A NEW MODEL OF SHORT CRACK CLOSURE

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ABSTRACT

The fact that crack closure in the short crack stage significantly increases soon after crossing the first grain boundary, and the existence of heavy crack path tortuosity suggest that plasticity induced closure and roughness induced closure interact during short crack growth. A new approach to combine different closure mechanisms for modelling short crack closure is presented. Based on this concept, two simple models are presented here to demonstrate this approach. Experimental results on short crack growth in notched specimens compare favourably with the predictions from the models.

KEYWORDS

Mixed Mode, Short Fatigue Crack, Crack Closure.

INTRODUCTION

Crack closure has been successfully used to explain the anomalous behaviour of short fatigue cracks for some time. However, most publications are centred on the effect of plasticity induced closure. Recent work on the early stage of short crack growth (Dowson *et al.*, 1992) suggests that after short cracks grow through the grain boundary, the amount of crack closure increases significantly. It is obvious that this phenomenon could not be explained by the effect of plasticity induced closure alone.

A further investigation has been made to discover the reasons for the significant increase of crack closure soon after the crack grows through the grain boundary. It appears that roughness induced closure plays a very important role in this case, due to crack deflection. It appears that in practice, it is not either plasticity induced closure or roughness induced closure but a combination of both that dominates the early stage of fatigue crack growth.
In this paper, a series of short crack growth tests have been performed on an aluminium with various loading ratios, R, in order to compare the new method to traditional crack closure calculations. An attempt then was made to combine plasticity induced closure and roughness induced closure (Dowson *et al.*, 1992). to predict short crack growth behaviour. Newman's analytical crack closure model (Newman Jr, 1981) has been applied to calculate the plasticity induced closure part, and the calculation of the roughness induced closure part

has been done by using Suresh and Ritchie's model (Suresh, 1983). The problem faced by our analysis was how to combine these two predictions in a meaningful way.

EXPERIMENTAL PROCEDURE

The material used in this study was aluminium alloy Ly12-CZ (similar to 2024-T3 aluminium alloy) sheet and plate, 2mm and 5mm thickness respectively. The compositions and mechanical properties of this material are listed in the Tables 1 and 2.

Table 1 Chemical compositions (wt%) of the material

Mg	Fe	Mn	Zn	Ni	Cu	Si	Al
1.35	0.29	0.46	0.15	0.016	3.99	0.23	Bal.

Table 2 Mechanical Properties of the material

Yield Stress σ (MPa)	UTS (MPa)	Elong.(%)
393.8	442.2	7.47

The microstructure of the material is typical recrystallised pancake-shaped grains with approximate grain size 50x75x150 μm. The specimens were 300x50 mm with a central hole or with double edge notches (arch or elliptic notches) respectively. The longitudinal axis of the specimens was parallel to the rolled direction. After machining, notches and holes were carefully polished in the longitudinal direction to avoid scratches in the crack initiating direction.

The experiments were respectively conducted on a 5kN and a 50kN MTS 880 servo-controlled electro-hydraulic material test systems at a frequency of 15Hz. Constant amplitude tests were carried out with Load ratio, R = 0.1 and maximum stress, σ, respectively 78 MPa and 98 MPa.

The measurement of short crack length was made in the notches or at the edge surface of notches. Fatigue crack length was determined using both replication techniques and a modified travelling microscope. Replicas were taken after each 10,000 cycles interval during the tests and after the tests they were carefully examined with an optical microscope with x80 magnification. The minimum crack length measurable was 50 μm, with a precision of 10 μm.

THE COMBINATION OF TWO TYPES OF CLOSURE

Characteristics of Short Crack Closure

Normally, cracks experience both plasticity-induced closure and roughness-induced closure simultaneously. For most cases of long cracks, this does not seem particularly important, for sizes of deflections of a crack path, compared to the size of crack opening, are too small to be considered. An exception is the crack growth near the threshold regime where sizes of defections of a crack path could be comparable to the size of crack opening, especially in coarse grained materials. For short cracks it is, however, another story. Small length means small crack opening, but small length dose not affect the sizes of crack deflections which are usually controlled by microstructure. In this case, the sizes of crack deflections are always comparable to the size of the crack opening. Therefore, the crack deflection cannot be neglect, in another word, the idealised flat crack path is not suitable to model short crack features.

Recent research of short crack closure in a near-alpha IMI 834 Ti alloy with in-situ SEM (Dowson *et al.*, 1992). studies reported that crack closure increased significantly soon after the short crack propagated through the first grain boundary. Obviously, only using continuum-based plasticity induced closure will not be able to explain this phenomenon. It appears that roughness induced closure, due to the deflection to when the short crack grows through the grain boundary, must be important. Furthermore, research has also reported that the subsequent growth, as crack length increased the level of crack closure appeared to decrease. It seems appropriate to rationalise this in terms of the crack path tortuosity and associated changes in fracture morphology. It is understood that because of the zig-zag shape of the crack the idealised calculation of plasticity induced closure, which is based on a flat crack surface, should be modified. It appears that in practice a combination of plasticity induced closure and roughness induced closure determines the early stage of fatigue crack growth.

Since the combination of these two closures is potentially very complicated, in this paper, our attentions will focus on explaining this idea of combination and demonstrating how much improvement it could achieve, using very simple models instead of involving in complicated analysis. Generally, we suggest that short crack closure behaviour can be divided into two cases: one where plasticity-induced closure dominates and another where roughness induced closure dominates. These will be termed "***Model 1***" and "***Model 2***".

Model 1 -- Combining plasticity and roughness-induced closure when plasticity dominates

In most cases, it has been suggested that plasticity induced closure dominates short crack growth, particularly for fine grained materials where crack defections are relatively small. To develop a model of this type of closure, plasticity induced closure will be considered as the major contribution to total crack closure with roughness part being added in to modify. Since the true combination of closures is complicated, here, a simple model is developed to show the idea. First, let us assume that the closure stress intensity value can be separated into two terms, named as $f_1(K_{op}^p, K_{op}^r)$ and $f_2(K_{op}^p, K_{op}^r)$, with a linear relationship. It is proposed that

$$K_{op} = f_1(K_{op}^p, K_{op}^r) + f_2(K_{op}^p, K_{op}^r) \qquad (1)$$

where K_{op} is a total crack opening stress intensity factor; K_{op}^p and K_{op}^r are the crack opening stress intensity factors due to plasticity induced closure and due to roughness induced closure respectively. Since this model is considered as plasticity dominated, we may assume that one of the two terms, f_1, is related only to plasticity induced closure and the other, f_2, is a combination of both closures with the major part contributed by roughness induced closure, we thus call the second term the roughness part. In the roughness part, It is proposed that:

$$f_2(K^p_{op}, K^r_{op}) = UK^r_{op} \qquad (2)$$

where $$U = \frac{K^p_{op}}{K_{\max}} \qquad (2a)$$

here K^p_{op} and K^r_{op} can be calculated from Newman's analytical model (Newman Jr., 1981) and Suresh and Ritchie's model (Suresh, 1983), respectively.

For the plasticity induced closure $f_1(K^p_{op}, K^r_{op})$, it is proposed that:

$$f_1(K^p_{op}, K^r_{op}) = [1-(1-\Delta d/\eta)/n]K^p_{op} \qquad (3)$$

where Δd is crack length in the new grain (see Fig 1) normalised by the mean grain size, ie $\Delta d = \Delta a/d$; η is a material parameter >1, which describes the sensitivity of the microstructure; n is the number of grains traversed by the crack;

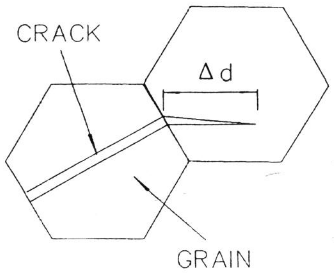

Fig. 1 Illustration of crack defection and parameter d

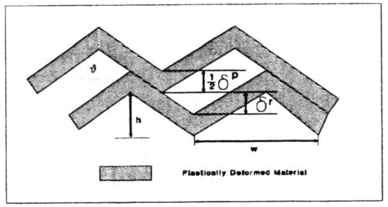

Fig. 2 Geometry used in Model 2 analysis, showing the idealised plastic wake

In Eq.(3), the reduction in the amount of closure due to crack tip overlapping is assumed to be related to the distance between the crack tip and the grain boundary where crack deflection happened. The effect of this distance on closure will be modified by the material parameter η and will be reduced gradually by n as the crack grows.
Substituting Eq.(2) and Eq.(3) into Eq.(1) gives:

$$K_{op} = [1-(1-\Delta d/\eta)/n]K^p_{op} + UK^r_{op} \qquad \text{for } a>d; \qquad (4a)$$

where a is the crack length and d is the grain size.
Since there is no deflection when crack growth is in the first grain, nor is there roughness induced closure; we add one more equation:

$$K_{op} = K^p_{op} \qquad \text{for } a<d; \qquad (4b)$$

Model 2 -- Combining plasticity and roughness-induced closure when roughness dominates

In some cases, however, the roughness induced closure is believed to dominate the short crack growth stage, especially in coarse grain materials. In this case, the deflection during crack growth is large compared to the crack tip plastic zone which produces the material's plasticity-induced closure. Materials such as aluminium alloys, titanium alloys etc. have been often reported to have such a behaviour (James and Garz, 1991). The model which have been developed here will consider this case, ie. the domination of roughness induced closure. In this case, the contribution of plasticity induced closure can be simply counted through the existence of the plastic residual wake left along the crack surfaces. Since the crack is oblique, the crack tip plastic zone, which generates mixed mode conditions, is smaller than that in pure Mode I. The thickness of the plastic wake is actually smaller than that calculated. This, however, is a correction which not be discussion in this paper. In this model, the plastic wake is assumed to be uniform along the crack surface, since results from Newman's model show a very small change of the thickness of the plastic wake (Fig. 2). Based on Ritchie and Suresh's model and considering the existence of the plastic residual wake to be equivalent to the effect of plasticity induced closure, a relationship of the combination of the two types of closure can be derived, the results is following:

$$K_{op} = \overline{U}K^r_{op} \qquad \text{for } a>d; \qquad (5a)$$

where
$$\overline{U} = \sqrt{1+\left[\frac{K^p_{op}}{K^r_{op}}\right]^2 \frac{2\gamma}{\sqrt{4\gamma^2+1}}}$$

where and K^p_{op} can K^r_{op} be calculated from Newman's analytical model (Newman Jr., 1981) and Suresh and Ritchie's model (Suresh, 1983) respectively.

Again, since there is no deflection when crack growth is in the first grain, nor is there roughness induced closure; we add one more equation:

$$K_{op} = K^p_{op} \qquad \text{for } a<d; \qquad (5b)$$

where a is the crack length and d is the grain size. Fig. 3 shows crack closure predicted by Model 2 changing with various parameters. The parameters x and γ are the same as those defined by Suresh and Ritchie. Increase of the surface roughness γ results in a large decrease of da/dN due to the increase of roughness induced closure. The ratio of Mode II to Mode I displacement x has similar effects.

RESULTS AND DISCUSSION

Prediction of Short Crack Growth in CCT Specimens

Figure 4 shows the results of predictions of short crack growth by using both the author's model and Newman's model (Newman Jr., 1981). The experimental results for both long and short crack came from El Haddad (1987). The material used in the test is CSA G40.11 Steel. Since this is a fine grained material, the roughness induced closure is not expected to be dominant, so Model 1 was used in this application.

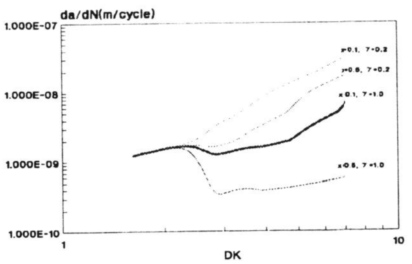

Fig. 3 Crack growth predictions in the aluminium alloy using Model 2 with various parameters.

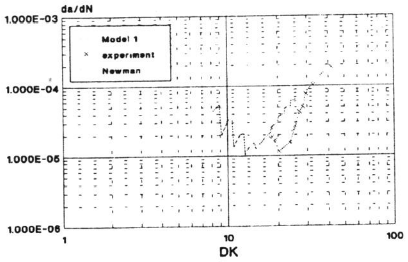

Fig. 4 Comparison of prediction of short crack growth (R=-1) on CCT specimen by using Model 1 and Newman's model

The predictions of both Newman's model and the Model 1 show good correlation to those from experiments. The prediction of Model 1 also shows a crack growth rate in an oscillating manner which indicates the influence of grain boundaries. The fluctuations decrease when the crack grows longer because the influence of grain boundaries becomes weaker. So in this case, whilst the model does not improve on predictive accuracy, it does reproduce a known feature of short crack growth which Newman's cannot. The prediction from Newman's model forms an upper bound to the present theory.

Prediction of Short Cracks Emanating From a Notch/Hole under a Constant Amplitude Load

Since in aluminium alloys roughness induced closure is significant, Model 2 will be used to predict aluminium alloy results. Long crack data were taken from (Herman *et al.*, 1987) and (Tanaka *et al.*, 1990). Figure 4 shows crack opening stress versus crack length in the aluminium alloy calculated by using Newman's model. These results will be used in the calculation of the plasticity induced closure part in the following predictions.

Results of predictions are plotted in ΔK-da/dN diagrams shown in Fig. 6-7. The results of the predictions from both Newman's model and the author's model 2 are not as good as in predicting CCT specimens above. Part of the reason is that the ΔK-da/dN data of long cracks were obtained from publications of other researchers (cf. Herman *et al.*, 1987; Tanaka *et al.*, 1990) and the material and heat treatment are not exactly the same. Those should affect the predictions, which are clearly different at high da/dN.

Despite this problem, the predictions from our Model 2 still show a clear improvement compared with that from Newman's model and a tendency to predict a minimum point

in the growth rate curve, ie. the short crack behaviour. This indicates that the principle of combining different crack closures is reasonable. However, more study is needed to be carried out in this area.

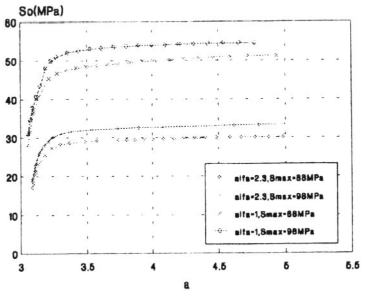

Fig. 5 Calculated crack opening stress as a function of crack length for a central hole (r=3mm) specimen for the aluminium alloy.

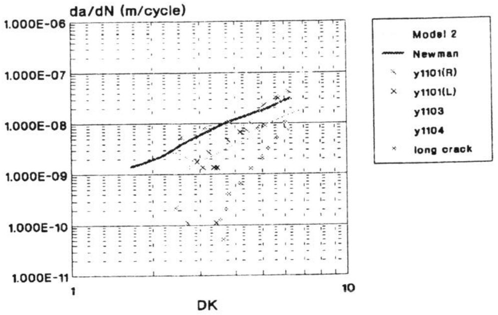

Fig. 6 Prediction of short surface crack growth at notched specimens of the aluminium alloy under constant amplitude loading.

As mentioned at the beginning, the two models presented above are only simple examples to present our ideas about closure behaviour in short cracks. The advantage of these two models is that they include both micro- and macro- factors. It is well known that for the short crack problem, local factors (such as grain size, orientations etc) dominate the growth but global factors (load, notch etc.) still play important roles. The change from the short crack to the long crack occurs as the local factors gradually lose their domination and global factors take over. The new model of closure attempts to quantify this change so the model itself can be used to predict a crack growth or a component life through the whole crack growth range. Furthermore, from an engineering point of view, it is convenient to still use the stress intensity factor since it has been widely and successfully used in engineering applications. Another advantage of this approach is that it shows how two different mechanisms of closure can be combined in two different ways.

CONCLUSIONS

(1) Crack closure in the short crack stage is a combination of plasticity induced and roughness induced closure. So, any closure models dealing with the short crack should ideally consider the combination of both closures;

(2) Two new models were proposed for combining these different types of closure; The results of prediction from the two proposed models show reasonable improvement compared with those from Newman's plasticity induced closure model;

(3) Overall, the advantages of proposed models gives us confidence that the idea of combining the two closures is effective. However, more work needs to be done before better models can be developed.

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