INFLUENCE OF STRESS STATE ON CRACK-TIP DRIVING FORCE

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Summary In this paper, a two-parameter crack-tip driving force in terms of K_{max} and ΔK^+ has been developed to account for load interaction effects on fatigue crack growth behavior. The development is based on the premise that the load interaction effects depend upon the applied and residual stress state at the crack tip. Examples from the literature regarding crack growth behavior due to an overload application in air and vacuum are analyzed and discussed.

INTRODUCTION

The accurate modeling of load interaction effects associated with the application of an overload is a prerequisite for an accurate prediction of fatigue crack growth behavior under variable amplitude loading. The load interaction effects on fatigue crack growth behavior are commonly introduced through the modification of the crack-tip driving force. In the past, several mechanisms have been proposed to account for the crack-tip driving force modification namely, crack closure, residual stresses, crack-tip blunting or branching, strain hardening, and environmental influence. In the vast majority of investigations the Elber plasticity-induced crack closure concept [1], which operates behind the crack tip, has been adopted as the critical mechanism responsible for load interaction effects in metallic materials. In such approaches, an effective stress intensity factor range is defined as

$$\Delta K_{eff} = K_{max} - K_{op}, \qquad (1)$$

where K_{max} and K_{op} are the stress intensity factors calculated for the maximum, P_{max}, and the crack opening load, P_{op}, respectively. This implies that only the load range between the opening load, P_{op}, and the maximum load, P_{max}, would affect the crack tip action during the load cycle. However, for most metallic materials, plasticity-induced phenomena are present not only in the crack wake but also in front of the propagating crack. In particular, when an elastic-plastic material is loaded, a plastic zone is developed, leaving compressive stresses at the crack tip after unloading. Therefore, not only crack closure behind the crack front, but also compressive stresses ahead of the crack front, would modify the actual crack-tip driving force. In other words, the load interaction effects depend upon the applied and residual stress state ahead of the crack tip and could significantly affect fatigue crack growth behavior depending on the environment [2-5]. This is in contrast with crack closure approach that explores the phenomena occurring behind the crack tip.

ASSUMPTIONS AND ANALYSIS

It is well known that for ductile materials the crack driving force is mostly affected by ΔK, whereas for brittle materials by K_{max}. Usually, the relative contribution of ΔK or K_{max} to crack driving force also depends on material's cyclic properties (hardening or softening), temperature, and environment. To account for these effects a two-parameter crack-tip driving force developed in Ref. 6 has been adopted

$$K^* = (K_{max})^{\alpha}(\Delta K^+)^{1-\alpha} \qquad (2)$$

where ΔK^+ is the positive part of the stress intensity factor range and α is a parameter that characterizes the apparent sensitivity of the K^* to the K_{max} value. In general, when α=1 the crack driving force is solely defined by K_{max} *(very brittle materials)*; however, when α=0 it is defined only by ΔK^+ *(ductile materials in vacuum)*. The two-parameter crack-tip driving force is based on the following premises:

- The damage at the crack-tip process zone is an interplay of two damage processes, namely a monotonic damage due to K_{max} and a cyclic damage due to ΔK^+.
- The damage action at the crack-tip process zone is controlled by the elastic field around it.
- Existence of the tensile stresses in the process zone, $K_{max} = (K_{app} + K_{res}) > 0$, is a necessary condition for fatigue crack propagation, where K_{app} and K_{res} are the stress intensity factors calculated due to the applied load, P_{max}, and due to residuals stresses, respectively.
- The residual stress field induced by an overload is not relaxed significantly by subsequent fatigue crack extension. This assumption is based on the experimental evidence obtained using X-ray measurements [7].

It has been demonstrated that the two-parameter crack driving force, K*, unifies the overall crack prediction methodology regarding load ratio effects for both the long- and short-crack growth behavior [6]. In this paper, the K* driving force approach has been extended to account for crack growth retardation behavior by incorporating the effects of residual stress field due to an overload application.

Estimation of residual stress induced by an overload

In order to estimate residual stresses induced by an overload a simple analytical model was developed. The crack tip stress distribution obtained by Rice [8] for Mode III loading was modified for Mode I crack and the Ramberg-Osgood stress-strain relationship. This modified solution was used to estimate the stress distribution normal to the crack plane as a function of distance ahead of the crack tip. Applying Rice's superposition argument of the reversed flow during unloading, the residual stress after overload was evaluated. This simple modeling was compared with finite element analysis results and a reasonable agreement was found. Then, the weight function approach was utilized to calculate the resulting stress intensity factor, K_{res}, due to residual stress field versus crack extension and hence the $K_{max} = K_{app} + K_{res}$ at the crack-tip was obtained. Finally, the two-parameter driving force, K*, was determined and used to predict retardation behavior following an overload application.

COMPARISON WITH EXPERIMENTAL DATA

Taking examples from the literature, a crack growth transient behavior due to overload was analyzed in terms of the two-parameter driving force. Due to application of an overload, the crack first accelerates, then the crack slows down to a minimum growth rate, and finally the crack recovers to the pre-overload growth rate. The residual stress created by the overload affects both the maximum and the minimum crack-tip stress intensity factors [7]. As a result, at the crack-tip only the K_{max} is modified whereas the corresponding ΔK is unaffected. The minimum growth rate after overload is associated with a crack growth increment of about one-fourth to one-third the overload forward plastic zone size. It is shown that this corresponds to the minimum value of K_{max} at the crack-tip calculated from the applied load and residual stresses due to overload. As the crack advances near the boundary of the overload forward plastic zone both the crack-tip K_{max} and crack growth rate stabilize to the pre-overload values.

The proposed approach is then used for a comparative study of the fatigue crack growth behavior due to overload in air and vacuum environments. The results indicate that the transient behavior in the two environments is essentially the same. The observed quantitative variations are associated with the inherent differences in the fatigue crack growth behavior in air and vacuum. The apparent crack growth retardation behavior is coupled with the stress/environment interaction in the process zone ahead of the crack tip. In particular, the period when crack growth rate is recovering from the slowest transient growth rate to the post-overload stabilized value is sensitive to environment.

CONCLUSIONS

A new two-parameter crack driving force that takes into account the influence of residual stress state due to overload is proposed. The proposed parameter yields fairly good correlations between overload effects observed experimentally for a number of materials including steels, aluminium and titanium alloys compared in this study. The analysis shows explicitly the link between residual stresses induced by overload and the delayed crack growth retardation.

It unifies the load interaction prediction methodology regarding load ratio, overload, and environment on fatigue crack growth behavior and bridges the existing gap between them. Further studies are needed to examine the potential application of this new parameter for variable amplitude loading.

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