EFFECTS OF NEGATIVE R VALUES ON FATIGUE CRACK GROWTH

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The effect of compressive load excursions has been the subject of a number of experimental programs during the past several years. A review of the results of these investigations indicates that the assumption that compressive cycles do not contribute to fatigue crack growth is incorrect. It is concluded that the assumption can lead to nonconservative predictions and a critical examination of the behavior involved is presented.

INTRODUCTION

Pompetzki, et al(1) performed compressive overload tests on Al2024-T351 and SAE 1045 steel. They found that intermittent compressive overloads produced stress amplitude versus cycles to failure curves which were below the curve for which no overloads were applied. Yu, et al(2) found that intermittent compressive loads applied to cracked Al2024-T351 specimens resulted in threshold values which were lower than for tests with no compressive overloads. Topper (3) has reported similar results for CSA G40.21 steel and a variety of other metals(4,5). Kemper et al(6) conducted tests on an ultra-fine grained, mechanically alloyed Al IN-905XL, copper and Al 20244 and concluded that the ASTM recommendation of using only the tensile portion of cyclic loading for crack growth analyses was valid only when obstruction to

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closure was absent. Only the Al IN-905XL satisfied this requirement. Tack and Beevers(7) conducted fatigue crack growth tests on three bearing steels for ratios from R = 0.1 to -2.5. They found that the rates of crack growth increased with increasingly negative R values.

Blakeley(8) has recently obtained data on three alloys: Waspaloy, IN-9052 and M 50 NiL. The test specimens and procedures were similar to those used in previous experiments by Tack and Beevers(7). In these tests Blakeley measured crack growth for tests in which a constant value of max stress and min stress with positive R were applied. The tests were then interrupted, and although the max stress was maintained, the min stress was reduced to a negative, compressive value so that R was negative. After an interval, the initial loading was resumed. The data for Waspaloy in Figure 1 reveals that the rate of crack growth (the slope) is discontinuous at each change in loading condition. The rate of growth for R=-2 loading is substantially greater than that for R=0.1. It also appears that the final slope for the initial R=0.1 phase is slightly greater than the initial slope for the final R=0.1 loading. This suggests that the interposed R=-2 loading may have introduced a transient retardation behavior upon resumption of the R=0.1 loading. The relative slopes during the R=0.1 and R=-2 loadings in Figure 2 for M50 NiL are analogous to those observed in Figure 1 for Waspaloy. However, the final slope for the first R=0.1 phase is only slightly lower than the initial slope for the second R=0.1 loading. Although this appears to suggest that retardation was not involved, it may be noted that since the crack had grown from a length of about 2.0 mm to about 2.6 mm, and had an intervening exposure to an accelerated growth rate, the growth rate could be expected to be significantly greater than that observed. The loading sequence for the IN-9052 test data presented in Figure 3 differed from that for the results of Figures 1 and 2. Here, the initial and final loading were under R=-2 and the intermediate phase was under R=0.1 loading. Again, the slopes at the loading changes are discontinuous, and the rates for R=-2 are distinctly greater than those for the intervening loading of R=0.1. The slopes at the end of the first R=-2 loading and that at the beginning of the second R=-2 phase are very nearly the same. Once again, however, since the crack length had grown substantially, it could be expected that the second slope should be significantly larger than that for the first.

DISCUSSION

In considering the consequences of compressive excursions, it appears unlikely that a single mechanism is responsible for all of the observed effects. Of the metals tested by Kemper, et al(6), two could be analyzed by use of the ASTM recommendation(9); i.e., the compressive excursions could be ignored and the effective range of the stress intensity factor could be set equal to K_{max}. For IN-905 XL the crack surfaces were very flat, so closure obstruction was minimal. The relative roughness of the fracture surfaces is dependent on microstructure and deformation characteristics, as noted by Kemper, et al(6). Copper was the second material and although its fracture surfaces were not flat, closure obstruction appeared to be eliminated when sufficiently high compressive loads were applied.

At least a part of the abrupt changes in crack growth rates observed by Blakeley(8) may be attributed to a difference in the effective stress intensity factor range for the two loading conditions. This can be shown by reference to features of a discrete asperities model for closure obstruction(10, 11) which is illustrated in Figure 4 as a plot of the variation of the mode I stress intensity factor with external load. With no closure obstruction the loading path cycles along the line OA. If, during unloading from point A, closure obstruction is encountered at point B, the model for a single asperity results in a straight line load path which moves downward and to the left of B, but above line OB. For two asperities it can be shown that two straight line segments will be developed. For a number of asperities an increasing number of contacts will occur during unloading, and the curve to the left of point B represents this behavior. If the heights of the asperities are inelastically reduced, it may be anticipated that unloading would drop below the elastic solution, as shown by the dashed curve. For purposes of illustration consider the two loading conditions of $R = 0$ and $R = -2$. For cyclic loading between O and Q_{max} ($R=0$) in Figure 4 the range of the effective stress intensity factor would be measured on the K axis from point D to point C, where $K>0$ because of closure obstruction. For loading between Q_{min} and Q_{max}, the range of the effective stress intensity factor would be measured from point F to point C. Since the magnitude of the distance from F to C is greater than that from D to C, it would follow that the rate of crack growth for $R = -2$ should be greater than that for $R = 0$. The difference depends upon the distance from F to D.

It has been suggested that tensile overload effects may be the result of more than one operative mechanism(12). Several mechanisms which may be operative during compressive excursions have been identified. One of these can be described by reference to the analytical assumption that the crack surfaces are perfectly flat. A uniformly applied compression can be reasonably expected to produce a uniform, compressive stress state in such a cracked body. Tack and Beevers(7), however, observed that even under maximum compressive loading complete closure did not occur. The gap or void adjacent to the crack tip could result in a very large effective, compressive stress concentration. A very large compressive stress could produce localized compressive yielding. Upon unloading, there would then be a tensile residual stress in front of the crack tip. The residual tensile stress would be superimposed on the stresses produced by the externally applied load. It has been observed that this could result in a response which is opposite to the retardation effect described by a Willenborg type model(13). A mixed mode model (14) which includes the effects of a jog in the crack path provides a description of the variations of K_I and K_{II} during a load cycle. Under normal mode I loading, the value of K_I decreases with decreasing external load. The model exhibits this type of response, but it should be observed that K_{II} increases with decreasing load. The maximum value of K_{II} then occurs at the minimum load or the largest applied compression. K_I and K_{II} are out of phase with one another. Nonproportional low-cycle fatigue loading is usually, however, found to be more damaging than in phase loadings(15). Pook(16) has recently identified issues which remain to be resolved in problems involving fatique crack growth under mixed mode loading. He concludes that little is known about cases in which out of phase or non-proportional loading occurs. Some insight into the complexity of the behavior may be gained by considering the cyclic plastic zone. Under mode I loading, the rate of crack growth has been considered to be proportional to the cyclic plastic zone size. Since the shapes for plastic zones for modes I and II are different, however, not only sizes, but also the shapes of these zones can be expected to be a factor. Crack growth rate laws which have been proposed are often based on a funtional relationship in which an effective ΔK is the driving force. If only mode I is considered, the effective ΔK cannot exceed max K_I for $R<0$. If a contribution from mode II loading is included, however, an effective ΔK could be based on alternate contributions from mode I and mode II loading integrated over a cycle. The effective ΔK could then exceed max K_I, and provide a rationale which could account for the experimentally observed behavior.

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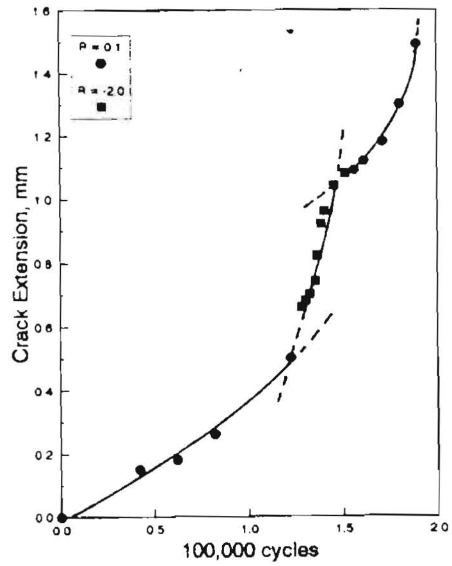

Fig. 1 Data for Waspaloy; $\sigma_{max}=300$ MNm^{-2}, $a_o=1.20$ mm

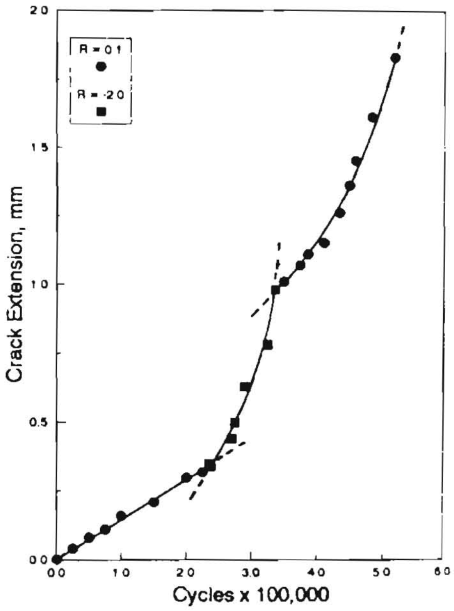

Fig. 2 Data for M50 NiL; $\sigma_{max}=108$ MNm^{-2}, $a_o=1.62$ mm

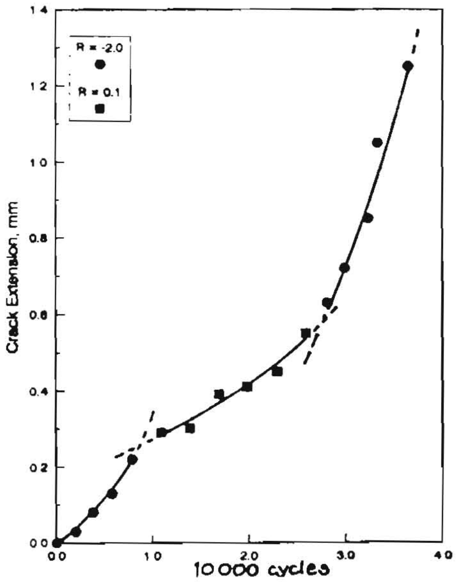

Fig. 3 Data for IN-9052; $\sigma_{max}=100$ MNm^{-2}, $a_o=1.55$ mm

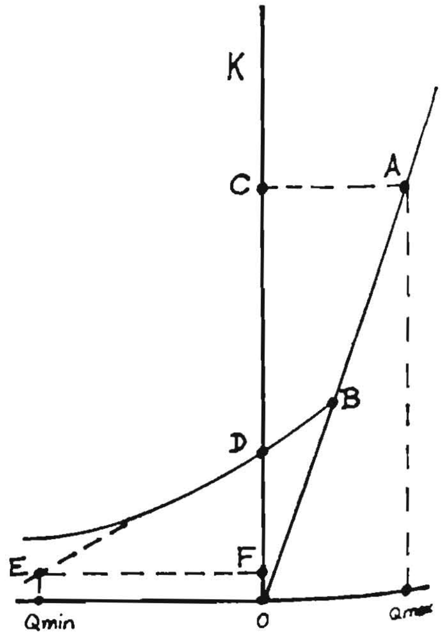

Fig. 4 Effect of closure on stress intensity factor