FATIGUE CRACK GROWTH BEHAVIOUR IN CONSTANT-LOAD AMPLITUDE AND CONSTANT-ΔK TESTS ON NOTCHED SPECIMENS

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The fatigue crack growth rate on specimens with very sharp notches was measured in constant-load amplitude tests. The material was ARMCO-iron and the stress ratio was -1. In such tests the typical short-crack growth behaviour can be observed.
The results of these tests were compared with the fatigue crack growth rate and the threshold values measured in constant-ΔK tests. The comparison shows that the crack growth rate da/dN depends only on ΔK and the crack length l measured from the notch root.

INTRODUCTION

The calculation of a fatigue limit or the prediction of life time with fracture mechanics concepts is difficult for components with small defects or notches. This is because the growth rate of short fatigue cracks is much greater than that of long cracks at the same stress intensity range, and also the threshold stress intensity range of short cracks is smaller than that of long cracks. In recent years, this behavior of short fatigue cracks has been discussed in a number of papers (Pearson (1), Suresh and Ritchie (2), Smith (3), Tanaka et al.(4), Morris and James (5), Lankford (6), Liaw and Logsdon (7), McEvily and Minakawa (8), Los Rios et al. (9), Pineau (10), El Haddad et al.(11)) and some conference proceedings (Bäcklund et al.(12), Davidson and Suresh (13), Beevers (14)). They show that the crack growth rate of short

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fatigue cracks may be influenced by many parameters:

$$\frac{da}{dN} = f(\Delta\sigma,\ a,\ \Delta K,\ R,\ \rho \text{ and } D) \qquad (1)$$

Where ρ is the radius of the notch root (which may even be infinite in an unnotched specimen) and D is the depth of the notch. This makes it difficult to predict the fatigue crack growth rate for short fatigue cracks.

This paper deals with the growth of cracks from extremely sharp notches. Experimental conditions were those of small scale yielding; i.e. the nominal stress was smaller than the yield stress and the plastic zone small compared with the notch depth. For $l > \rho/4$, ΔK is then only a function of $\Delta\sigma$ and of the "effective crack length" $a = D + l$ (Dowling and Wilson (15)), where l is the length of the crack measured from the root of the notch.

Tests were carried out both under constant-load amplitude and under constant-stress intensity range. The notch depth was 1 mm in the specimen tested at constant-load amplitude and about 10 mm for tests at constant ΔK. Therefore at aquivalent ΔK the stress range was in the constant-ΔK test about 1/4 of $\Delta\sigma$ in the constant-load amplitude test. A comparison of the results permits a simplification of eq.(1).

EXPERIMENTAL PROCEDURE

The material used was ARMCO-iron (analysis in weight %: C 0.007, Mn 0.008, P 0.015, S 0.015, rest iron). The constant-load amplitude experiments were performed on specimens as shown in fig. 1. The specimens were machined in the LT orientation from the hot rolled sheet. Notches with a radius of 3 to 8 µm were produced by plastic deformation of fatigue cracks (for details see Pippan et al.(16), Pippan and Stüwe (17)). The specimens were annealed for one hour at 1000°C in a vacuum furnace. The average grain size after annealing was 70 µm. The 0.2% offset yield stress of this material is 150 MPa and the ultimate tensile strength is 280 MPa.

The cyclic frequency was about 150 Hz. The tests were performed in air at room temperature, and the stress ratio $R = -1$ was maintained in all tests.

The fatigue limit $\Delta\sigma_{th}/2$ ($= \sigma_{max\,th}$) of unnotched specimens is about 150 MPa and $\Delta\sigma_{th}/2$ for the notched specimens as shown in fig. 1 is 45 MPa.

RESULTS AND DISCUSSION

Constant Load Amplitude

The number of cycles to initiate a crack on the notch was small. The crack length as a function of the number of cycles for three different $\Delta\sigma$ values is shown in fig. 2. Curve I is typical for a test with $\Delta\sigma$ below the fatigue limit. In this case the crack growth rate decreases monotonically with the number of cycles (or the increase of the crack length) up to crack arrest (meaning that the increase of the crack length during additional 10^7 cycles is not greater than few micrometers. For example: for $\Delta\sigma = 81$ MPa the increase of crack length from $N = 70 \cdot 10^6$ to $110 \cdot 10^6$ cycles was about 3 μm). Curve II is typical for $\Delta\sigma$ a little bit greater than the fatigue limit. In this case the crack growth rate decreases up to a certain crack length (it was between 0.3 and 0.6 mm measured from the notch root); and for greater crack length the growth rate begins to accelerate. Since the crack, at which the growth rate first begins to increase, has the higher stress intensity, the two cracks grow asymmetrically from then on. Curve III is typical for $\Delta\sigma$ much greater than the fatigue limit; in this case no significant decrease of the growth rate with an increase of the crack length can be observed.

The curves in fig. 2 can also be plotted in a diagram da/dN vs. ΔK (fig. 3). One can see that these three curves are typical examples for the so called "short crack behavior" (1)-(12). This figure also shows the da/dN vs. ΔK curve for long cracks.

The initial stress intensity range ($\Delta K = 1.1\ \Delta\sigma \sqrt{\pi a}$ and $a = D$) for the three indicated curves, which were obtained in a $\Delta\sigma = 81$, 113 and 162 MPa test, is 5, 7 and 10 MPa$\sqrt{m}$. One can see that these ΔK-values are smaller than the long crack threshold stress intensity range; and therefore a calculation of the fatigue limit with the long crack ΔK_{th} value and $a = D$ would be dangerous.

Tests at Constant ΔK

Fig. 4 shows crack growth rates da/dN for different values of ΔK. In all cases the growth rate decreases with increase of l (the crack length as measured from the notch root). For small values of ΔK the crack will finally be arrested. For large values of ΔK the crack will reach a constant growth rate on a lower level which corresponds to the growth rate of a "long crack". Between these two kinds of curves lies the threshold value ΔK_{th} for long cracks. In (16) these observations are discussed in more detail and explained by the effects of crack closure.

Comparison of Both Types of Test

Fig. 5 shows the results of fig. 4 plotted in a different way. The solid lines show corresponding values of ΔK and l with the growth rate da/dN used as parameter.

Curves measured at constant load amplitude $\Delta\sigma$ can also be entered in such a plot. This would be meaningful if eq.(1) can be simplified to

$$da/dN = dl/dN = f(\Delta K, l) \qquad (2)$$

(R has been kept constant in our experiments and shall not be discussed here). Fig. 5 therefore also includes (dotted lines) the values corresponding to the curves I, II and III from figs. 2 and 3. Such curves can be calculated from $\Delta\sigma$ and D alone. They will be nearly horizontal as long as l is small compared with D. They will bend upward with growing l and approach the slope 1/2 for large values of l (if the crack length is small compared with specimen width).

Fig. 5 shows that this type of diagram is well suited to predict the behaviour of short cracks. Curve I runs into the region of decreasing growth rate until the crack stops altogether. Curve II runs into a region of decreasing growth rate and later accelerates again. Curve III corresponds to a crack growing with a high constant growth rate. Even the values of the growth rate in fig. 3 are predicted reasonably well. Thus, the hypothesis eq.(2) seems to be a good approximation.

CONCLUSION

1) For the used assumption (small scale yielding and very sharp notches on defects) we have shown that the fatigue crack growth rate in the short crack region depends only on ΔK and l.

2) In such a case one can find simple conditions for both crack arrest and fracture (as shown in fig. 5).

SYMBOLS USED

a = crack length ($a = D + l$) (mm)

D = notch depth (mm)

da/dN = rate of fatigue crack propagation ($da/dN = dl/dN$) (mm/cycle)

ΔK = stress intensity range (MPa$\sqrt{m}$)

ΔK = threshold stress intensity range (MPa$\sqrt{m}$)

l = crack length measured from the notch root (mm)

N = number of cycles

R = minimum load/maximum load, load ratio

ρ = notch radius

$\Delta\sigma$ stress range (MPa)

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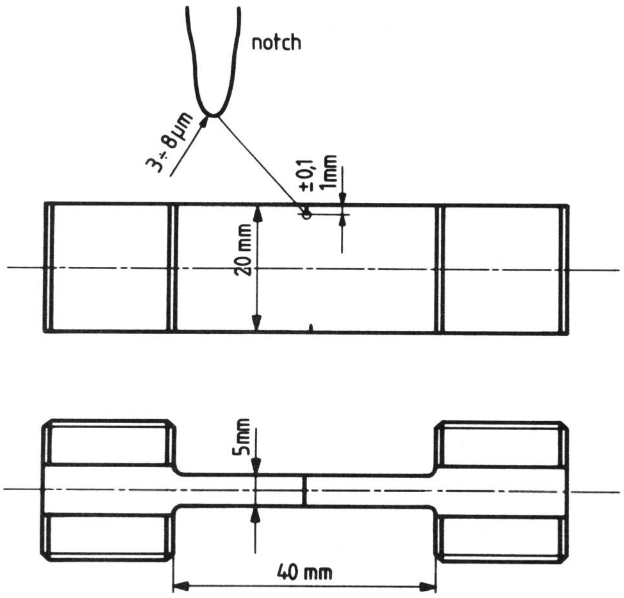

Figure 1 Specimens used in the constant-load amplitude test

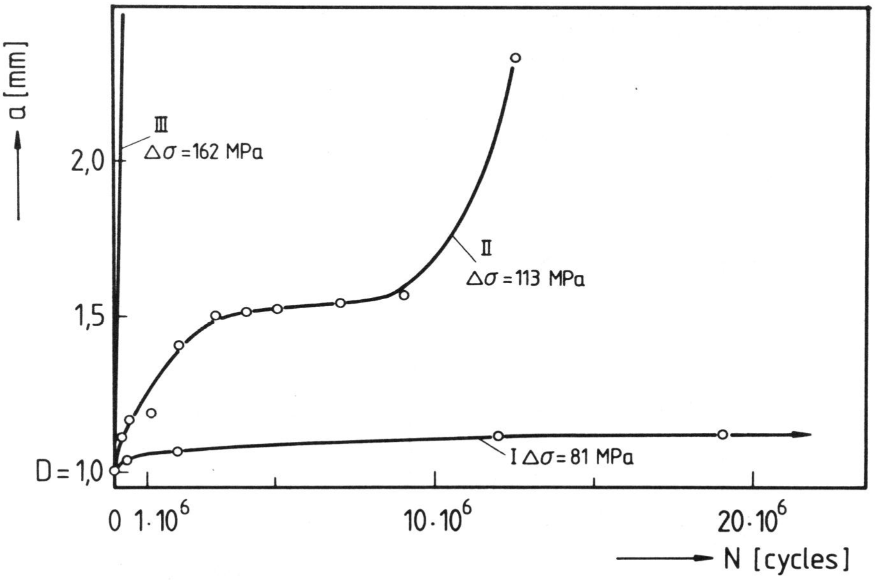

Figure 2 Crack length vs. number of cycles for three constant-load amplitude tests

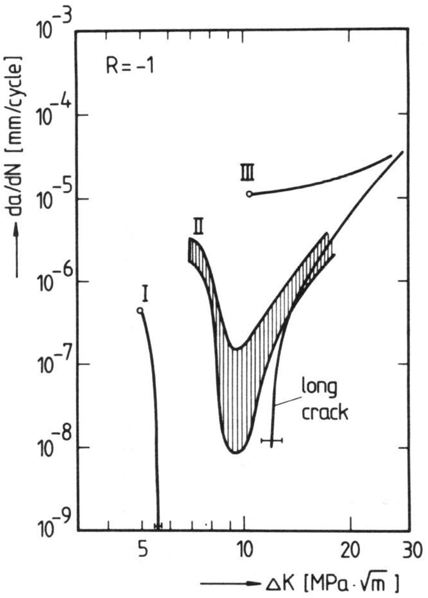

Figure 3 da/dN vs. ΔK, curve I, II, III corresponding to a constant-load amplitude test at $\Delta\sigma = 81$, 113 and 162 MPa

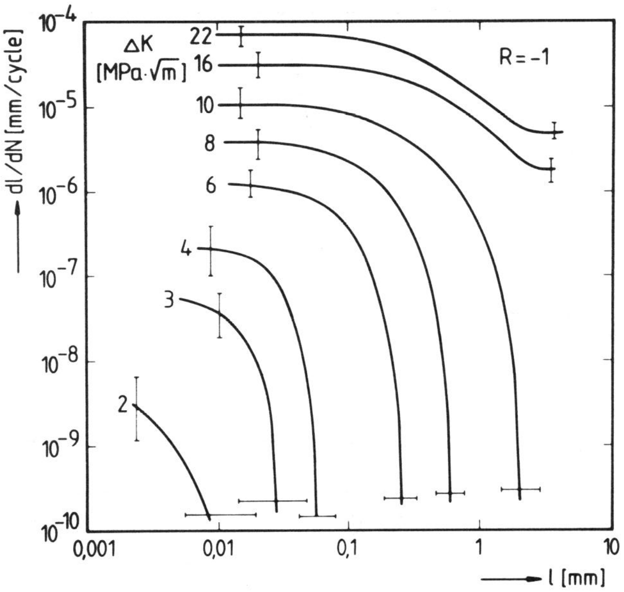

Figure 4 Crack growth rate vs. crack length measured from the notch root at constant-ΔK-tests (16)

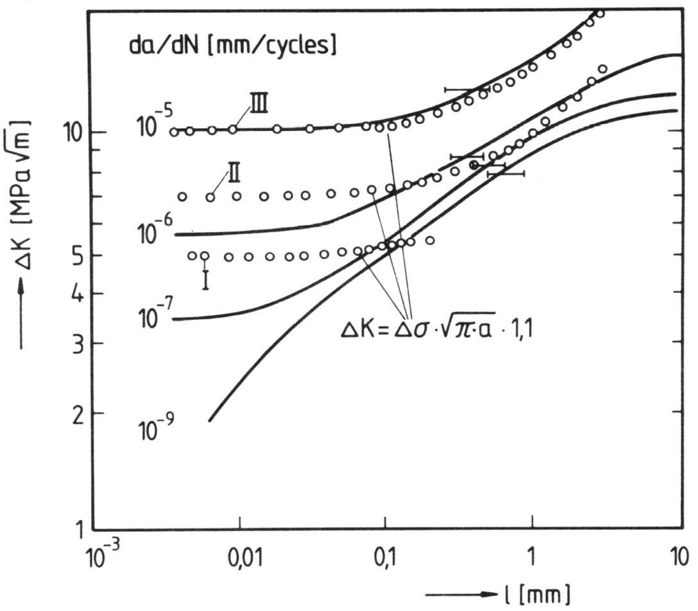

Figure 5 ΔK vs. l, solid lines corresponding to constant da/dN determined from constant-ΔK tests, dotted lines corresponding to ΔK in a constant-load amplitude test (a = D + l)