}t}(K)\,\mathrm{d}t. \tag{16.3}$$

- Can be used for a limited number of systems such as high strength steels.

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