On the Significance of Crack Closure in Fatigue Crack Growth

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ABSTRACT

The research of recent years has brought about a better understanding of the nature and the significance of fatigue crack closure. Important types of closure are plasticity-induced closure, roughness-induced closure, and oxidation-induced closure. These types of closure are discussed and their significance in understanding retardation effects after an overload, anomolous crack growth, and fatigue notch size effects is indicated.

KEYWORDS

Fatigue; fatigue crack propagation; crack closure

INTRODUCTION

Crack closure was discovered some twenty years ago (Elber, 1970, 1971), and ever since there has been interest in the nature of closure and in its significance in affecting aspects of the fatigue crack growth process. Crack closure means that during the unloading portion of a fatigue cycle the opposing crack faces near the crack tip come into contact before the minimum load of the cycle is reached. Similarly in the loading portion of the fatigue cycle the crack tip does not open immediately on loading , but only after the compressed region in the wake of the tip has itself separated. In most cases the opening load level and the closing load level are quite similar in magnitude. The interest in closure has stimulated a considerable amount of research, and as a result we now have a much better understanding of the process, and in fact, perhaps not surprisingly, have found that it is more complex than originally conceived. We have also found that closure not only can account for some of the influence of mean stress and overloads on fatigue crack growth behavior as originally proposed, but has also led to improved understanding of notch size effects and fatigue notch sensitivity, short crack growth behavior, and the role of microstructure in influencing closure.

In dealing with closure two approaches have been developed. One of these is a plane-stress continuum approach which is applicable to the surface regions in the case of a crack growing in a plane specimen. In this case there is a component of strain in the thickness direction which results in a displacement of material from the original surface plane to a location beneath the original surface plane. This displacement is evidenced by the lateral contraction observable along the crack at the surface. Since this displacement increases with increasing stress intensity range, ΔK, plane stress closure also increases with ΔK, in accord with Elber's original ideas. In plane strain however, the situation is much different, for in this case there is no lateral contraction, and hence no extra material to give rise to a closure effect, at least in the continuum sense. On the other hand closure has been observed under plane strain conditions, but for reasons other than a continuum type of closure. Included in these other reasons are the roughness of the fracture surfaces and the attendent interference effects that result due to poor intermeshing of the opposing fracture surfaces, as well as crack surface oxidation effects which also can lead to closure under plane strain conditions. There is one type of closure that occurs under plane strain conditions and is continuum in nature. This type of closure occurs when there is a reduction in mean stress as the result of a reduction in the range of the stress intensity factor at constant R, where R is the ratio of the minimum to the maximum stress in a cycle, or due to a reduction in R at a constant ΔK. The reduction in mean stress results in an elastic contraction of the specimen which leads to a localized type of crack closure at the crack tip which is through thickness in nature.

With respect to roughness effects we know that if the microstructure is fine enough, i.e., a grain size in the submicron range in the case of aluminum alloys, that the scale of roughness that develops is too fine to affect the closure process. For coarser microstructures, or if the crack front deviates out of the nominal plane of growth to develop a three-dimensional zig-zag fracture topography, then closure will develop. In fact a correlation has been developed (Hamberg et al., 1987) between the scale of roughness and the crack opening load. Their relation , modified to account for the influence of modulus is as follows

$$K_{op} = 1.2\,\frac{E}{E_{Steel}}\,H^{1/3} \qquad (1)$$

where H is the standard mean height deviation. It is noted that other results (Kemper et al.,1988) also are in accord with this relation. It is also noted that the scale of roughness is often much greater than the estimated value of the crack tip opening displacement in the near threshold range. For example, the roughness value might be 25 microns whereas the crack tip opening displacement might be only 0.1 micron. This indicates that the opposing fracture surfaces are well intermeshed, but that a small degree of mismatch is responsible for the observed closure. It is also noted that in some materials in contrast to the expectations of plasticity induced-closure, the roughness and related opening levels are independent of the range of ΔK in the near threshold region where roughness effects are important. Roughness develops because of the operation of a shear mode of growth rather than an opening mode of growth in the near-threshold region, and materials with pronounced planar glide tendencies may in fact exhibit an increase in closure as the threshold is approached due to the greater predominance of the shear mode. Such behavior is typical of the high strength aluminum alloys.

In the remainder of this brief review examples will be given of the importance of closure in affecting crack growth behavior after an overload, and in the growth behavior of short cracks. The first of these effects can be treated from a continuum point of view, whereas the other is strongly dependent on microstructure.

RETARDATION DUE TO AN OVERLOAD

The application of an overload results in a transient period during which the rate of fatigue crack growth is reduced as long as the crack tip remains in the overload affected region. Experimental work has shown that in low strength, relatively thin specimens the overload effect is associated with the plane stress overload zone at the specimen surface. Removal of the surface layer leads to a marked reduction in the retardation effect in the aluminum alloy 6061 of 6 mm in thickness, for example (McEvily, 1978). Retardation results from the extra closure that develops due to the relaxation of compressive residual stresses in the overload plastic zone. On the other hand, in high strenth, thick specimens a plane-strain through thickness effect may be more important (Matsuoka and Tanaka, 1980). In this case as the crack blunts and advances to a greater than usual degree during the overload, a more than usual amount of material is moved ahead of the crack tip into the larger plane-strain plastic zone. As a result a larger plastic region than that associated with the baseline cyclic level is created which is in compression on unloading. The relaxation of the stresses in this larger region as the crack passes can lead to additional closure and resultant crack retardation. The extent of retardation in this case is however much less than where plane stress effects dominate.

In recent work we have been interested in the effect of the baseline ΔK level on the extent of retardation. For aluminum alloys in general we have found that even at the threshold level where the plastic zone size to thickness ratio is least, the retardation effect is primarily associated with the surface layers. Removal of the surface layers leads to the virtual elimination of the retardation effect. We note also experimental results exist which relate the number of delay cycles to the ratio of the plastic zone size to specimenn thickness (Vecchio et al., 1983) for 2024 T-3 aluminum alloy. As shown in Fig. 1, the number of delay cycles was found to be a U-shaped function of this ratio. The large number of delay cycles at high values of the ratio is due to increase of the plastic zone size to thickness. The large number of delay cycles at threshold is due to the sensitivity of the rate of crack growth to the effective value of ΔK in this region, where ΔKeff equals Kmax - Kop.

The number of delay cycles is defined as the number of cycles required to traverse the overload affected zone minus the normal number of cycles to traverse this distance. The number of delay cycles can be computed with the aid of the following semi-empirical expression for comparison with the experimental results shown in Fig. 1. Due to the overload there is an excess closure developed in the plane stress regions which leads to a reduction in ΔKeff. We assume that the rate of fatigue crack growth is given by the following equation:

$$\frac{da}{dN} = A(\Delta K_{eff} - \Delta K_{effth})^2 \qquad (2)$$

We also assume as an approximation for illustrative purposes that the extent of this closure is constant through the affected zone which is taken to be

$$\text{Affected Zone Length} = K_{OL}^2/\pi\sigma_y^2 \qquad (3)$$

and the excess closure is given by

$$\text{Excess Closure} = \text{E.C.} = 0.6K_{OL}\ \{1 - \exp[-(\frac{K_{OL}^2}{2\pi{\sigma_y}^2 B})^{1/2}]\} \qquad (4)$$

Hence the number of delay cycles is given by

$$N_d = \frac{K_{OL}^2}{\pi\sigma_y^2\ A} \times [\frac{1}{(\Delta K - \text{E.C.} - \Delta K_{th})^2} - \frac{1}{(\Delta K - \Delta K_{th})^2}] \qquad (5)$$

This expression approximates the experimental results as shown by the solid curves in Fig. 1. The U-shape of the curves is understandable if one takes the derivative of Eq. 5 with respect to ΔKeff, then it can be seen that near threshold a term which depends upon the reciprocal of ΔKeff-ΔKth dominates, so that a small decrease in ΔKeff results in a large increase in the number of delay cycles. At high ΔK levels a term of the form exp(ΔK) dominates, and again the number of delay cycles is large.

In addition to this plane-stress surface effect in some alloys crack deflection may also play a role if the crack either deviates from its normal path during the overload or subsequently to avoid the affected zone (Suresh and Vasudevan, 1984; Venkateswara Rao and Ritchie, 1988).

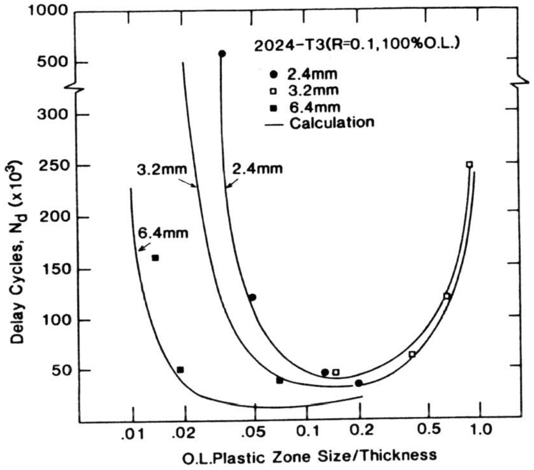

Fig. 1. The number of delay cycles, N_d, after a 100% overload as a function of the ratio of the overload plastic zone size, $K_{OL}^2/2\pi\sigma_y^2$, to thickness, B, for an aluminum alloy. Experimental results: Vecchio et al. 1983. Calculated results shown by solid curves.

CLOSURE DUE TO ROUGHNESS

In contrast to the continuum, plasticity-induced closure, the extent of roughness-induced closure is a function of the microstructure which affects the extent of Mode II dominated faceting in the near-threshold range. An aspect of this type of closure of particular interest is the rate at which roughness-induced closure builds up in the wake of a newly formed crack at a pre-existing defect. As the crack first starts to grow the closure level is zero, but as it extends and a wake develops, the closure level builds up to the value associated with a macroscopic crack. The value of Kop, the stress intensity level corresponding to the opening level in the transient region, has been expressed as a function of the crack length ,l, and the value of the macroscopic Kopmax as follows:

$$K_{op} = (1 - e^{-kl})\ K_{opmax} \qquad (6)$$

where k is a material constant. If l is expressed in mm, then k has the units of 1/mm. This increase in closure level during the transient leads to a number of interesting effects. For example, if we assume that the crack growth rate is given by Eq. 2 and calculate the rate of crack growth by the following equation

$$\frac{da}{dN} = A\ [\Delta K - (1 - e^{-kl})\ (K_{opmax} - K_{min}) - \Delta K_{effth}]^2 \qquad (7)$$

with A= 2×10^{-10} with da/dN in m/cyc, k=13/mm, ΔKeffth = 3.2 MPa $\sqrt{m}$, and Kopmax = 2.4 MPa$\sqrt{m}$, the results shown in Fig. 2 are obtained. In Fig. 2 the crack which starts at the lowest value of the stress intensity factor becomes non-propagating because the build up in closure offsets the increase in the value of the stress intensity factor as the crack extends. There is also an influence of closure build-up for larger initial flaw sizes as the cracks traverse the range between the Keff curve and the macroscopic growth curve. The type of growth in this interval has been referred to as "anomolous" crack growth, and is an important design consideration in the determination of critical flaw sizes to insure that they will be non-propagating.

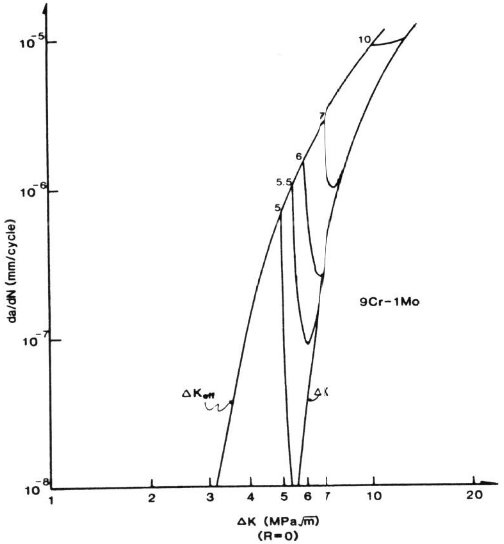

Fig. 2. The effect of closure development on the rate of fatigue crack growth in a 9Cr-1Mo alloy.

mind and a knowledge of the intended application area.

OXIDE INDUCED CLOSURE

Several researchers have shown that fretting and oxide build up can increase the closure level in the near-threshold range at room temperature (Stewart,1980, Suresh et al., 1981). At elevated temperatures oxide build up on the fracture surfaces has been shown to increase the closure level and affect crack growth behavior by increasing the threshold level (Nakamura, 1986). In order to assess the effects of oxidation results obtained from companion tests carried out in vacuum provide a basis for comparison. Fig. 4 provides an example of such a comparison for several steels tested at room temperature. The vacuum was 10^{-3} Pa. For the 2 1/4Cr-1Mo steel and the 4135 steel it is seen that the closure level at threshold in air is increased by 50% over that obtainied in vacuum. For the 9 Cr-1Mo steel which is much more resistant to oxidation due to the higher chromium content the closure levels in air are similar to those obtained in vacuum, and therefore oxide induced closure is not significant in this case. The similarity of the closure levels in this case is also an indication that rewelding of the fracture surfaces in vacuum did not occur. It is also seen that the opening levels in vacuum are constant independent of the ΔK level over the near-threshold range, a characteristic of a number of steels.

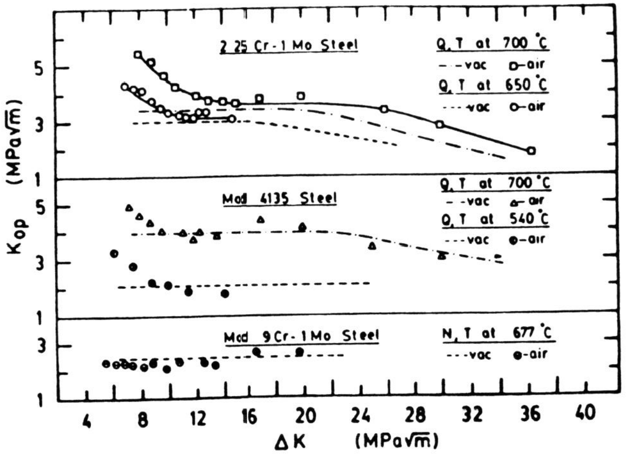

Fig. 4. A comparison of Kop levels determined in air and in vacuum for several steels. After Zhu et al., 1986.

CONCLUDING REMARKS

In addition to the topics discussed above consideration of crack closure has led to improved understanding of related matters as well. For example, one might wonder why it is that in certain tough alloys the rate of fatigue crack propagation is independent of R in the intermediate crack growth

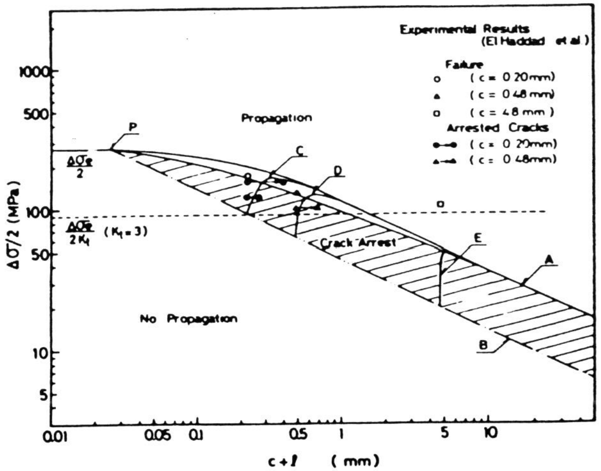

Fig. 3. Curves C, D, and E show the stress amplitude required to propagate a crack from holes of different radii, c, at a rate of 10^{-8} mm per cycle in medium strength steel. After McEvily and Minakawa, 1984. Experimental data due to El Haddad et al, 1979.

Similar considerations involving the build up of closure in the wake of a newly formed crack can be applied in considering the stress required to propagate a crack from a stress raiser. As a crack extends at a constant load amplitude the crack driving force increases as reflected in the increased value of the stress intensity factor. On the other hand an opposing tendency due to the development of closure acts to reduce the driving force by reducing ΔKeff. The stress range needed to maintain a constant rate of crack growth is given by the following expression:

$$\Delta\sigma = \frac{\Delta K_{eff} + (1 - e^{-kl})\ K_{opmax}}{\sqrt{\pi(c + l)}} \qquad (8)$$

The predictions based upon this analysis are shown in Fig.3 and compared with the experimental results of El Haddad et al.(1979) for a series of initial flaws in the form of circular holes of different radii, c. In making the calculations k was taken to be 10/mm, ΔKeffth as 2.5 MPa√m, and Kopmax as 3.8 MPa√m. Both the predictions and the experimental results show that the smaller the initial hole diameter, the higher the stress required for propagation to failure. Such results indicate that the development of closure is responsibe for the fatigue notch size effect as well as for the related fatigue notch sensitivity. A low value of k or a low value of Kopmax will lead to an increase in fatigue notch sensitivity for low R values. At higher R values however where the effects of closure are minimal the notch sensitivity should be high. Therefore attempts to modify the microstructure to obtain the benefits of closure should be made with such considertions in range. The reason for this behavior is that a shake-down process occurs such that the minimum load and the opening load coincide (McEvily, 1987). As a result the deformation range at the crack tip becomes independent of R.

A desired advance will occur when we have a better understanding of the microstructural processes governing the magnitude of the parameter k. Such understanding will permit of further developments in the quantitative treatment of fatigue crack growth.

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