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A MECHANISM FOR OVERLOAD EFFECTS IN FATIGUE

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CRACK GROWTH RETARDATION DUE TO MICRO-ROUGHNESS: A MECHANISM FOR OVERLOAD EFFECTS IN FATIGUE

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Introduction

The influence of overloads on fatigue crack growth behavior of engineering materials has been a subject of detailed investigations for many years. Although the phenomenon of crack growth retardation following single tensile overloads or high-low block loading sequences is experimentally well documented, the micromechanisms underlying such transient effects are not yet clearly understood. Previously suggested arguments to explain the influence of overloads on fatigue crack growth include models based on i) residual compressive stresses at or close to the crack tip (1) and the concomitant yield zone interactions (2), ii) crack tip blunting (3), iii) closure due to residual plastic deformation in the wake of the crack (4) and iv) crack tip strain hardening (5). Although it is widely recognized that a single mechanism may not completely account for the complex behavior of crack growth retardation or arrest following load excursions, the role of different mechanistic possibilities has thus far not been well characterized.

Discussion of Existing Models

Fig. 1 shows the fracture surface features of 2024-T3 aluminum alloy denoting i) pre-overload crack growth by striation mechanisms (region A), ii) stretch zone due to the application of a single overload (region B) and iii) the post-overload zone (region C), from the work of von Euw et al. (6). Based on Elber's crack closure arguments (4), these authors suggested that permanent tensile displacements resulting from the overload cycle generate crack surface interference in the wake of the advancing crack front, which accounts for not only the attenuated crack growth rates, but also delayed retardation. However, for the following reasons, it appears that such (plasticity-induced) crack closure is not the primary mechanism of crack growth retardation following single overloads.

Firstly, a careful examination of Fig. 1 reveals that crack surface interference and abrasion occur in the post-overload crack growth zone (region C) as evidenced by the rough surface morphology, and not in the stretch zone created by the overload (region B) where the fracture features are clearly identifiable. As it is known that crack closure due to residual tensile displacements during Stage II growth can occur in plane stress constant amplitude cyclic loading without any abrasion marks or obliteration of striations (4), it is inconceivable that the same mechanism of crack closure can remove the striation marks on the surface (region C) by an abrasion process in the post-overload zone (6). Moreover, post-overload crack tip profiles obtained by Lankford and Davidson (7) in a number of aluminum alloys have shown that the main crack remains blunted (at the crack location corresponding to single overload cycling) even after the retarded crack has progressed well into the post-overload zone. A typical example of the blunted crack (denoted by A) is shown in Fig. 2 for a 6061-T6 aluminum alloy at about 160 cycles after the application of a 100% tensile overload with a base-line $\Delta K = 10$ MPa$\sqrt{m}$. Such blunt crack tip profiles are also inconsistent with the argument that crack face interference occurs due to the enlarged residual plastic deformation generated by the overload. Also, a large body of experimental evidence indicates (e.g., ref. 8) that the process of (plasticity-induced) crack closure arising from residual tensile displacements in the wake of the crack plays a dominant role only under plane stress conditions and yet, considerable crack growth retardation occurs following single overloads at lower ΔK levels where predominantly plane strain

conditions exist (9-13). Thus, based on fractographic features (6), blunt crack tip profiles (7) and plane strain attenuated growth rate data (9-13), it is inferred that crack closure due to residual tensile displacements is not the primary mechanism for retardation following single overloads. (It is, however, emphasized that crack closure due to residual displacements could occur in other types of loading situations such as plane stress constant amplitude and block tensile overload cycling tests (4)).

Jones (5) pointed out that crack tip strain hardening cannot be a viable mechanism for retardation since pre-strain hardening was found to accelerate, rather than retard, crack propagation rates. While several workers have suggested the importance of residual compressive stresses in attenuation of crack growth rates (1,2), the region of crack growth retardation, in many instances, is not comparable to the size of the overload plastic zone, especially in plane strain situations where the crack length over which retardation occurs is found to be considerably larger than the extent of cyclic plastic zone directly ahead of the crack tip (9-13). Electron channelling patterns obtained during load excursions (14) clearly show that the actual shape and size of the plastic zones generated by overloads could be significantly different from those calculated for plane stress and plane strain situations (which have been used by numerous investigators for comparison with the retarded crack growth distance). In addition, while post overload growth is known to be microstructure sensitive (10,11), correlation of the retarded crack length with the plastic zone size alone may not be fully valid for all materials. Thus it appears that although residual compressive stresses could play an important role in crack growth retardation, such a mechanism cannot solely account for the observed effects. Fig. 2 clearly shows that crack tip blunting does occur (7) due to the application of single overload. However, crack tip blunting, by itself, is not the controlling mechanism of retardation since the post overload crack branches out (away from the blunted crack) to propagate through one of the shear bands generated by the overload and tends to align itself in a direction perpendicular to the loading axis within a few cycles following the overload (Fig. 2).

The purpose of this note is to present new mechanisms for crack growth retardation based on a "micro-roughness" model. It is shown that this model, which does not exclude the role of other factors such as residual stresses or blunting, provides a rationale for the occurrence of several hitherto unexplained overload effects on crack growth retardation reported in the literature. In addition, further sources of crack growth attenuation arising from fracture surface oxidation are discussed.

Micro-Roughness Model for Crack Growth Retardation

It is now a well documented observation (7,14) that the application of a single overload produces intense shear bands at the blunted crack tip. As the crack begins to propagate along one of the shear bands (Fig. 2) and changes direction (shown by the arrow in Fig. 2) on intersecting a grain boundary and/or tending to align itself along the pre-overload crack, the effective stress intensity at the crack tip is substantially reduced due to crack branching as well as residual compressive stresses. It has been shown that the effective ΔK in the retarded zone could be close to the threshold stress intensity range for fatigue crack propagation, ΔK_0 (7,13, 14). Thus, even though the post-overload (baseline) stress intensity range is large enough to propagate the crack by two simultaneous or alternating slip systems (akin to Forsyth's Stage II mechanism (15,16)), the local conditions at the crack tip are governed primarily by the micromechanisms of near-threshold crack growth. Such near-threshold crack propagation is known to occur along a single slip system (akin to Forsyth's Stage I mechanism), resulting in serrated or zig-zag fracture paths (15,16). The large Mode II crack displacements accompanying such crack advance thus readily provide a mechanism for contact between fracture surface asperities above the minimum K during post-overload (baseline ΔK) cycling (Fig. 3). The occurrence of Mode II shear displacements following single overloads has been confirmed experimentally by means of in situ SEM analyses (7) and fractography (7,10). The contact between the two fracture surfaces due to Mode II displacements can also be observed from the post-overload crack paths (7). Thus the micro roughness model provides an explanation for sustained retardation even when residual compressive stresses are not operational such as in plane strain crack growth well beyond the cyclic plastic zone. As mentioned earlier, while residual compressive stresses may (at least partially) activate near-threshold conditions by initially lowering the effective ΔK, fracture surface micro-roughness further lowers the effective ΔK with the aid of Mode II displacements. The fact that events such as cracking along the shear band, crack branching and initiation of Stage I conditions have to occur in the post-overload zone before growth is further retarded by abrasion due to micro-roughness and Mode II displacements, is consistent with the phenomena of delayed retardation. After the minimum crack growth rate, as the retarded crack grows away from the elastic-plastic boundary, a progressive increase in effective ΔK (and

hence, lower abrasion and Mode II displacements) occurs until the crack eventually catches up with the pre-overload baseline growth rates. Based on simple geometric considerations, it can be shown that reduction in effective ΔK values in excess of 30% could occur due to fracture surface contact, consistent with experimental information of effective ΔK values (7). Such quantitative analyses will be discussed in detail in a future publication (13). Note that although the microroughness mechanism leads to crack face contact and hence crack closure, such closure processes are entirely different from the mechanism of plasticity-induced crack closure originally proposed by Elber (4).

Evidence in Support of Micro-Roughness Model

The micro-roughness model rationalizes not only the occurrence of abrasion following an overload, but also the paucity of discernible striation formation (Fig. 1 and refs. 6,11). As pointed out earlier, the above model is consistent with phenomena such as retardation beyond the cyclic plastic zone (especially under plane strain) and delayed retardation. Prior work has revealed that the reduction in effective ΔK could be more pronounced at lower baseline ΔK levels following an overload (for a given overload ratio) (17). Such behavior can be explained in terms of the micro-roughness model by considering that near-threshold conditions (which activate fracture surface contact and decrease in effective ΔK) can be achieved more easily for an overload applied at a lower baseline ΔK level. An important aspect of this model is that it does not exclude other mechanisms such as residual compressive stresses or blunting, but provides a mechanistic basis for additional sources of retardation which have not been fully explored thus far.

This micro-roughness model also rationalizes the pronounced effects of microstructure (10, 11) and crack tip-grain boundary interactions (7) observed in the post-overload growth region. While Stage II crack growth is predominantly microstructure insensitive, near-threshold crack advance has been found to be highly sensitive to microstructure (16). Since the model suggests that post-overload growth is governed by the micromechanisms of near-threshold crack propagation, the microstructure-related influences on attenuated crack growth are consistent with the present arguments.

Environmental Effects on Retardation

Since near-threshold crack growth mechanisms could locally dominate the conditions at the crack tip in the post-overload retardation zone even though intermediate ΔK conditions might exist globally, environmental factors (which markedly influence near-threshold crack growth) could be of paramount importance in the retarded crack growth region. It has been shown that in some alloys, delay effects following overloads may be less pronounced in an aggressive environment compared to an inert gaseous medium (12). It is also possible that in moist environments, fretting contact between the fracture surfaces at low load ratios and rubbing due to Mode II displacements could result in the formation of enlarged corrosion deposits (whose thickness could be comparable to the extent of the crack tip opening displacement) and prolong the retardation following overload by further reducing the effective ΔK in alloys which are prone to significant oxidation at near-threshold conditions (18-20). While crack closure enhanced by corrosion deposits has been found to play a significant role in the near-threshold growth behavior in a number of low strength steels (18-20), the importance of such additional closure processes is found to be a strong function of aging treatment and microstructure in aluminum alloys (21). Fig. 4 shows thick deposits of oxide layers found on crack faces in the post-overload region, indicating the possibility of enhanced retardation due to oxidation in a 2-1/4Cr-1Mo steel (SA542 Class 3). In certain situations (depending on the overload ratio and the baseline ΔK) the thickness of the oxide layer in the post-overload zone is found to be somewhat higher than that formed at the same ΔK level in the pre-overload zone (13,22). Additional evidence of the importance of oxidation effects following overloads is obtained from the work of Vasudevan et al. (22) who found that application of single tensile overloads at intervals of 8000 cycles increased the fracture surface oxidation by about a factor of five compared to constant amplitude cycling at the same baseline ΔK level.

Conclusions

A new mechanism for fatigue crack growth retardation following an overload is presented in this paper, based on a micro-roughness model. It is reasoned, with the aid of extensive experimental evidence available in the literature, that retardation following an overload is governed by the micromechanisms of near-threshold crack growth. This model is found to rationalize a number of hitherto unexplained experimental observations. Moreover, the present arguments, which suggest that plasticity-induced crack closure is not likely to be the primary mechanism

for retardation following single overloads, do not exclude the role of residual stresses or blunting, but provide further mechanistic basis to account for the inconsistencies in the previous models. Additional sources of prolonged retardation, in terms of crack closure due to corrosion debris formed in moist environments, are suggested. It is pointed out that such environmental effects could play an important role in post-overload crack growth in certain alloy systems.

Acknowledgments

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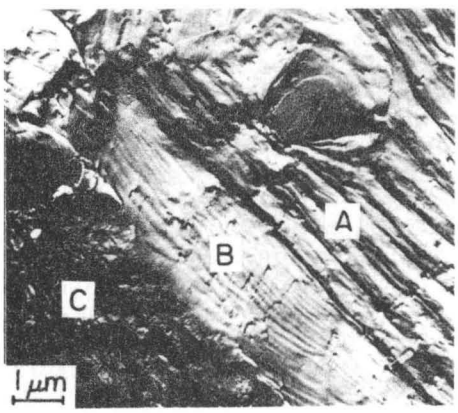

FIG. 1 Fractograph showing the surface appearance in the pre-overload zone (A), stretch zone (B) and the post-overload zone (C) in 2024-T3 aluminum (after ref. 6).

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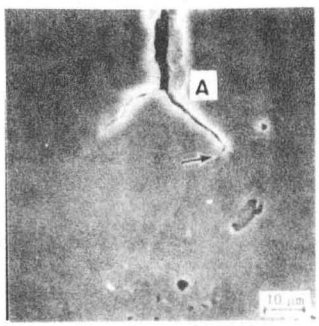

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FIG. 2 In-situ SEM photograph of crack tip blunting and branching in 6061-T6 aluminum alloy at 160 cycles following a single overload (after ref. 7).

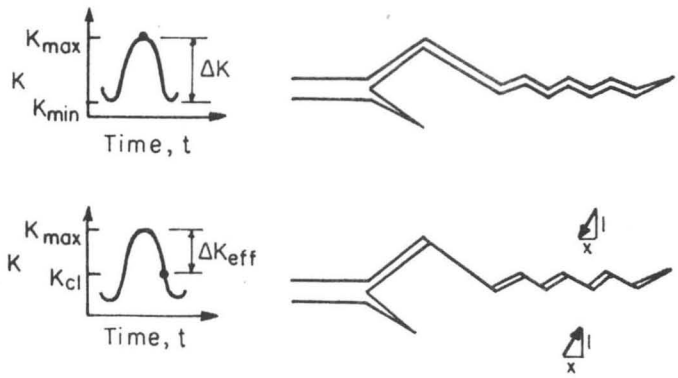

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FIG. 3 Schematic showing the mechanism for decrease in effective ΔK due to micro-roughness in the post-overload zone. x is the ratio of Mode II to Mode I displacements.

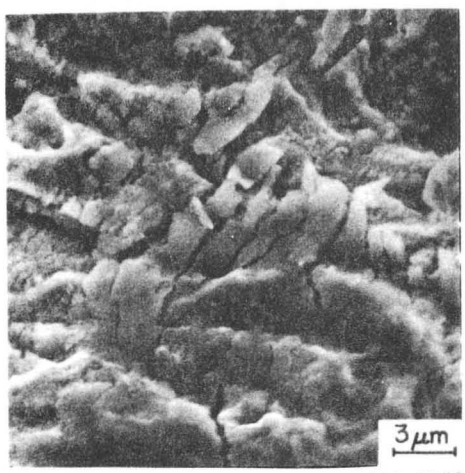

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FIG. 4 Fractograph showing enlarged oxide scales formed due to fretting and rubbing following a single overload in a 2-1/4Cr-1Mo steel.

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