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ON CRACK CLOSURE IN FATIGUE CRACK GROWTH[1]

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INTRODUCTION

Crack closure is a term used to indicate that the opposing faces of a fatigue crack make contact before the minimum load in a cycle is reached, a phenomenon first noted by Elber [1],[2], some ten years ago. Since that time the subject has attracted considerable interest as a means of rationalizing the effects of mean stresses and overloads on the rate of fatigue crack growth. The closure effect itself is relatively easy to detect with appropriately placed strain or COD gauges, and is manifested by a continuous increase in specimen compliance on loading until the crack surfaces are fully separated. Thereafter with further loading in the linear elastic range the specimen compliance remains constant at a maximum value. Upon unloading from the maximum load in the cycle the reverse process takes place, usually with some hysteresis. Although the overall phenomenon is easily detected, the precise determination of the opening load itself does require some sophistication in measurement technique, especially after an overload. For $R = 0$ loading (R being the ratio of the minimum to maximum stress in a loading cycle), Elber has observed that the opening load is one-half of the maximum load with the ratio decreasing as the R value is increased. In Elber's approach to crack growth analysis, only the portion of the loading cycle above the opening load is considered to be effective in propagating the crack, and the effective stress intensity factor, K_{eff}, which is defined as the difference between K_{max} and K_{open} is used as a correlating parameter. However, there has been some uncertainty as to the nature of the closure process itself and also as to whether or not it explains the observed effect of mean stress on the rate of crack growth.

The controversy usually centres on whether the closure phenomenon is a plane stress effect which involves primarily only the near-surface region of the specimen or whether it is an effect present throughout a thick specimen, that is in both the plane strain as well as the plane stress regions. In addition, although it is clear that closure can occur at macroscopic distances behind the crack tip, especially in plane stress, closure of the tip itself is more difficult to ascertain, however, Bowles [3], using a plastic impregnation technique to replicate the crack tip region, has found that the tip remains blunt on unloading, but with some evidence of point-to-point contact present behind the crack tip. With respect to closure in the plane strain region, Lindley and Richards [4] tested a variety of steels and found that the effect vanished as the thickness increased. They concluded that it was a near surface effect associated with the greater stretch of material in the plane stress region. In more recent tests of 25 mm thick compact

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[1] Professor McEvily kindly consented to present this Plenary Paper on Crack closure at short notice. The text is an edited transcript of his actual lecture.

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tension specimens of a high strength aluminium alloy, Paris and Hermann [5] found that closure occurred in plane strain with the ratio of the opening load to maximum load being about 0.5. However, this level of closure was found only in the near-threshold region. At higher values of the stress-intensity factor the ratio dropped to 0.23. The tendency for the closure level to decrease with increase in stress intensity was also noted by Bachmann and Munz in the case of the titanium alloy Ti-6Al-4V [6], and by Kikukawa *et al* for a variety of alloys [7]. In order to learn more of the influence of the surface region as well as that of K_{max} and overloads on closure the following experiments were carried out.

CLOSURE EXPERIMENTS [8]

A fatigue crack was grown at $R \approx 0$ in a high strength aluminium alloy under decreasing stress intensity conditions, and the near-threshold region was approached. Strain gauges were then placed immediately ahead of the crack as well as across the crack to study crack opening behaviour. In these studies the ratio of opening load to maximum load was found to be about 0.5. The specimen thickness was then reduced by carefully machining 1.5 mm from each face of the initially 6 mm thick specimen. The opening load characteristics were then rechecked with strain gauges and it was found that the K_{op}/K_{max} ratio was still high, about 0.4, a finding which indicated that a significant closure effect was present in the plane strain portion of the specimen when tested in the near-threshold region. At higher stress intensity levels, however, the K_{op}/K_{max} ratio decreased in these tests to less than 0.1.

An important question which then arises is why does the K_{op}/K_{max} ratio decrease in plane strain specimens as the level of K_{max} increases. On this point the studies of several steels by Otsuka *et al* [9],[10], appear to be particularly helpful, for they have observed that the crack growth mode changes as the stress intensity level is increased. In the near-threshold region crack growth occurs in a shear mode on planes inclined to the direction of crack growth. This mode of growth is also known as Forsyth's Stage I or as Mode II of fracture mechanics. At higher stress intensities where a power law can be used to represent the dependency of the crack growth rate on the stress-intensity factor range, a shift to an opening mode of growth occurs which is accompanied by the appearance of fatigue striations on the fracture surface. In related work, Yoder *et al* [11], have observed that for Ti-6Al-4V the transition to power law dependency occurs when the plastic zone is equal to the average size of a Widmanstätten packet in this α-β alloy. Above the transition the fracture surface is featureless except for a regular array of fatigue striations. Below the transition striations are not observed, and the microstructural detail of the alloy is clearly revealed on the fracture surface, an indication that in this region the crack advanced by following easy paths through the complex microstructure and, based on Otsuka's observations, probably by a shear mode of propagation.

Since the threshold is generally above the opening load, crack growth in the near-threshold may occur by a combination of a sliding mode as well as an opening mode, with the presence of the sliding mode accounting for the observed high value of the K_{op}/K_{max} ratio in the near-threshold region. The higher the ratio the more important will be the contribution of the sliding mode, and, in fact, for certain aluminium alloys, Kikukawa *et al* have found the ratio to be equal to unity. In the wake of a shear crack a zig-zagged fracture surface may develop upon the material. However, in order for a crack to extend in this manner it may be necessary that fatigue

crack growth alternate with tensile rupture to keep the average crack plane normal to the direction of principal tensile stress, and some evidence of mixed fatigue and tensile mode growth in the near-threshold region has been obtained by Pickard *et al* [12]. At higher stress intensities the opening mode becomes dominant and there is a corresponding decrease in the K_{op}/K_{max} level, at least for specimens of sufficient thickness to ensure that plane strain conditions prevail. In thin specimens it is possible that closure levels are much higher, a matter which should be checked in further experiments.

CLOSURE AND OVERLOADS [8]

Next, let us consider opening load behaviour above the threshold region as influenced by an overload. Paris and Hermann have made careful determinations of opening load behaviour after overloads of the order of 100% and found that two opening loads were observable. The first of these opening loads is less than that measured prior to the overload, whereas the second is higher and exhibits at first an increase in closure level followed by a gradual decrease as the crack advances through the overload plastic zone. The lower opening load is ascribed to a loss of contact behind the crack tip, and the second to a loss of contact at the crack tip itself. The application of the overload results in a considerable retardation in the subsequent rate of fatigue crack growth, and Paris and Hermann attribute this retardation to the low value of ΔK_{eff} which is present above the higher of the two opening loads. In this view the closure effect is not thickness dependent, but is considered to arise from a general residual stretch of the material behind the crack tip. However, the relative contribution of near surface regions and interior regions was not established.

To learn more of the contribution of the surface region to closure and retardation phenomenon after an overload we have carried out the following experiments. A fatigue crack was grown in a compact tension specimen of the aluminium alloy 6061-T6 and a 100% overload was applied. Constant amplitude cycling was resumed and the usual delayed retardation phenomenon was observed. When the crack had grown beyond the region of influence of the overload, a second 100% overload was applied, and 1.5 mm was machined from each face of the 6 mm thick specimen. Cyclic loading was then resumed at one-half of the previous load amplitude to compensate for the reduction of thickness. In this case, virtually no retardation was observed. A similar test was carried out with a second specimen which was machined after the first overload but not the second. Again after machining the retardation effect was virtually absent, whereas it was most pronounced after the second overload of the thinned-down specimen. These results demonstrate that in the linear-elastic range retardation is strongly related to the stretch of material and resultant closure in the near-surface region. These results also suggest that the first opening load observed by Paris and Hermann may be due to crack opening in the interior of the specimen, and the second may be due to opening at the surface. Since the experiments indicate that retardation is primarily due to a surface effect, it is to be expected that the magnitude of the retardation effect will decrease with increase in specimen thickness. It also seems likely that delayed retardation is related to the shape of the crack front and interactions between surface and interior regions since the crack progresses ahead more rapidly in the interior of the specimen rather than at the surface following an overload.

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