ON THE SIGNIFICANCE OF THE THRESHOLD FOR FATIGUE CRACK GROWTH

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ABSTRACT

This paper relates the threshold for the propagation of large cracks together with consideration of the closure process to the propagation of small cracks from notches. In addition the effect of closure on the initial stages of crack growth in smooth specimens as a function of the R ratio is also considered. The need for accurate determination of the closure characteristics of small cracks is stressed.

INTRODUCTION

The purpose of the present paper is to review certain aspects of fatigue crack growth behavior in the near threshold region in order to elucidate the important role of crack closure and the significance of the threshold. It will be shown that topics such as the non-propagation of cracks, notch sensitivity, the notch size-effect in fatigue, and material selection for fatigue resistance can each be related to the threshold, and that the threshold level and accompanying closure characteristics are both important aspects of the fatigue process.

LARGE CRACK BEHAVIOR

The importance of crack closure on threshold behavior can be seen in Figs. 1-3. (McEvily and Minakawa, 1984) The materials involved are two high strength aluminum powder metallurgy alloys designated IN9021 and 7090. An important distinction between them is their average grain size, that of 9021 being 0.2 microns and that of 7090 being 3 microns. In the case of 9021 no crack closure was detected and no dependency of the threshold level, which was quite low, on the R ratio was observed. On the other hand closure was found to be present in the case of the 7090 alloy. This closure was found to depend on the R ratio, and there was a corresponding dependency of the threshold on R. However these threshold values are not correlatable in terms of $\Delta K_{effective}$, which may be a further indication that Mode II growth as well as Mode I growth is important in the growth of cracks in this alloy in the near threshold region.

The occurrence of closure in the near threshold region has been attributed to fracture surface toughening arising from combined Mode I and Mode II growth, and Suresh and Ritchie (1982) have developed the following expression for the extent of closure:

$$(K_{cl}/K_{max}) = (2\gamma x/1+2\gamma x)^{1/2}$$

where γ is a non-dimensional roughness factor given by the ratio of the height to width of a fracture surface asperity, and x is the ratio of Mode II to Mode I crack displacements. However, since the 9021 alloy exhibited no closure another factor must also be considered, namely the absolute size of the facets or asperities on the fracture surface which lead to roughness-induced closure. These facets are extremely small in the case of the 9021 alloy because of its exceptionally fine grain size. Larger grain sizes in these aluminum alloys result in higher thresholds due to increased closure, at least at low R ratios, a characteristic which should have an important bearing on the development of more fatigue resistant alloys.

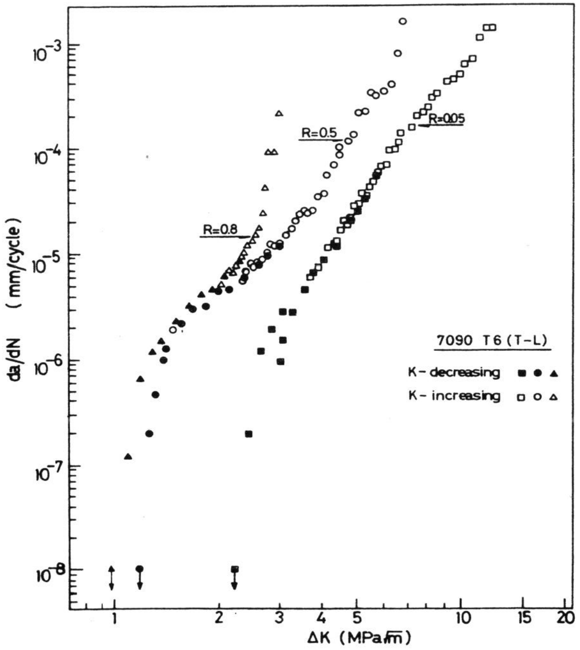

Fig. 1. Fatigue Crack growth rate, da/dN, as a function of ΔK for 7090-T6 aluminum alloy at three R ratios [6].

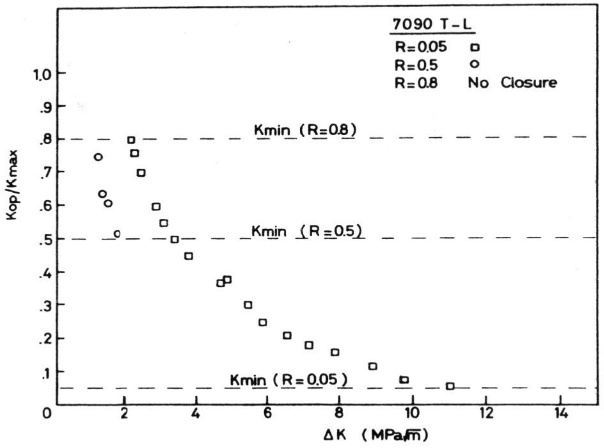

Fig. 2. Crack opening level in terms of the ratio of K_{op} to K_{max} as a function of ΔK for 7090-T6 aluminum alloy at three R ratios.

The extent of the distance behind the fatigue crack over which crack closure occurs is an important consideration. For the aluminum P/M alloy 7090 it has been found that at threshold, the dominant closure event occurs over a distance of less than one millimeter (Minakawa, Newman and McEvily, 1983). Any closure that occurs at distances of more than one millimeter behind the crack tip has only a very minor effect on the threshold level. As will be discussed, this circumstance plays an important role affecting the fatigue crack growth characterisitcs of short cracks.

THE GROWTH OF SHORT CRACKS FROM NOTCHES

A basic consideration in this treatment of the growth of short cracks from notches is that when a crack is initially formed there is no crack closure but that as the crack grows, crack closure develops to create an impediment to further growth. The experimental and theoretical work of Morris (Morris and James, 1983) and of Tanaka (Tanaka and Nakai, 1984) are of interest in this regard. A manifestation of the effects of crack closure in the very early stages of crack growth is that in axially-loaded notched specimens, fatigue cracks are often observed to form in the mid-thickness region (plane strain) rather that at the surface (plane stress). The explanation afforded is that the higher closure associated with the surface regions impedes crack growth relative to the mid-thickness region where closure is less pronounced.

Figure 4 shows how, on average, the extent of this closure process is assumed to develop behind the tip of a newly formed crack in a steel of medium strength [6]. As a simplification, the closure

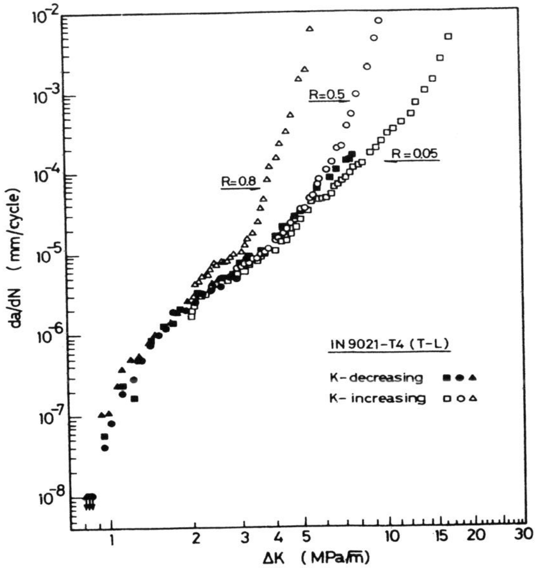

Fig. 3. Fatigue crack growth rate, da/dN, as a function of ΔK for the IN9021-T4 aluminum alloy at three R ratios. No closure observed.

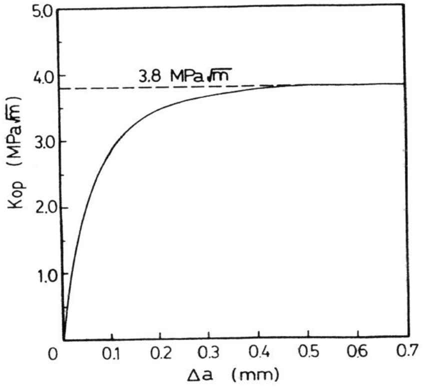

Fig. 4. Assumed development of closure as a short crack propagates from zero length to a length of 0.5 mm.

reaches its maximum value, corresponding to that of a large crack, in a distance of 0.5 mm, although in fact there may be additional closure as the crack advances, but as mentioned above, this additional closure appears to be of little influence in the near-threshold region. The advancing, newly-formed crack is thus subjected to two opposing influences which affect its growth rate. One is the increase in crack length which tends to accelerate the growth rate. The other is the increase in closure which serves to reduce the effective stress intensity factor and reduce the growth rate. If the latter factor dominates anomalous short-crack growth behavior or the non-propagation of the newly formed crack may occur. (McEvily and Minakawa, 1984)

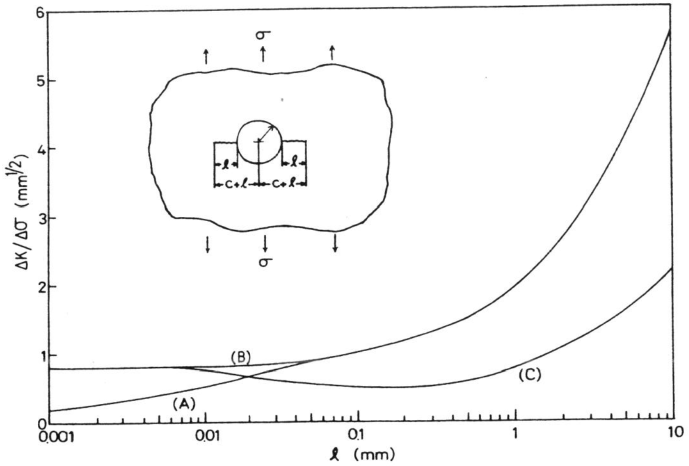

Fig. 5. Variation of $\Delta K/\Delta\sigma$ as a function of crack length, ℓ, for three cases: (A) based on short crack, ℓ, from a hole of radius c equal to 0.2 mm; (B) based on a crack of length, ℓ + c; and (C) based on crack of length ℓ + c, as influenced by the development of closure.

Figure 5 depicts three possible interpretations of the variation of the stress intensity factor for a crack of length ℓ emanating from a circular hole of radius c. (A) is the linear elastic solution for a crack growing from a hole. (Tada, Paris and Irwin, 1973) (B) is the the linear elastic solution for a crack of length c + ℓ. (C) represents the variation of K_{eff} as closure develops as in Fig. 4. Further, to account for the non-linear elastic behavior of short cracks (Smith and Miller, 1977) the stress intensity factor of the crack is initially raised to that of a crack of length c. This assumption is not critical for the important feature is that a minimum in ΔK effective occurs. A minimum will also be present in curve A if closure were considered.

Figure 6 shows how the stress required to propagate a crack varies with the initial value of c. Curve B represents the condition for propagation in the absence of closure for the medium-strength steel under consideration. Curve A represents the condition for propagation with closure fully developed and corresponds to the large crack threshold. The left hand terminus of curve A is the endurance limit of the steel. Curves C, D, and E indicate how the required stress for propagation varies as closure develops

corresponding to (C) of Figure 5. These particular curves were selected in order to compare with the experimental results of El Haddad et al (1979). The solid symbols relate to non-propagating (arrested) cracks; the open symbols relate to propagating cracks. Reasonable agreement between the closure-modified stress intensity factor and these data are obtained, and a rational physical explanation for the development of non-propagating cracks is provided.

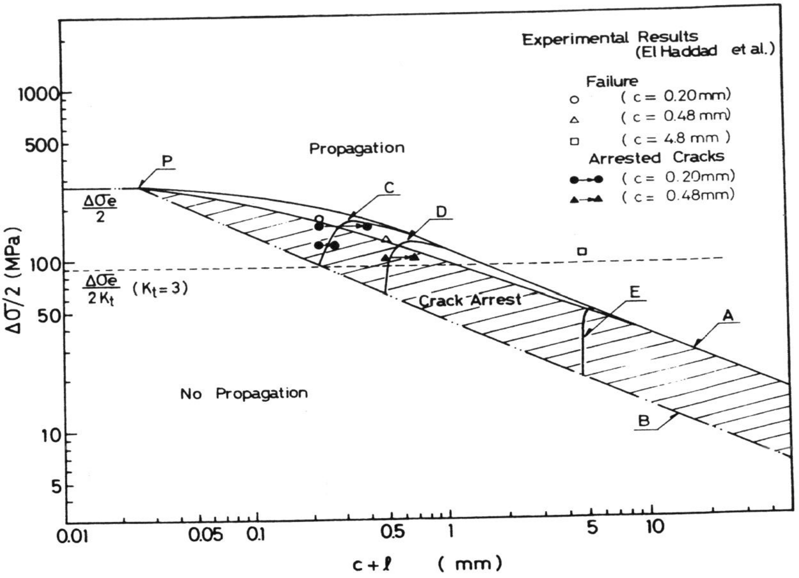

Fig. 6. Influence of crack closure as the stress to propagate fatigue cracks in a steel of medium strength as a function of notch or flaw size. R=-1.

A number of other long-standing aspects of fatigue lore are also understandable in the light of the influence of crack closure on fatigue crack growth. For example it is noted that the stress for propagation of a crack corresponding to the maxima of curves C, D, and E decreases with increase in hole size. This circumstance provides a ready explanation of the notch size effect. Fatigue notch sensitivity can also be understood, for as the strength of a steel increases there is less closure and the distance between curves A and B will decrease, resulting in an increase in notch sensitivity. It is also noted that in the presence of a flaw, a material of low strength may be more resistant to crack growth than a material of high strength. Finally it should be borne in mind that many of the beneficial effects of crack closure are found at low R ratios. At high R ratios closure may be completely absent and much lower stress amplitudes will be required for propagation, a point emphasized by Richie (1983).

THE GROWTH OF SHORT CRACKS IN SMOOTH SPECIMENS

The rate at which closure develops behind the tip of a newly formed crack is particularly important in initial stages of growth of cracks in smooth specimens. The rate of development of closure shown in Fig. 4 was chosen so that curve A of Fig. 6 would be tangent to the stress level corresponding to the endurance limit for a smooth specimen. For the chosen rate of closure development the increase in the stress intensity factor is initially just offset by the development of closure with the result that curve A is initially fairly flat. This implies that once a crack is initiated in a smooth specimen that stress level is sufficient for propagation, i.e., non-propagating cracks will not form. However there is evidence that non-propagating cracks can form in smooth specimens. Such evidence was obtained for example by Forrest and Tate (1964-65) in fine-grained brass, but not in large-grained brass. This suggests that the closure process developed rapidly in the fine-grained brass as soon as the crack traversed the first grain boundary.

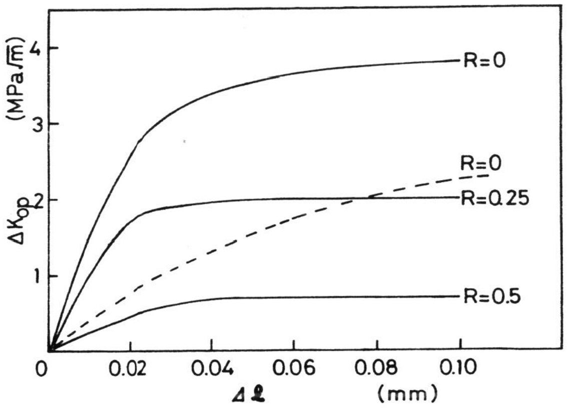

Fig. 7. Closure development as a function of R at a rate higher than that of Fig. 4 (shown dashed) ($\Delta K_{op} = K_{op} - K_{min}$).

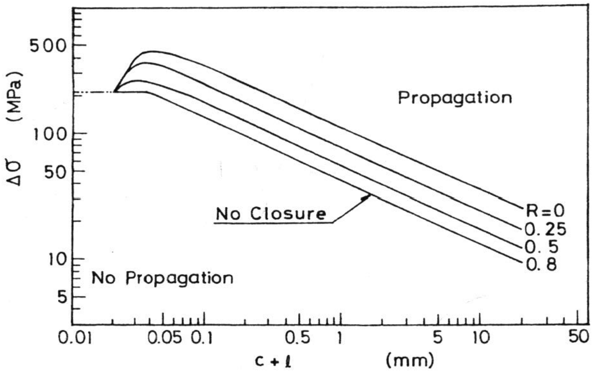

Fig. 8. Propagation conditions as a function of R and the closure development showing Fig. 7.

The closure process in smooth specimens should also depend on the R ratio. We have seen that in the absence of closure, as in the case of the 9021 alloy, that the threshold level does not depend on R. It would be of interest to know if the S/N curves for this material are R dependent but unfortunately the experimental data are not yet available. In cases where closure does develop it is of interest to determine the influence of a more rapid development of closure than depicted in Fig. 4 on the crack propagation characteristics of short cracks in smooth specimens. An illustration of the development of closure at a more rapid rate than in Fig. 4 for several positive R ratios is given in Fig. 7. A comparison with the rate of Fig. 4 is included for comparison. The influence of these selected closure characteristics on the early stages of crack growth in smooth specimens is shown in Fig. 8. In preparing this figure the fatigue strengths as a function of R were estimated using the modified Goodman procedure, and the curves in Fig. 7 were drawn to give a similar rate of approach to the maximum level for each value of R. It is noted that the maxima of the propagation curves correspond to the minimum stress required for propagation to failure to occur and that these maxima occur well before the closure process reaches its maximum. Hence the early stages of the closure process are critical in this case. Furthermore, Fig. 8 suggests that the R dependency of the S/N curves is related to the closure process since it is assumed that the slip-band initiation process is dependent only on the range of stress. If the closure process develops rapidly as depicted, non-propagating cracks can be expected in smooth specimens. In order to check on these predictions some critical experimental work is clearly needed. In particular efforts should be directed to the precise determination of the development of closure of newly formed cracks as a function of R.

CONCLUSIONS

The threshold level together with closure considerations are both significant features of the fatigue process. They relate to topics such as the non-propagation of cracks, notch sensitivity, size effects, and material selection. In addition the link between large crack behavior and the S/N curves, including R dependency, may be afforded through improved understanding of the development of the closure process.

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REFERENCES

Forrest, P. G., and Tate, A. E. L. (1964-65). J. Inst. Metals, 93, 438.
El Haddad, M. H., Topper, T. H., and Smith, K. N. (1979). Engng. Frac. Mech., 11, 573.
McEvily, A. J., and Minakawa, K. (1984a). Scripta Met., 18, 71.
McEvily, A. J., and Minakawa, K. (1984b). To be published in D. L. Davidson and S. Suresh (Eds.), Fatigue Crack Growth Threshold Concepts, Proc. of Intl. Symposium, AIME, Warrendale, PA.
Minakawa, K., J. C. Newman, Jr., and Mc Evily, A. J. (1983). Fatigue of Engng. Mater. Struc., 6, 4, 354.
Morris, W. L., and James, M. R. (1983). Engng. Frac. Mech., 18, 871.
Smith, R. A., and Miller, K. J. (1977). Intl. J. of Mech. Sci. 19, 11.
Suresh, S., and Ritchie, R. O. (1982). Met. Trans. A, 13A, 1627.
Ritchie, R. O. (1983). Private communication.
Tada, H., Paris, P. C., and Irwin, G. R. (1973). In The Stress Analysis of Cracks Handbook, Del Research Corp., Hellertown, PA.
Tanaka, K., and Nakai, Y. (1984). To be published in D. L. Davidson and S. Suresh (Eds.), Fatigue Crack Growth Threshold Concepts, Proc. of Intl. Symposium, AIME, Warrendale, PA.