FATIGUE BEHAVIOUR OF SHORT CRACKS

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A review is presented of the engineering approach to the fatigue behaviour of short cracks . The main methods of the fatigue life prediction are referred and an analysis of the most relevant parameters of short crack propagation are also presented . These parameters include local plasticity at the crack tip ,crack closure ,and microstructure.

The different regimes of short crack propagation are described . Data for some engineering alloys are quoted to illustrate the applicability of prediction techniques .

INTRODUCTION

This review deals with the problem of crack initiation and propagation of physically short cracks, , i.e. cracks with size below 500 μm . In terms of fatigue life of most engineering components it is known that a great percentage of fatigue life is spent in the propagation of these tiny cracks . Hence it is very important to understand the basic mechanisms of fatigue crack growth of physically short cracks . This was made possible through extensive developments in elastic-plastic fracture mechanics and also in the experimental techniques for crack detection and measurement .

In this paper a brief review is presented of the micromechanisms of subcritical crack growth of fatigue microcracks . Comparisons are presented of the behaviour of short and long cracks . Cracks are assumed small in three different situations :

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i) when their growth is small compared with relevant microstructural dimensions (grain size , distance between second phase particles , etc.) ,

ii) when their length is small compared with the local plastic zones (microcracks embedded in plastic zones of notches or with a size close to its own crack tip plastic zone , tipically less than 10 μm in high strength materials and between 0.1-1mm in low strength materials). In this case is a limitation of the LEFM methods,

iii) when their size is physically short , i.e. a < 0.5-1mm .

Microcracks referred in(i) are called microstructural short cracks where as those defined in (iii) are called mechanically short cracks . The plot nominal stress against crack length in Fig.1 shows the different regimes of short crack behaviour as reviewed by Miller (1) .

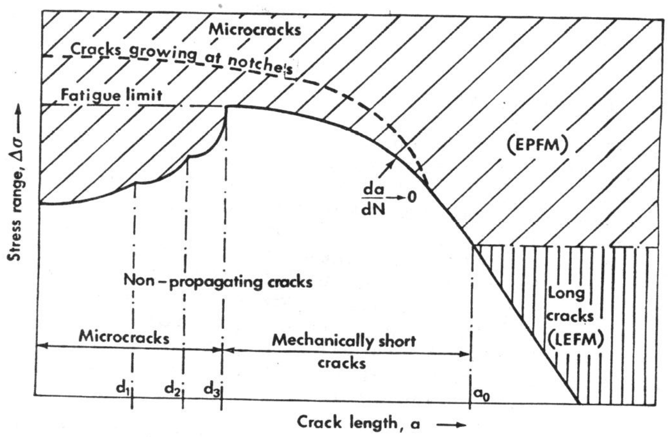

Fig.1 - The three regimes of microcrack behaviour .

In Fig.1 , d_1 , d_2 and d_3 are the dimensions of microstructural barriers where the nominal stress required to cross these barriers is progressively higher in d_1 , d_2 and d_3 . Thus d_3 is the size of the dominant barrier and should be related with the fatigue limit of the material . d_3 defines the boundary between the microcracks and the mechanically short cracks .

Many authors like Daceubler (2) assume that the phase where $a < d_3$ is crack growth within a single grain (Stage I crack propagation) and when $a > d_3$ the crack changes for stage II, where its growth is not influenced by microstructure . However other authors like Taylor (3) assume that d_3 covers several grains.

The upper limit a_o (Fig.1) for the physically short cracks is material dependent . Its maximum value is given by the equation

$$a_o = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\frac{2}{3}\sigma_{ys}}\right)$$

where ΔK_{th} is the fatigue threshold of the stress intensity range and σ'_{ys} is the cyclic yield stress. The shaded area in Fig.1 includes the cracks referred in (ii) above which LEFM should not be applied . In this group are included all the microcracks subjected to very high stress levels or cracks growing from notches where the local stress $\Delta\sigma$ is usually very high $\Delta\sigma > \frac{2}{3}\sigma'_{ys}$).

The main parameters of microcrack propagation will be presented such as the similarity approach microstructure , local plasticity , growth mechanisms and crack closure .

SIMILARITY APPROACH

For long cracks it is known that K or J describes the stress and strain fields at crack tip . Also the similarity approach is valid , which implies that two

cracks of different sizes, but subjected to the same ΔK in a given material , environment and microstructure , should have the same plastic zone sizes at their tip and similar stress and strain distributions at the crack tip . Therefore equal crack growth increments should be obtained . However this concept can not be applied if

i) the crack size is close to the local microstructural dimensions
ii) the crack size is close to the local plastic deformation
iii) there is a considerable amount of crack closure
iv) the environment changes the crack growth rate .

Hence for short cracks , crack growth is controlled by the local values of fracture mechanics and not by the nominal (global) values of these parameters .

Microstructural effects

A great amount of experimental data obtained by researchers like Ritchie (4) , Kitagawa (5) , Blom (6) and Remy (7) has shown that crack growth rate in microcracks (0.006 < a < 0.5mm) is higher for the equivalent long crack and for the same value of ΔK . A typical plot illustrating this behaviour is shown in Fig.2, taking results obtained by Pearson (8) in precipitation hardened aluminimum alloys . Microcracks tend to nucleate preferably in persistent slip bands , grain boundaries and second phase particles .

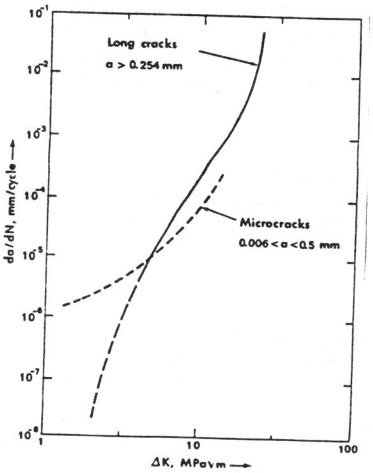

Fig.2 - da/dN vs . ΔK (8)

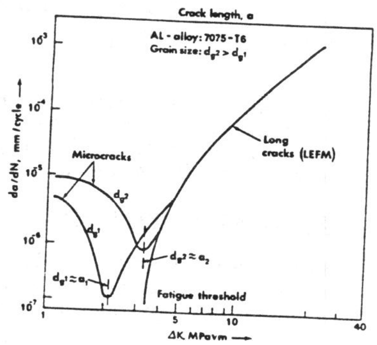

Fig.3 - da/dN vs. ΔK . (9)

Additional data plotted in Fig.3 and obtained by Lankford (9) shows that fatigue crack growth rates in microcracks can be up to two orders of magnitude above the crack growth rate for long cracks . Also , crack propagation in microcracks occurs for values of the stress intensity factor well below the threshold stress intensity factor for long cracks , ΔK_{th} . Attempts to explain the crack propagation behaviour of microcracks (Figs.2 and 3) put the emphasis on crack closure phenomena and local microstructural interactions , such as grain boundaries .

From these results it is clear that ΔK_{th} values for long crack and for short cracks can be significantly different . However using LEFM concepts , ΔK_{th} should be independent of crack length . (ΔK_{th} = Const.) . Work done by Kitagawa (10) has revealed that below a certain critical value of crack length , ΔK_{th} for

short crack decreases when the crack length increases and the nominal stress range , $\Delta\sigma_{th}$ becomes closer to the plain fatigue limit of the material , Fig.4 . This become known as the Kitigawa diagram . The zone (a) in Fig.4 defines the conditions for crack propagation until fracture , while in zone (b) no crack propagation occurs .

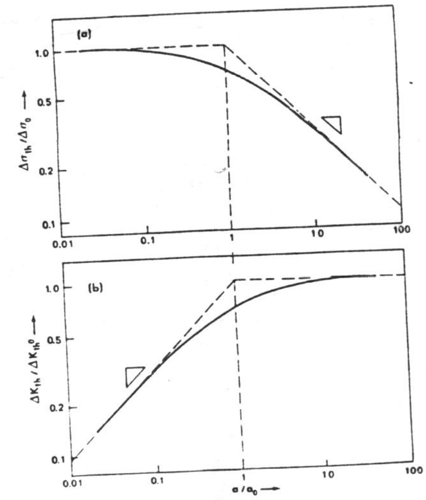

Fig.4 - Kitigawa diagram . $\Delta\sigma_{th}$ and ΔK_{th} against crack length (10) .

Results for a_0 point , where there is a transition between zones (a) and (b) in Fig.4 , range between 1-10μm for high strength materials ($\sigma_{ys} \approx 2000$ MPa) , up to 0.1-1mm for low strength alloys .

Effects of local plasticity

The strain intensity factor approach developed by Haigh (11) gives a better correlation with the fatigue crack growth rate for microcracks embedded in plastic strain fields in comparison with the stress intensity factor .

Another approach due to El Haddad et al (12) is an empirical one, based on the intrinsic crack length value , a_0 . The equation for the stress intensity factor was rewritten in terms of the physical crack length value plus a_0 . Hence

$$\Delta K = Y \Delta \sigma \sqrt{\pi (a + a_0)}$$

where Y is the geometrical and loading factor ; a_0 is assumed to be equivalent to the crack length above which ΔK_{th} becomes constant and equal to the threshold stress intensity factor for long cracks , ΔK_{th}^{a} , Fig.4 .

Although this approach can eliminate the differences between fatigue crack growth rates for long and short cracks , it is a totally empirical approach since there is no relation between a_0 and any microstructural dimension .

Fracture mechanics methods have been applied to study fatigue crack growth from notches . Smith and Miller (13) have assumed that a crack of depth a propagating in a plain specimen is equivalent to a crack of length l propagating from a notch , when both cracks have the same crack growth rate .

The traditional Neuber approach (14) associated with the El Haddad method was also used to describe crack growth from notches .

Effect of crack closure

For long cracks detailed studies have shown that for ΔK values close to ΔK_{th} crack closure mechanisms explain most of the effects on crack growth rate of stress ratio , yield stress , grain size , environment and random loading . However the crack closure mechanisms are particularly relevant for the crack closure behaviour of long cracks simply because its effect is predominant in the plastic wave left by the crack . In short cracks the plastic wave is very limited and therefore it is expected that the crack closure effect should be different for microcracks and long cracks and hence microcracks have small closure effect .

Fracture surface roughness is a very important parameter for crack closure . Detailed studies of surface roughness were carried out by Mc Carver and Ritchie (15) . They found that for R=0.1 and for microcracks ΔK_{th} was below the value for long cracks while for a high stress ratio of 0.7 no difference in threshold values was obtained . Also Tanaka and Nakai (16) using the compliance technique for microcrack growth from notches , have reported a great reduction in closure for very small cracks . When the da/dN data is plotted against ΔK_{th} i.e. taking into account the experimental values of ΔK for crack opening , K_{op} a single curve is usually obtained for short and long cracks .

A second closure effect is plasticity induced closure. The effect is however small in microcracks with a size below the plastic zone dimension at its crack tip . According to the same authors (16) plasticity induced closure is one of the reasons why short cracks can propagate from notches at ΔK values below ΔK_{th}^{o} . Essentially these cracks can initiate and propagate for ΔK values below ΔK_{th}^{o} since there is no crack closure . However as crack length increases the plastic strains at the crack surfaces increase and the crack closure reduces the effective ΔK value at the crack tip . Hence crack growth rate decreases and eventually the crack will become arrested . It is seen that these explanations are in agreement with the phenomenology of microcrack growth from notches referred above .

A summary of all the main interrelating parameters can be described as follows as reported by Tokaji (17)

Physically short cracks

Microstructural small cracks	Mechanically short cracks	Long cracks

Fracture of microstructural small cracks

Stage I crack propagation
Very fast crack propagation
Great influence of microstructure

Fracture of mechanically short cracks

Stage II crack propagation
Very fast crack propagation
Low level of crack closure
Small influence of microstructure

Assumed long cracks

- Stage II crack propagation
- Crack closure level similar to the long cracks
- Little influence of microstructure

RESULTS

In this section results obtained by the authora in a research programme concerning short crack growth behaviour will be presented .

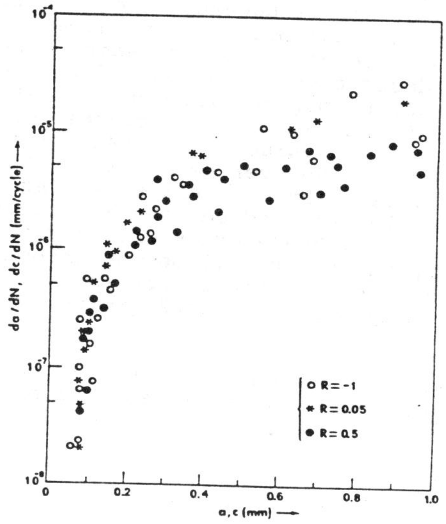

Fig.5 - da/dN and dc/dN against ΔK for short and long cracks . Corner notch . AlMg alloy 5083 .

Fig.5 shows the da/dN ; ΔK results obtained by the author (18 , 19) in the Al-Mg 5083 and for crack propagation from a microcorner notch of 45 μm depth and length loaded in bending for R=-1 . This short crack data is separated in two regimes , i.e. for values of a, c < 300 μm and for a , c , > 300 μm . For the short cracks (a , c, < 300 μm) crack growth rate data is considerably above the long crack growth rate data obtained in CT specimens of the same material , thickness , frequency and environment but for R=0.05 . In the long crack regime (a, c > 300μm) the da/dN data is converging for the long crack curve of the CT specimen providing the same correlation of results . The short crack data gives a good agreement with the long crack data obtained in the CT specimens for R=0.8 .

Hence when crack closure is very unlikely to occur as it should happen in the CT specimens for R=0.8 , da/dN gives similar results for short and long cracks. Crack closure is therefore one of the key controlling parameters of the fatigue crack propagation behaviour of short cracks .

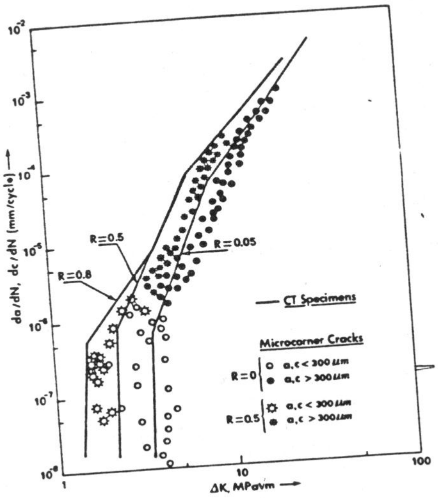

Fig.6 - da/dN and dc/dN against crack length a and c. Corner notch . AlMg alloy 5083 .

The variation of crack growth rates da/dN and dc/dN with the crack size a and c is depicted in Fig.6 also for the same corner crack of the results in Fig.5 . It is seen that the crack growth rate is decreasing as the crack is moving away for the tiny notch and after approximately 1.0mm in depth and length behaves like a long crack . There is no stress ratio effect at initiation (a , c < 0.2mm) that is when closure is not significant .

CONCLUSIONS

The growth of microcracks by fatigue is one of the most challenging research topics in the area of mechanical behaviour of materials . This is an area where an interface occurs between Fracture Mechanics methodologies and the classic mechanical engineering approach dealing with the assessment of total fatigue life .

Differences between microcrack and long crack behaviour are due to several distinct phenomena :

i) inadequate description of the stress and strain fields due to the non inclusion of higher order terms in the elastic solution of the stress intensity factor and also excessive plasticity at the crack tip.

ii) influence of notch stress and strain fields for cracks emanating from notches .

iii) interaction of microstructural short cracks with the microstructure including : grain boundaries , inclusions and second phase particles with a size similar of the crack length .

iv) differences in propagation mechanisms .

v) crack closure effect varying with the crack size .

vi) environmental differences at the crack tip .

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