The Influence of Crack Closure and Plastic Zone Geometry on Fatigue Crack Propagation

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INTRODUCTION

At very low cyclic stress intensities, ΔK, it has been found [1-4] that for several steels the rates of crack propagation become very sensitive to changes in the mean stress intensity, K_{MEAN}. Furthermore [1-4], for a given ratio of maximum to minimum stress intensity K_{MAX}/K_{MIN}, the rate of growth is not proportional to ΔK^m. Similarly the rate of growth falls to zero in many materials as ΔK tends towards some critical value, ΔK_o. The value of ΔK_o itself is also strongly dependent on the mean stress [1-4]. At higher values of ΔK ($>\sim 15 MNm^{-3/2}$) the rate of crack growth becomes almost independent of mean stress [5] provided the maximum stress intensity of the fatigue cycle, K_{MAX} remains less than $\sim 0.7\ K_{1c}$. Although empirical expressions are available [1-3] which describe fatigue crack growth at small values of ΔK, no satisfactory physical model exists. Recently, however, Elber [6,7] has proposed that the plastic zone left in the wake of a propagating fatigue crack interferes with subsequent growth. In this model the crack is closed during the lower part of the fatigue cycle even under tension/tension loading and therefore the effective values of ΔK are less than those calculated. Experimental support [6-9] has been provided by surface displacement, residual stress and photoelastic measurements. It has been proposed [4] that at higher mean stresses there is less closure and therefore higher growth rates should result from increases in mean stress. The potential importance of crack closure during fatigue crack growth is considerable and we decided to examine the phenomenon further using AC and DC current resistance techniques. These techniques should have an advantage over the measurements of surface displacement in that they rely on bulk properties.

EXPERIMENTAL

Fatigue cracks were grown in 8 mm thick single edge notched specimens of a 1% carbon steel in the spheroidised condition for 4 mm under constant ΔK and K_{MAX} conditions (achieved by making frequent small load adjustments). Following the 4 mm growth the specimens were incrementally loaded to reproduce the K variations applied during the previous fatigue cycling. The amount of crack closure was estimated using the calibration obtained during those 4 mm growth assuming that any closure occurred initially at the crack tip and progressed towards the starting notch. The conditions of the tests were predominantly plane strain and typical results are shown in Fig. 1. Within the limits of the experimental conditions (equivalent to a change in crack length of 0.2 mm in the case of the AC technique and 0.02 mm for the DC), no closure was observed between K_{MAX} and K_{MIN} of the cycle for zero-tension or tension-tension loading using the AC and the DC techniques (Fig. 1). The loads were then reduced to give K values less than K_{MIN} until closure was detected. In the case of zero-tension tests, compressive loads were required before closure occurred. For tension-tension tests again the loads had to be reduced beneath K_{MIN} before crack closure was detected but in this case the loads were still tensile. According to these experiments crack closure, at least under predominantly plane strain conditions does not occur during fatigue crack growth unless the minimum loads are compressive or K_{MIN} is reduced during a test. Even in this latter situation we noticed a surprising effect when K_{MIN} was reduced during a test but ΔK remained the same (Fig. 1(c)). Initially 2.3 mm of the crack was closed at K_{MIN} but after 10 cycles only 0.5 mm was closed and after 100 cycles the crack was open for the whole cycle. However, this severe drop in

K_{MIN} arrested crack growth for 40,000 cycles. This behaviour has also been observed following single overloads[10,11]. For the 1% C steel therefore, overloads or K_{MIN} reductions arrest crack growth by introducing residual compressive stresses in the plastic zone ahead of the crack tip and not by causing more severe crack closure behind the crack tip.

DISCUSSION

The surface displacement measurements showing actual or apparent closure still have to be explained. The possibilities that the observations apply only to the surface regions (or plane stress conditions) or that some materials may exhibit closure whilst others do not are being investigated.

In cases where closure does not occur, a model is proposed which could account for the gradual fall off in log growth rate with log ΔK at low values of ΔK. This model emphasizes the large angles of plane strain shear bands to the plane of the crack surface at low stresses. Hitherto the zones have always been assumed to form at angles of 45° which is only true at general yield for certain loading geometries. The calculations of Rooke[12] show that the angle varies with stress (or K) and at very low stresses the maximum shear stress is close to 90° to the plane of the crack. Large angle shear zones have been observed in silicon iron by Richards[13] and by Rosenfield and Hahn[14]. It is proposed that in the low stress limit the deformation does not contribute towards crack growth since re-sharpening of the crack tip does not occur during the unloading part of the cycle. Increasing the mean stress causes the deformation bands to form at more acute angles to the plane of the crack thus providing for re-sharpening during unloading and the observed increase in rate of crack propagation. At large values of ΔK for zero-tension loading only the lowest part of the cycle would be associated with large angle shear. Thus a small increase in K_{MIN} would raise the rate of growth slightly but further increases would have no effect. This precise behaviour has been observed in several steels[5].

The results so far using resistance measurements show that crack closure plays no part in plane strain fatigue crack propagation except during tension-compression loading and the first few cycles following load reductions. A model emphasizing the large angles of shear bands to the plane of the crack at low stresses is described. This model provides a possible explanation for the gradual fall off in rate of growth at small values of ΔK and K_{MAX} and the effect of mean stress in cases where crack closure does not occur.

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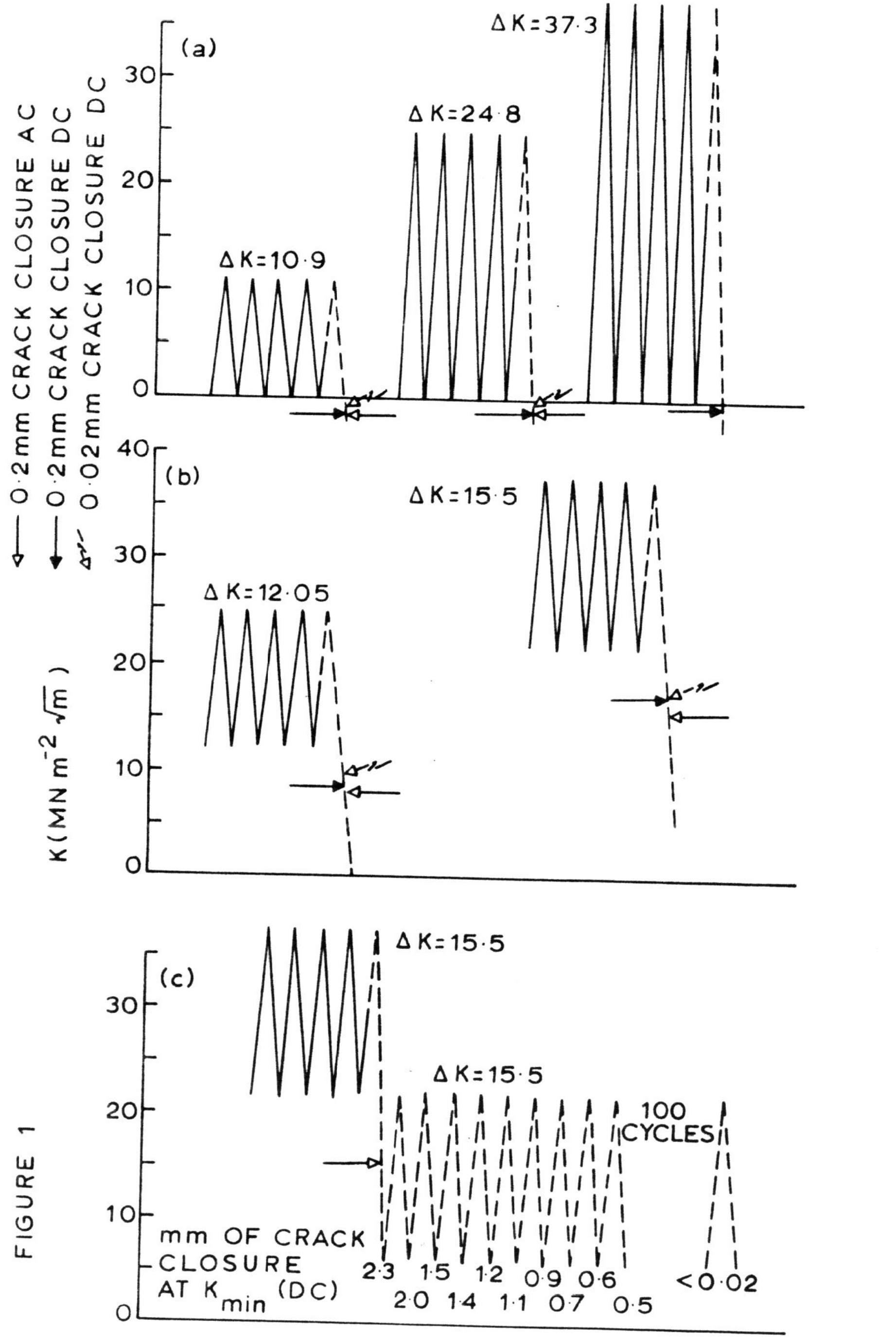

FIGURE 1