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SHORT CRACKS AND CRACK CLOSURE IN AL 2024-T3

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Abstract

Short fatigue cracks are known to propagate at rates faster than corresponding long cracks at the same nominal driving force. This anomalous behaviour can be considered to arize from a number of different reasons. In this paper it is shown that one significant contribution to the different behaviour of short and long cracks is due to plasticity-induced crack closure effects. The effective range of stress intensity factor at short crack lengths is greater than at long crack lengths and the crack propagates faster. The analysis is carried out by elastic-plastic finite element calculations for a growing fatigue crack.

I. Introduction

Current design of both military and civil aircrafts relies on damage tolerance concepts in order to ensure adequate durability and strength of fatigue damaged structures. Although there exist differences in the adoption of damage tolerance requirements in different countries, as well as differences between military and civil requirements, most existing specifications resemble the USAF mandatory specification MIL-A-83444(1). In this document it is specified that a small corner crack of .005" radius (0.127 mm) shall be assumed to exist at every hole. Such small cracks are of importance in structural joints, e.g. pressure cabin longitudinal joints, where a high stress intensity factor may be produced at a short crack due to high fastener load transfer.

However, recently it has been recognized that there exists a short crack anomaly, typically for crack lengths less than about 0.5-1.0 mm depending on material system. Several researchers(2)-(7) have found that, at the same nominal driving force, the growth rates of short cracks are greater than the corresponding growth rates of long cracks, schematically depicted in Figure 1.

Although most experimental studies on short fatigue crack growth have been performed with constant-amplitude loading there exist some results conducted with spectrum loading(8) showing the same type of short crack growth anomalies as mentioned above.

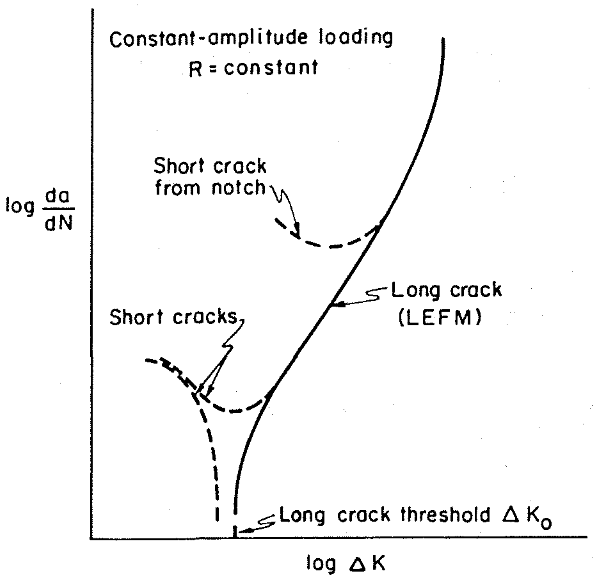

Figure 1. Schematic representation of typical fatigue crack propagation rate (da/dN) data for long and short cracks as a function of the stress intensity factor range (ΔK).

Thus, it may be concluded that the current use of existing long crack data together with concepts of linear fracture mechanics, as adopted in damage tolerant lifetime calculations, yields non-conservative life predictions when the initial flaw size is in the short crack regime.

In this paper it will be discussed how the differences in short and long crack growth behaviour may be rationalized in terms of appropriate fracture mechanics characterisation and the physics and mechanisms involved in crack advance. Further on, it will be shown that a major cause for the short crack anomaly may be attributed to crack closure effects. Finally, an elastic-plastic finite element analysis of a short fatigue crack is presented. It is shown how plasticity-induced closure gradually increases towards a steady-state value as the crack grows.

II. Short Crack Anomalies

In this section it will be discussed which phenomena that may cause the differences between the short and long crack growth behaviour. For a more detailed discussion it is referred to several recent reviews(9)-(12).

Limitations in Linear Elastic Fracture Mechanics

Conventional long fatigue crack growth data are plotted versus the range of the elastic stress intensity factor K. Thus, it is assumed that the local crack tip stresses σ_{ij} can be adequately characterized in terms of the K singular field:

$$\sigma_{ij}(r,\theta) = \frac{K_I}{\sqrt{2\pi r}} f_{ij}(\theta) + \sum_{n=1}^{\infty} C_n r^{(n-1)/2} f_{n_{ij}}(\theta) \tag{1}$$

where K_I is the Mode I stress intensity factor, r is the distance ahead of the crack tip, θ is the polar angle measured from the crack plane and f_{ij} is a dimensionless function of θ.

However, as the crack length decreases it has been shown(13) that higher order terms, as shown in equation (1), may have an appreciable effect since the size of the singular region is reduced for shorter cracks in the normalized sense. Consequently, conventional LEFM approaches can be inappropriate for short cracks, even under elastic conditions, since higher order terms than $r^{-1/2}$ normally are neglected.

When the crack size is small compared to the plastic zone size r_p, see equation (2) where σ_y is the yield stress and C is a constant varying between $1/2\pi$ and $1/24\pi$ depending on whether in plane stress or plane strain and if monotonic or cyclic conditions are assumed. LEFM is no longer valid, which may partly explain the short crach anomaly when data are plotted versus ΔK.

$$r_p \sim C \left(\frac{K_I}{\sigma_y}\right)^2 \tag{2}$$

The utilization of elastic-plastic fracture mechanics has partly been shown to resolve the short crack problem. In Figure 2 short crack growth results obtained by Dowling(14) are plotted as function of ΔJ (J being Rice's path independent integral(15)), and it is seen that short and long crack growth data correlate quite well. However, this approach is not sufficient since the influence of crack closure, to be discussed in more detail subsequently, is not accounted for. Also, the use of ΔJ in situations involving alternating plasticity is questionable, since J is derived using deformation theory of plasticity and hence becomes unvalid if unloading occurs.

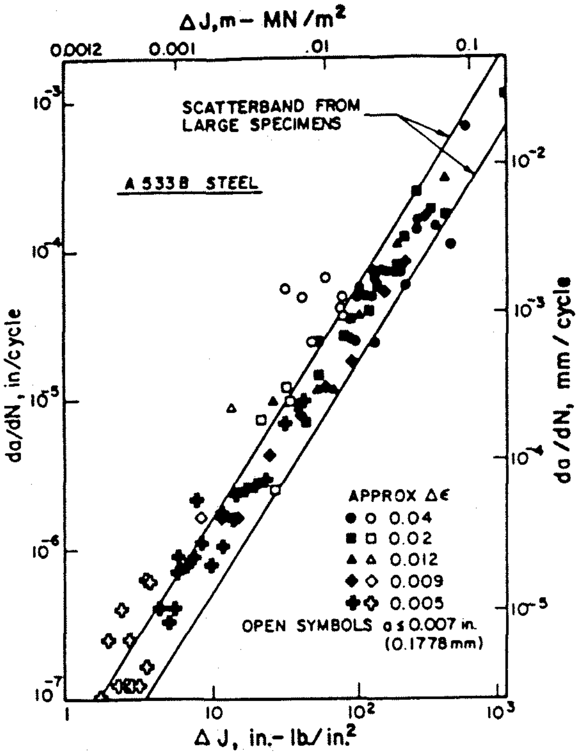

Figure 2. Fatigue crack growth rates for short and long cracks in A533B steel as function of ΔJ. (Ref. 14).

Notch Tip Plasticity

Frequently, fatigue cracks are initiated from notches rather than at smooth surfaces. Here the behaviour of short fatigue cracks is found to be influenced by the plastic zone due to the notch(16), Figure 3. It is generally found that short fatigue cracks nucleated at a notch tip initially grow faster than longer cracks, then follows a deceleration in growth rate until the crack arrests or assumes the growth rate for longer cracks(6).

It is yet unclear why this fatigue behaviour occurs for short cracks initiated at notches, but it is assumed that crack closure, to be discussed subsequently, is a major contributing effect.

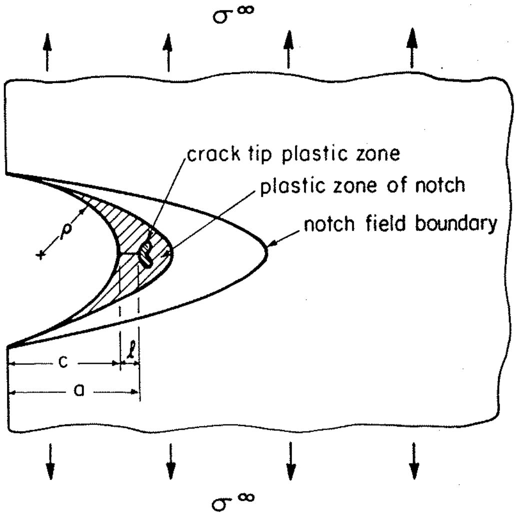

Figure 3. Plastic zone sizes of crack tip and notch tip. (Ref. 16).

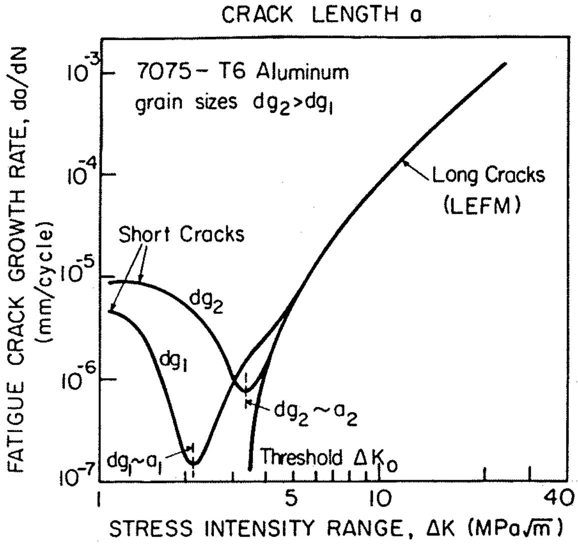

Figure 4. Effect of grain size (d_g) on the crack growth rate of microstructurally short cracks in Al 7075-T6. (Ref. 17).

Microstructural Influence

For very short cracks, the length of the crack may become less than or equal to the characteristic microstructural features, e.g. grain size or inclusions, of the material. If this is the case, continuum considerations may not be adequate but some micro-mechanics analysis should be used to characterize the short fatigue crack growth behaviour.

Generally, it is found that microstructurally short cracks initially, at stress intensity ranges well below the threshold stress intensity factor, have growth rates up to two orders of magnitude faster than those of long cracks(11, 17), Figure 4. When the cracks grow they will decelerate, or even arrest, before merging with the long crack data. It is seen in Figure 4, for a 7075-T6 aluminium alloy, that the short crack growth rate minima occur approximately for crack length equal to the grain size. Several workers(5, 17-19) have found that grain boundaries act as an impedence to short crack growth. It has been proposed(18) that this result can be explained by considering the combined effect of cessation of propagation into a new grain until a mature plastic zone is developed and the retardation of propagation due to an elevated crack closure stress.

Other workers(11, 20) explain the interaction of short cracks with microstructural features as resulting principally from crack deflection(20) and associated crack closure mechanisms(6).

Crack Extension Mechanisms

It has been pointed out(9) that the restraint of the elastic surrounding on a short crack at a free surface is different compared to slip at a crack tip of a long crack tip inside the material. At a free surface there is low restraint on cyclic slip, and also less effective strain hardening due to dislocations running out of the material, promoting cyclic slip along the slip system with the highest critical resolved shear stress. This results in initial Mode II and Mode I slip band cracking. For a long crack though, it becomes very difficult to maintain slip band cracking in one single direction in each grain since this is incompatible with a coherent crack front. As the restraint on cyclic plasticity increases more slip band systems will become activated and as a result the crack will grow in a non-crystallographic mode of crack advance by alternating or simultaneous shear (striation growth). At low ΔK-values, where the extent of local plasticity is very small, even long cracks propagate in the single shear mode with the orientation of the slip band cracking changing at each grain boundary, thus leading to a faceted crack path morphology(9, 11). A shear mode of crack growth in conjunction with a faceted fracture path will significantly influence the amount of crack closure(11, 20-22), which will further enhance the differences in short and long crack growth behaviour.

Crack Closure Effects

It is now well recognized that fatigue cracks may be closed during a part of the load cycle even if the loading is nominally tension-tension. This phenomenon, denoted crack closure, occurs as a result of permanent tensile plastic deformation left in the wake of a propagating crack(23). Since short cracks only have a limited wake it is expected that there will be less crack closure than for longer cracks. Thus, it is assumed that for the same nominal driving force, short cracks will be subjected to a larger effective value compared to the longer cracks, and hence shorter cracks may be expected to grow faster than longer cracks. As will be shown in the next section, such differences in effective driving forces for short and long cracks do indeed occur due to the above discussed plasticity-induced crack closure effect. However, at low ΔK-values, where short cracks normally are studied, not only plasticity-induced closure but also other crack closure mechanisms prevail, Figure 5.

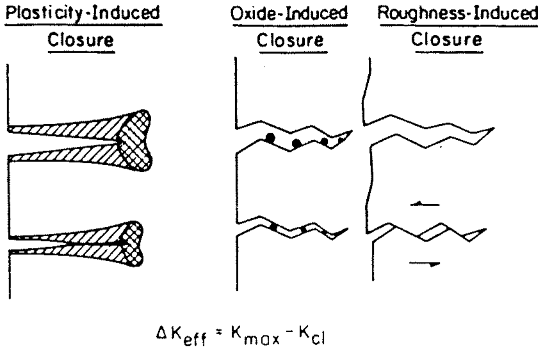

Figure 5. Different crack closure mechanisms. ΔK_{eff} is the effective stress intensity at which the two fracture surfaces come into contact. (Ref. 24).

Oxide-induced crack closure(21, 22, 25, 26) results from corrosion debris formed on freshly exposed surfaces at the crack tip due to fretting between the fracture surfaces arising from plasticity-induced closure. Oxide-induced closure will be further promoted from the effect of roughness-induced crack closure(21, 22, 24, 26, 27) which arises from surface roughness and an irregular fracture morphology in conjunction with a Mode II shear displacement. A long crack will at near-threshold levels have developed a faceted morphology and the crack surfaces will due to the local shear displacements come into contact early during unloading. Such premature closure will not occur for a short crack with a length less than one grain diameter since it will not have changed direction at a grain boundary and will not have formed a faceted morphology, although the crack extension occurs via the same single shear mechanism(11).

It is likely that the major reason for the anomalous behaviour of short fatigue cracks, as compared to longer cracks, can be attributed to less crack closure for short cracks. In fact, some workers(6) have been able to correlate short and long crack growth data into one single curve, Figure 6, by measuring the extent of closure as the crack grows and then plotting the data in terms of the effective stress intensity range ΔK_{eff} incorporating the experimental closure measurements.

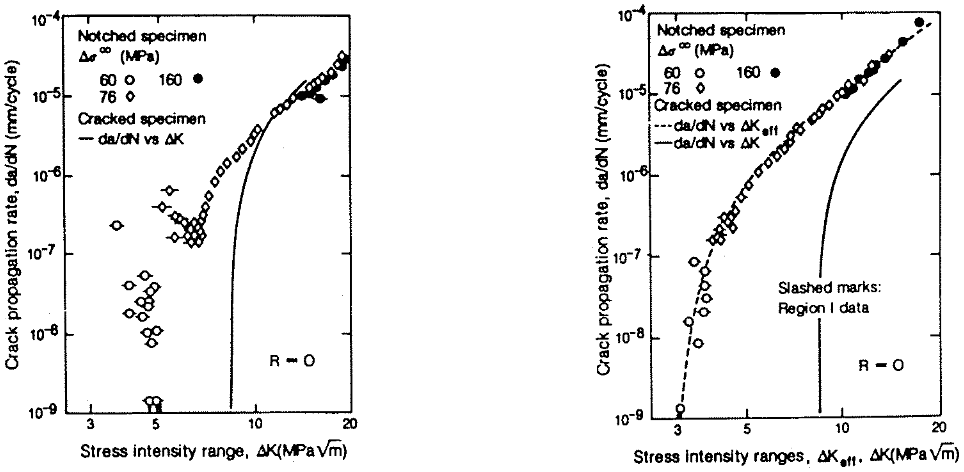

Figure 6. Variation of crack propagation rate with nominal and effective stress intensity ranges, ΔK and ΔK_{eff}, respectively, in a mild steel. (Ref. 6).

Environmental Interaction

The discussed differences in crack growth behaviour between short and long cracks have sofar been largely concerned with the threshold regime. However, large differences have also been found well outside the threshold regime due to environmental factors. In Figure 7 it is shown how corrosion fatigue crack propagation rates of short cracks can be up to two orders of magnitude faster than corresponding rates of long cracks at the same ΔK level, although behaviour in inert atmosphere was essentially the same for both short and long cracks(28).

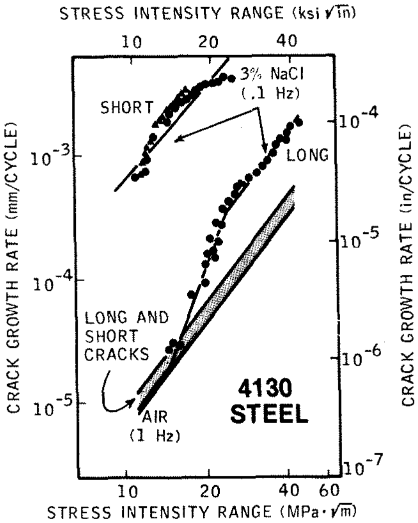

Figure 7. Fatigue crack growth rate as a function of ΔK for short (0.1-0.8 mm) and long (~50 mm) cracks for 4130 steel tested in moist air and in aerated 3% NaCl solution. (Ref. 28).

This environmentally-assisted behaviour of short cracks is not yet clearly understood, but it was proposed(28) that the effect could be attributed to differing local crack tip environments as a function of crack length, principally depending on different electrochemically-active surface to volume ratios of the cracks, on the diffusive and convective mass transport of the embrittling medium to the crack tip and on the distribution and areal coverage of cathodic and anodic sites for the electrochemical reactions. Each of these processes is sensitive to crack depth, opening profile and surface roughness.

III. Finite Element Analysis

The calculations were carried out for a three-pont-bend specimen, finite element discretization of half the specimen is shown in Figure 8, under a state of plane strain and subjected to a constant cyclic load with a stress ratio $R=\sigma_{min}/\sigma_{max}=0$. The assumed material properties are for a 2024-T3 aluminium alloy and are given in an earlier publication(29).

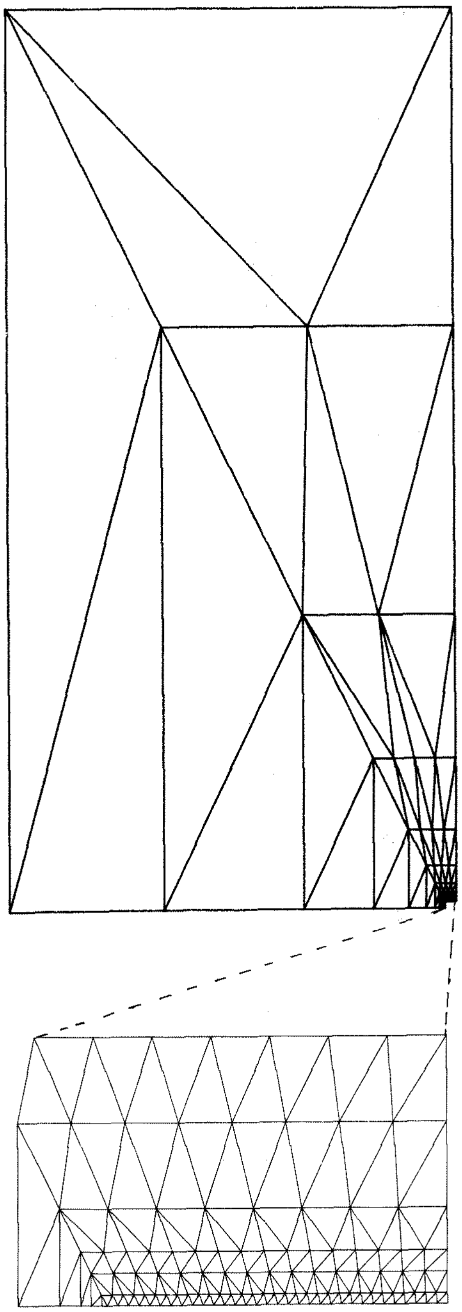

Figure 8. Finite element discretization of the three-point-bend specimen.

The numerical procedure has been described in detail in an earlier paper(29) and consists of elastic-plastic finite element calculations taking into account the crack propagation by releasing the crack tip node, changing the boundary conditions and solving the contact problem occurring at the crack surfaces. In the computer programme, which is a modified version of the LUCAS(30) programme, an initially isotropic strain hardening is used and the finite elements are two dimensional triangels with cubic base functions. The initial crack length is 0.01 mm and the size of the crack tip elements is 0.00125 mm. Since the mesh in the vicinity of the crack tip is fine, the correct crack tip singularity is expected to be obtained.

IV. Results and Discussion

The plastic zone develops rapidly at short cracks and local plastic flow is much easier than in the case of longer cracks. This difference is clearly seen in Figure 9 where the plastic zone size and shape is shown for:

a) a short crack, with length a=0.01 mm, subjected to a nominal stress intensity range $\Delta K=2.31$ MPa $\sqrt{m}$,

b) a long crack, with length equal to half the specimen width, subjected to a nominal stress intensity range $\Delta K=2.56$ MPa $\sqrt{m}$,

c) the same crack as in b) but subjected to a nominal stress intensity range $\Delta K=6.4$ MPa $\sqrt{m}$.

The nominal stress intensity ranges were calculated from the elastic displacement fields.

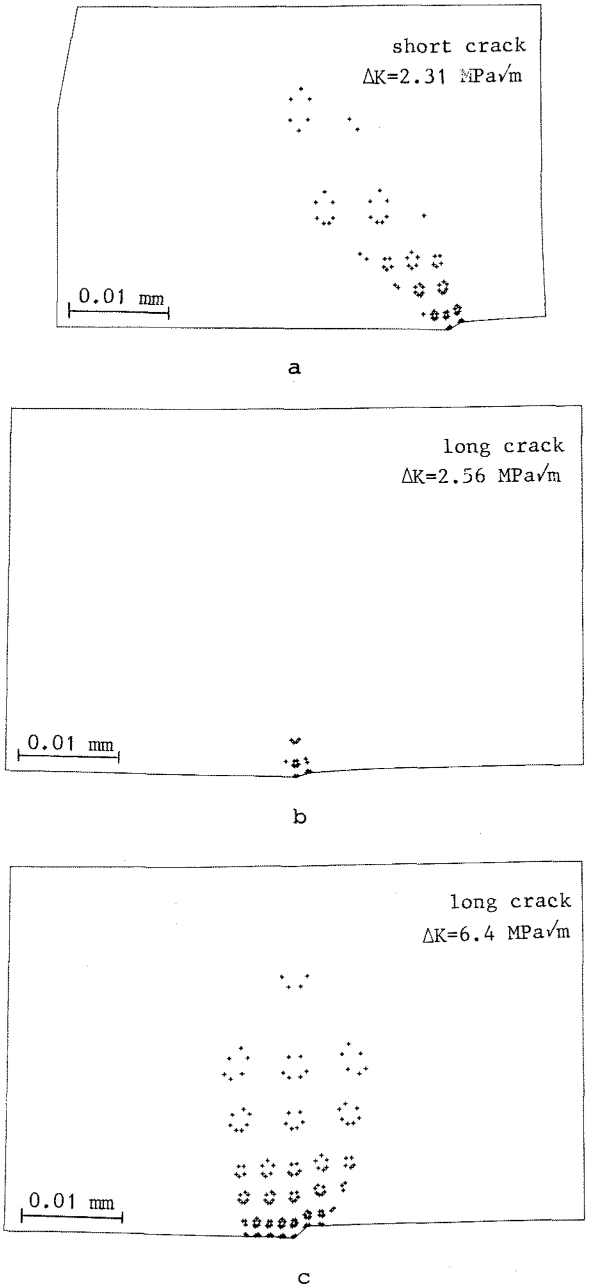

Figure 9. Plastic zone size and shapes for short and long cracks.

In Figure 10 the retardation parameter $U=(P_{max}-P_{c\ell})/(P_{max}-P_{min})$ is shown as function of crack length. In order to obtain U for a wide range of crack lengths the calculations were carried out for different initial crack sizes. In Figure 10a it is shown that the crack closure results converge to the same values in a few load cycles irrespective of the initial crack length.

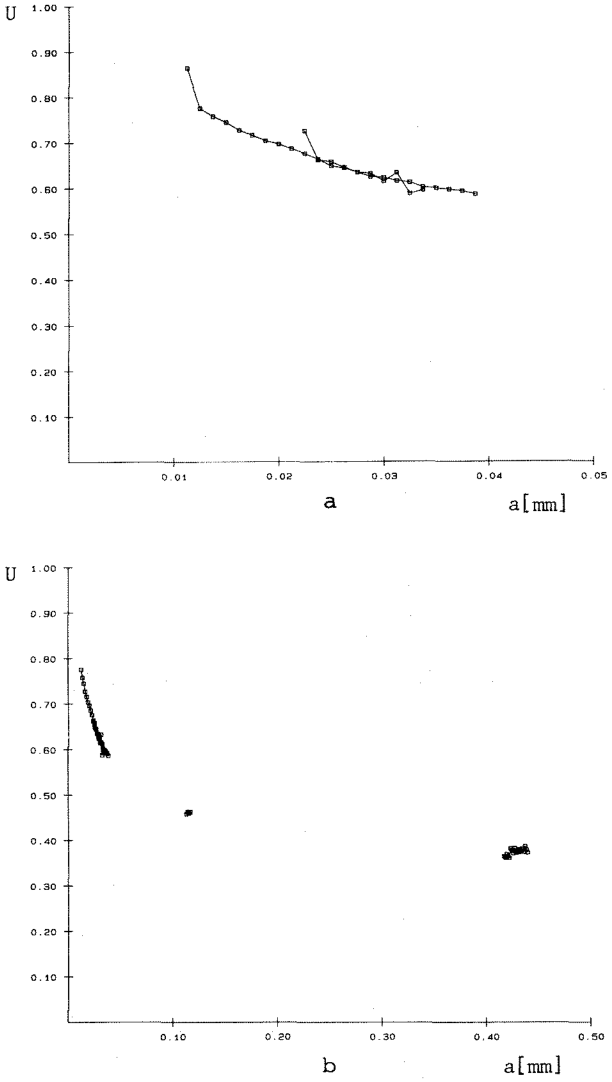

Figure 10. Variation in U with crack length.

It is found that U decreases strongly with crack length for short cracks, Figure 10b. This means that plasticity-induced crack closure increases with crack length and thus that short cracks are subjected to higher effective driving force than long cracks under the same nominal force. Consequently, it has been shown, based on pure continuum considerations, that short fatigue cracks may grow faster than longer cracks. As was discussed earlier plasticity-induced crack closure alone may not be sufficient to explain the anomalous behaviour of short cracks, but this mechanism is necessary in order to promote other mechanisms such as roughness-induced crack closure. The numerical values of U, shown in Figure 10b, for the longer crack lengths are small compared to values reported in the literature(31) for long cracks in plane stress. One reason for this is the use of an isotropic hardening material model in the present paper whereas a combination of isotropic and kinematic hardening was used in Ref. (31).

V. Conclusions

Several different phenomena can be used to explain the anomalous behaviour of short fatigue cracks. It is believed that crack closure effects are of paramount importance in this respect. Plasticity-induced crack closure was found to increae with crack length for short fatigue cracks, thus causing a higher growth rate for short cracks than long cracks at the same nominal driving force due to higher effective driving force for the short crack.

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