ON THE ROLE OF CRACK CLOSURE IN FATIGUE CRACK GROWTH

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INTRODUCTION

Closure has been invoked to account for mean stress effects, threshold levels, overload behavior, and the transition from flat to slant fracture in sheet specimens. It is therefore important that we understand the nature and influence of this phenomenon on fatigue crack behavior. The present paper presents a brief review of this subject.

NEAR-THRESHOLD BEHAVIOR

The characteristics of crack closure in the near threshold region are shown in Fig. 1. It is seen that in this region the closure effect as measured by the ratio of Kop to Kmax, increases markedly as the threshold level is approached, although in absolute terms the value of Kop may itself not change significantly in this range. The possibility has been raised that in this region closure behavior may be influenced more by closure well behind the crack tip rather than at the crack tip itself due to the nature of the load reduction scheme employed in approaching threshold [1]. In such a case the threshold level would have no physical significance. To check on this possibility we have removed material in the wake of a crack by electro-discharge machining and have found that there still is a threshold, although at a slightly lower level [2]. Closure at the crack tip itself is clearly an important factor affecting the threshold level. A determination of the plastic deformation processes has shown that in the near threshold region Mode II is an important deformation mode. The usual interpretation given is that the fatigue plastic zone size is less than that of some critical metallurgical feature such as the grain size, then Mode II growth will be favored over Mode I. Mode II growth will in turn lead to a roughening of the fracture surface, and the potential for contact due to mismatch is thereby increased as shown in Fig. 2 [3]. Thick oxide or corrosion products also increase closure levels in the near-threshold region [4]. Formation of oxide products, in moist air is associated with fretting action between the mating fracture surfaces at the crack tip and therefore the Mode II crack growth enhances formation of oxide products. However in aggressive environments such as corrosive solutions and/or elevated temperatures, Mode II crack growth may not be necessary for high closure.

INTERMEDIATE REGION

In the intermediate region of crack growth rates Elber proposed that the effect of mean stress could be accounted for if the rate of crack growth were expressed as a function of $\Delta Keff$, where $\Delta Keff$ equals Kmax-Kmin [5]. If the mechanism of fatigue crack growth were to remain constant on change of mean stress this might be a reasonable assumption. However, this is often not the case, because as the mean stress is increased at a given ΔK the value of Kmax is also increased and as a result the incidence of static modes of separation becomes more likely.

In one view it is the static modes of separation that are responsible for mean stress effects. For example, in steels of high toughness wherein static modes of separation do not operate, mean stress effects are minimal. On the other hand, in low toughness steels and aluminum alloys static modes of separation are more easily operated and there is a correspondingly high dependence on mean stress effects [6]. The following equations have been proposed to account for these mean effects from these different points of view:

a. Mean stress effect related to static modes [7]:

$$\frac{\Delta a}{\Delta N} = A(\Delta K - \Delta K_{TH})\left(1 + \frac{\Delta K}{Kcc - Kmax}\right); \quad Kmax = \frac{\Delta K}{1-R} \qquad (1)$$

where A is constant and Kcc is the cyclic fracture toughness.

b. Mean stress effect related to influence of mean stress on $\Delta Keff$ [8].

$$\Delta Keff = (1-0.1R^3-0.25R^2-0.2R-0.45)\ Kmax \qquad (2)$$

TRANSITION FROM FLAT TO SLANT FRACTURE IN THE HIGH GROWTH RATE REGION

The transition and the use of Eq. 2 has been related to a constant value of $\Delta Keff$ by Schijve [8]. Reasonably good agreement with data has been obtained, Fig. 3. An alternative approach would be to consider that the transition is related to the tendency to develop static modes of separation. In Eq. 1 this tendency is reflected in the second term in the final parentheses, i.e., $\Delta K/Kcc-Kmax$. If we consider that this term is constant at the transition, then we can write $\Delta K = \frac{C\ Kcc}{1 + \frac{C}{1-R}}$ Fig. 3 indicates that this form also correlates well with the data if, the constant C is taken to be 0.19 and Kcc is taken to be 86 $MN/m^{3/2}$. It is interesting to note that for thicknesses of Alclad

2024-T3 above 1 mm the value of stress intensity range at transition, ΔKtr was independent of thickness [8]. Such a result would be expected in the second approach, but perhaps not in the first. In any case, further critical experiments are needed to establish clearly the nature of the factors responsible for this transition.

OVERLOAD EFFECTS

It is now recognized that crack retardation due to an overload is associated with crack closure in the surface layers of a specimen. This has been shown by machining away the surface layers and noting upon continued cyling that the extent of crack retardation had largely been eliminated [10]. One conclusion that can be reached is that for a given overload, the extent of retardation will be thickness dependent. It is also to be expected that crack closure will play an important role in crack growth under variable amplitude loading, but this is a topic for future study.

CONCLUSIONS

The crack closure process is an important aspect of the fatigue crack growth mechanism. However since the extent of crack closure varies in a three-dimensional sense, the phenomenon is more complex than originally envisioned. The closure process is importantly involved in the establishment of the threshold level and in the retardation effect due to overloads. The influence of closure on the rate of fatigue crack growth in the intermediate range is a function of mean stress, and on the transition from flat to slant fracture in sheet specimens the influence of closure may be of lesser significance.

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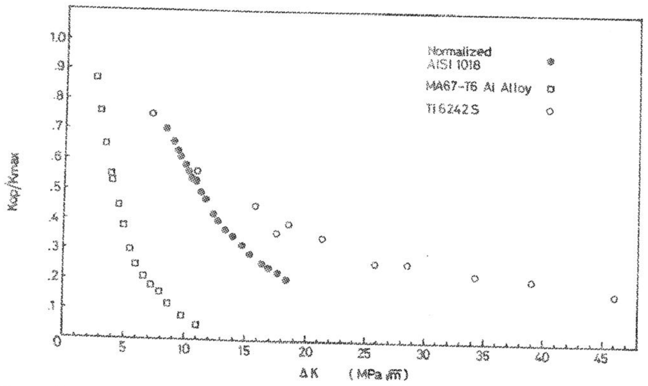

Fig. 1. Crack closure level Kop/Kmax vs. ΔK.

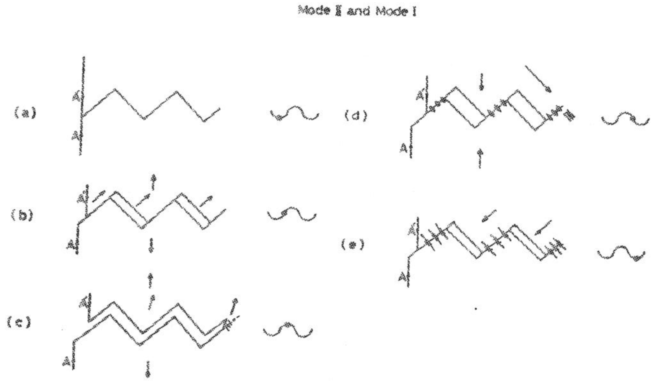

Fig. 2. Schematic diagram of Mode II and Mode I crack growth.

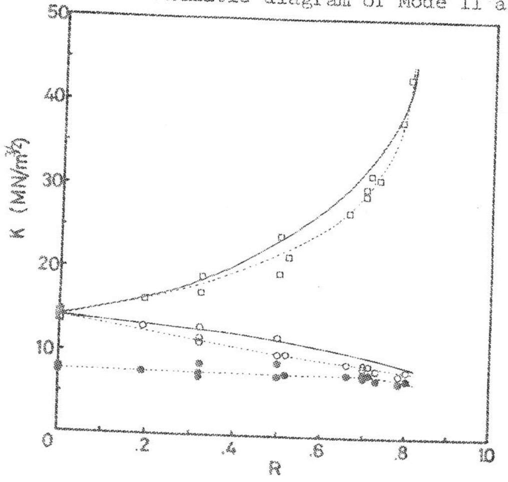

Fig. 3. K values for transition from flat to slant fracture as a function of R. Solid and dash lines are obtained from eqs. 1 and 2, respectively. Data for transition (□: Kmax, ○:ΔK, ●: ΔKeff) were taken from reference [9].