CLOSURE EFFECTS IN SHORT AND LONG FATIGUE CRACKS

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ABSTRACT

Closure effects in short and long fatigue cracks are reviewed. Their importance in allowing accurate prediction of delayed crack growth after overload application to long cracks is demonstrated. Examples are presented of predictions of short and long crack growth as a function of stress ratio, R, and degree of constraint at the crack tip, where closure effects are taken into account.

KEYWORDS

Fatigue (materials); cyclic loads; crack growth; crack closure; short cracks.

INTRODUCTION

The growth of fatigue cracks has commonly been predicted using the relation proposed by Paris and Erdogan (1963). This has the form:

$$da/dN = C\Delta K^m \tag{1}$$

However, where either load fluctuations or overloads occur, equation (1) is inadequate as the fatigue crack does not necessarily start to open along its length when the tensile part of the load cycle commences: this is because of residual stresses which may hold the crack closed until sufficient external load is applied to overcome them.

Accordingly, upon recognizing this crack closure phenomenon, Elber (1970) proposed a modified fatigue crack growth equation,

$$da/dN = C'(U\Delta K)^m \tag{2}$$

in which U is termed the effective stress range factor and is defined by

$$U = (\sigma_{max}-\sigma_{op})/(\sigma_{max}-\sigma_{min}) \tag{3}$$

σ_{max} and σ_{min} being respectively the maximum and minimum values of stress in the specific cycle of interest, and σ_{op} being the stress at which the crack starts to open along its length.

Equation (2) may also be written in the form:

$$da/dN = C'(\Delta K_{eff})^m \qquad (4)$$

ΔK_{eff} being the effective range of stress intensity factor.

The determination of σ_{op}, and hence ΔK_{eff}, has been made experimentally (Shaw and Le May, 1979), and analytical methods for its estimation have been formulated (Dill and Saff, 1976; Newman, 1981, 1982). This has been done primarily in connection with "long" fatigue cracks, in which the crack tip plastic zone is small in comparison with the crack length, and the length exceeds the grain size by a considerable factor.

The relationship expressed by equations (1) or (4) covers the greater part of fatigue life, however, it does not hold at low levels of ΔK down to the threshold condition, ΔK_{th}, or at high values of ΔK where K_{max} approaches the fracture condition. This is illustrated in Fig. 1, which shows schematically the classic growth curve. More complex equations which give rise to the observed sigmoidal shape and which take into account the effect of stress ratio $R(=\sigma_{min}/\sigma_{max})$ have been developed, a recent review being given by Swift (1983). However, a complication has been the observation that "short" fatigue cracks may propagate at values of ΔK below threshold and apparently do not obey a Paris or other classic growth law.

Figure 2 shows crack growth data for short and long cracks obtained by Taylor and Knott (1981), while Fig. 3 shows schematically the growth rate for a short crack. At low values of applied stress range (e.g., $\Delta\sigma_2$) the crack becomes non-propagating as ΔK never reaches ΔK_{th}. Interest in short cracks stems from the much higher growth rates occurring in the early stages than would be expected using the conventional approach illustrated in Fig. 1, and from the fact that growth takes place below ΔK_{th}.

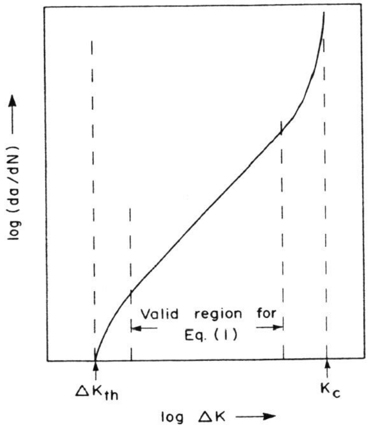


Fig. 1. Fatigue crack growth plot illustrating the region of validity for the Paris law.

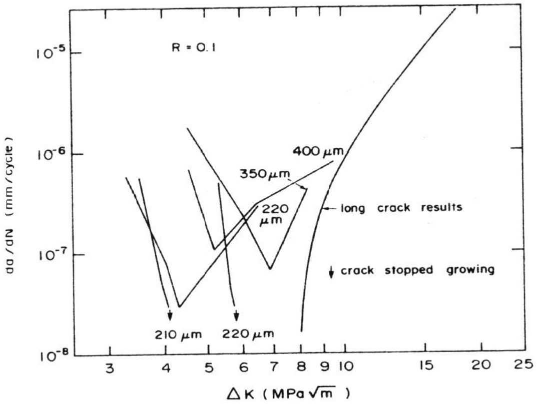


Fig. 2. Five different constant load range tests on short cracks in an aluminum bronze, the final crack length being shown for each. After Taylor and Knott (1981).

A useful plot illustrating short crack growth is shown in Fig. 4, in which the threshold range is plotted as a function of crack length. The point of intersection of the fatigue limit line and the line having a slope of -½ on the log/log scale has been defined as being at a crack length ℓ_o (El Haddad and others, 1980), and this may be considered the minimum crack for propagation at the endurance limit.

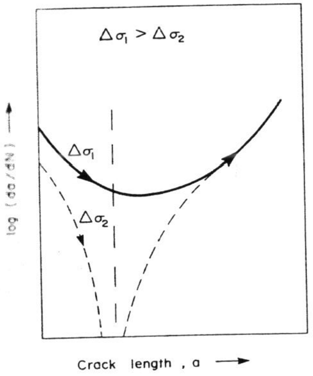


Fig. 3. Schematic plot showing the growth behaviour of a short crack. At $\Delta\sigma_1$ the crack continues to grow as a long crack after initial decelleration. At $\Delta\sigma_2$ the crack becomes non-propagating as ΔK never reaches ΔK_{th}.

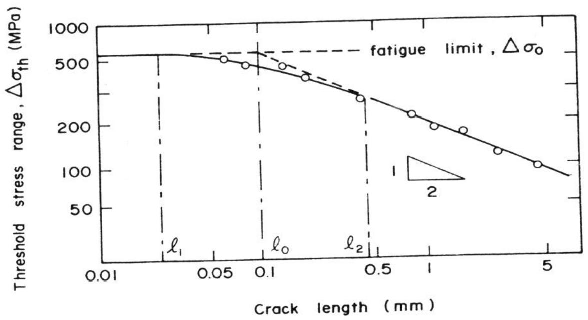


Fig. 4. The threshold stress range for fatigue failure as a function of crack length. The experimental data are from Kitagawa and Takahashi (1976).

The causes of the anomalous behaviour of short cracks are the subject of considerable debate. The effects may be caused by: (a) an absence of crack closure effects at very short crack lengths or where the plastic zone at the tip is not small with respect to crack length; (b) a wedging open of the crack from oxidation or other corrosion products; or (c) a wedging action produced by coarse grains subject to combined Modes I and II crack growth, as illustrated in Fig. 5 (Minakawa and McEvily, 1982). However, it does seem that the reduced closure has a major influence unless the microstructure is coarse and the controlling microstructural features are of the same order as the crack length (Le May, 1983).

The present paper reviews some effects of crack closure as they affect the growth of long and short cracks, and discusses appropriate modelling techniques.

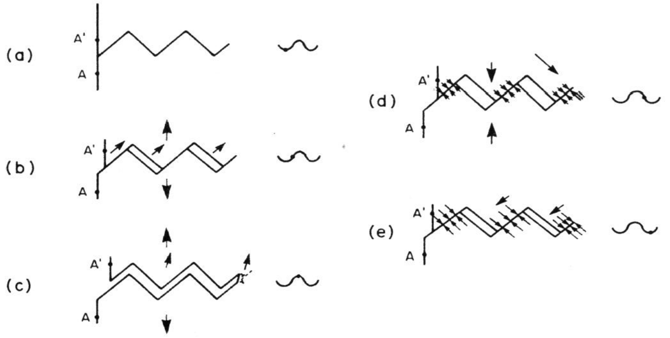
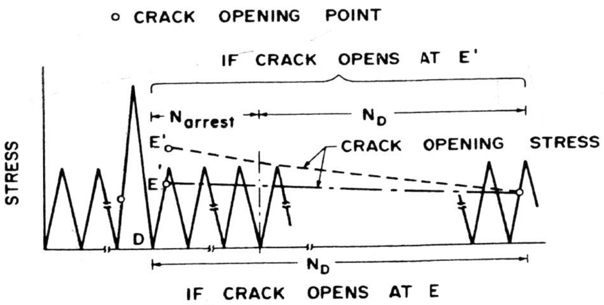


Fig. 5. Combined Mode I and Mode II fatigue crack growth. After Minakawa and McEvily (1982).

CRACK CLOSURE IN LONG FATIGUE CRACKS

As noted previously, one of the ways in which crack closure manifests itself is the delay in crack growth after an overload. Figure 6 shows schematically an overload cycle and its effect in raising the value of σ_{op}: the result is illustrated in Fig. 7.



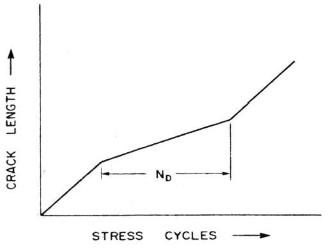


Fig. 6. The effect of an overload cycle in raising the value of the crack opening stress, σ_{op}, so delaying crack growth.

Fig. 7. Delayed crack growth as a result of an overload.

Lal and Le May (1980b) made a simplified analysis to predict the closure effect and the number of delay cycles before the increased closure was overcome. Table 1 shows the predicted and experimentally observed delay cycles for 2024-T3 aluminum alloy, experimental data being taken from the work of Trebules and others (1973). Good correlation is observed. Similarly, the effects of high-low-high block loading have been predicted to give good agreement with observed growth rate variations (Lal and Le May, 1980a; Pelloux, Faral and McGee, 1979).

TABLE 1 Delay Cycles for 2024-T3 Aluminum Alloy Following Overloads

No. of Overloads	Observed Delay Cycles	Predicted Delay Cycles
1	6500	6495
1	5500	7195
1	9500	9186
1	5000	4691
2	6000	6588
4	5500	5183
10	7000	7071
10	6000	5436

The simple analysis of Lal and Le May (1980) involves the assumption that the closure effect is independent of crack length. This assumption is shared by other models and is essentially correct for long cracks. However, it is not true for short cracks, and such models cannot be applied to predict closure in short cracks.

Most of the models treat the problem as a two-dimensional one, involving consideration of plane stress, rather than plane strain, whereas there is plane stress at the surface and plane strain in the centre of the specimen. There is much greater surface closure than in the centre, and the centre region of the crack front may remain open when the surfaces are closed (Shaw and Le May, 1979; Lindley and Richards, 1974). The model of Newman (1981, 1982, 1983) attempts to consider this by dealing with a degree of constraint. However, much remains to be done in determining closure effects as a function of specimen thickness, loading and crack geometry.

CRACK CLOSURE IN SHORT FATIGUE CRACKS

The rapid growth in the early stages of the propagation of short cracks can, as indicated, be explained on the basis of an absence of closure and a resulting higher value of ΔK_{eff} than for a comparable long crack under identical nominal ΔK. The (large) plastic zone may cause the crack to remain open after unloading, as shown in Fig. 8. Such conditions are relevant in the absence of wedging.

Newman's analysis (1981, 1982, 1983) for modelling crack closure does not make assumptions with respect to crack length, and appears to be applicable to long and short cracks. In this analysis, closure can be considered in terms of the total plasticity-induced forces applied at the crack tip and along the wake. During short crack growth at positive R, the compressive force from the plastic zone is larger than that applied along the crack surfaces. Thus, little compressive force along the wake results when modelling the short crack (Cheung and Le May, 1984). As the crack grows to the long crack regime, the total force at the tip may become tensile, the closure force arising from the wake.

Cheung and Le May (1984) applied Newman's analysis to short and long cracks in 2219-T851 aluminum alloy. Figures 9 and 10 show the predicted growth curves from short crack to long crack regimes. The effect of R shown in Fig. 9 is noteworthy, higher positive values producing little crack closure.

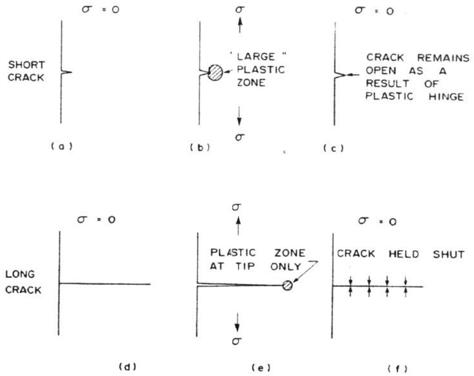


Fig. 8. Schematic showing the plastic yielding in a short crack serving to maintain it open after unloading, and comparison with a long crack.

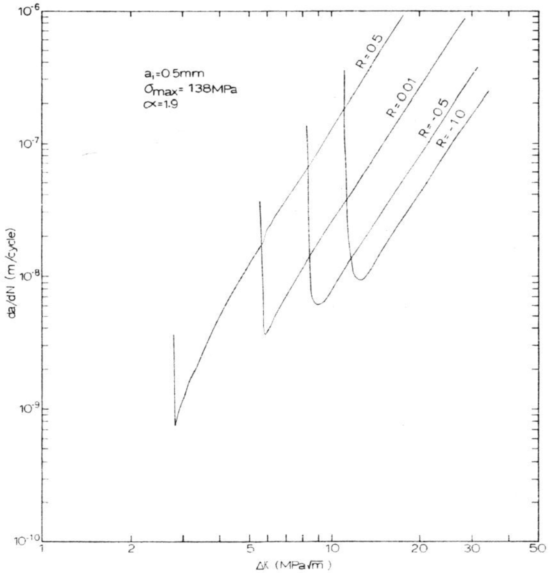


Fig. 9. Predicted crack growth from an initial crack length of 0.5 mm as a function of R in 2219-T851 aluminum alloy (Cheung and Le May, 1984).

The plots of Fig. 10 indicate the effect of the degree of constraint and, thus, the three-dimensional nature of the analysis. The greater the degree of plane strain, the less is the closure. This agrees with observations.

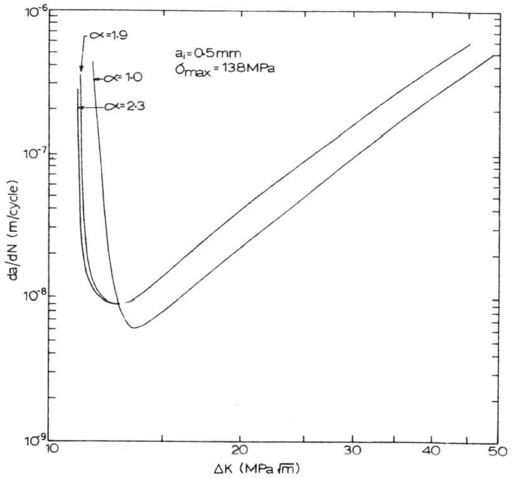


Fig. 10. Predicted crack growth in 2219-T851 as affected by the degree of constraint (Cheung and Le May, 1984).

The analysis is being extended to cover overloads, block and spectrum loading, and experimental data will be generated for comparison with the predictions. Newman (1983) has also provided a comparison of predicted growth curves with experimental data of Taylor and Knott (1981) with reasonable success. Much remains to be done to fully justify the analysis, but it does show clearly the effects of different variables on the short crack phenomenon.

CONCLUDING REMARKS

The paper has attempted to highlight some of the more important aspects of crack closure, particularly the need to consider the phenomenon when modelling and predicting fatigue crack growth from long and short cracks. While the emphasis has been on consideration of an essentially structureless continuum, mention has been made of the important role of microstructure in the growth of short cracks. Where microstructural features are coarse, the continuum approach clearly is invalid, and considerable analysis and experiment are required in this connection.

With the increasing importance of damage tolerance evaluation, a more complete awareness of short crack phenomena and how to treat them analytically will be required in future.

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