THRESHOLD OF FATIGUE CRACK GROWTH IN A LOW ALLOY STEEL

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ABSTRACT

The effects of stress ratio, thickness and environment on the threshold, ΔK_{th}, of fatigue crack growth in BS4360-50D steel have been investigated. ΔK_{th} was found to decrease with increasing stress ratio and also with increasing thickness. The threshold was not affected by salt water at high stress ratios but, at low stress ratios, a higher value of ΔK_{th} in salt water than in air was obtained.

Crack closure was used to explain the effects of stress ratio and thickness on ΔK_{th}.

KEYWORDS

Threshold; stress ratio; crack closure; fatigue crack growth; corrosion fatigue.

INTRODUCTION

Fatigue crack growth in steels has been successfully described by means of a sigmoidal relationship between fatigue crack growth rate, da/dN, and the stress intensity factor range, ΔK. This relationship predicts the existence of a threshold, ΔK_{th}, for non-propagating cracks [1]. The need to understand the conditions in which a non-propagating crack occurs should not be underestimated. ΔK_{th} is essential in design calculations for extended fatigue lives, for components subjected to high frequencies, and in welded structures.

Attempts have been made to define criteria for non-propagating cracks in terms of other material properties [2,3]. However, this approach has not so far accounted for the experimentally observed sensitivity of ΔK_{th} to such factors as stress ratio, thickness, environment, stress history and microstructure. This paper deals with the first three effects.

STRESS RATIO

One of the most widely quoted relationships of stress ratio, R, and threshold, ΔK_{th}, is that originally proposed by Klesnil & Lukas [4], in the form:

$$\Delta K_{th} = \Delta K_{oth} (1-R)^{\gamma} \quad (1)$$

where ΔK_{oth} is the threshold value at $R = 0$ and γ is a constant. Unfortunately, γ is material dependent.

A relationship independent of γ has been proposed by Branco et al [5]:

$$\Delta K_{th} = \Delta K_{oth} (1-R^2)^{\frac{1}{2}} \quad (2)$$

Recently, Davenport & Brook [6] suggested an expression which also included fracture toughness, K_c, and obtained a satisfactory correlation for a 0.15% C, 1.5% Mn steel.

THICKNESS

To date, no specific results have been reported. It has usually been assumed that the effects of thickness are those associated with changes in the state of stress at the crack tip observed at high stress intensities. Since plane strain conditions are prevalent at low stress intensities, no distinct effect should be observed.

Previous results obtained by the present authors [11] indicated a significant influence of stress ratio and thickness at low growth rates and the present study is a continuation of that work.

SALT WATER ENVIRONMENT

Experimental data on the influence of the environment on the threshold are most comprehensive in aluminium alloys [7]. Tests performed on mild steel immersed in brine, tap water and oil [8] showed some environmental influence, although other results [5,9] were inconclusive. More recently, results on 13 Cr cast steel [10] showed that salt water did not affect ΔK_{th} at high stress ratios, but caused a substantial decrease of ΔK_{th} at low stress ratios.

EXPERIMENTAL

The material tested was a low alloy structural steel, BS4360-50D, which was available in three plate thicknesses, 12 mm, 24 mm and 50 mm.

Using compact tension specimens, tests were carried out on a Dowty electro-hydraulic fatigue machine. Threshold fatigue tests were performed in air at stress ratios, R, varying from -0.7 to 0.9 and at 30 Hz cyclic frequency. Additional tests on the 24 mm thickness were carried out in 3.5% NaCl solution. Two different methods were developed to obtain threshold values, ΔK_{th}. In the first technique, referred to here as the "constant R" technique, the value of ΔK was progressively reduced by applying 10% K-steps. The threshold value, ΔK_{th}, was considered to have been reached after "no growth" in 3 to 4 million cycles. This criterion was reliable, but rather time-consuming. Consequently, a second and much faster "increasing R" technique was devised. This involved the stepping-down

of ΔK at increasing R-values. The maximum load was kept constant, but the minimum load was increased in steps. It was found that the values of ΔK could be reduced by much larger steps of up to 30% ΔK without noticeable load history effects. The testing time could therefore be reduced by as much as half of that taken using the "constant R" technique.

Crack length measurements were made using both a travelling microscope and also an AC potential drop microgauge [12], both of which could detect crack increments of the order of 0.02 mm. The microgauge digital output voltage had a linear variation with crack length.

The fatigue crack growth rate, da/dN, was obtained from the experimental data using the second method. The stress intensity factor, K, was calculated using the standard formula recommended for the CTS geometry.

RESULTS AND DISCUSSION

Figures 1, 2 and 3 show the typical experimental data close to the threshold region, plotted in terms of da/dN versus ΔK. The effects of stress ratio were found to be most significant in the 12 mm thickness and almost negligible at positive stress ratios in the 50 mm thickness [13].

In Fig. 4, ΔK_{th} values are plotted against the respective stress ratios. This figure shows that the effect of R on ΔK_{th} is dependent on thickness. It is also seen that ΔK_{th} decreases with increasing R to a minimum value, $\Delta K_{c,th}$, and then remains constant. This minimum value of ΔK_{th} seems to be the same for all three thicknesses and averages about 3 $MN/m^{3/2}$. The value of R, $R_{c,th}$, at which ΔK_{th} equals $\Delta K_{c,th}$ seems to be thickness dependent, decreasing with increasing thickness.

Figure 5 shows the variation of ΔK_{th} with thickness at low and high stress ratios. The trend of the curves bears some resemblance to those in Fig. 4, suggesting that varying thicknesses at low stress ratios may produce similar effects as varying stress ratios for thin sections. Apart from other factors, such as the change of the crack tip constraint and environmental effect, crack closure [14] seems to be the most suitable explanation of this interaction.

The present results are compared with recently reported investigations on other steels in Fig. 6. No simple relationship between ΔK_{th} and R seems to exist, but a linear correlation prevails. Moreover, all the curves tend to point towards a limiting value of ΔK_{th}, $\Delta K_{c,th}$, reached at high positive R ratios. This trend contradicts the suggestion by Blacktop & Brook [16] that ΔK_{th} can be extrapolated to zero at a $R = 1$. It will be realised that, at high stress ratios, the maximum stress intensity factor, K_{max}, will also be large and both the plasticity effects and slow crack growth will be substantial.

At present, there is little doubt that the effects of stress ratio and thickness are influenced by crack closure. The present tests (Fig. 7) have shown that for a particular thickness, the level of stress intensity for crack closure, K_{CL}, does not vary significantly with stress ratio. The value of K_{CL} can be arrived at from da/dN versus ΔK data using a series of ΔK versus R curves at constant levels of growth rates. This is shown in Fig. 7 for the 12 mm thickness. The knee of the curve gives the specific values of R and ΔK, designated as R_c and ΔK_c, respectively, at which the applied K_{min} equals the K_{CL}. Thus, K_{CL} may be expressed:

$$K_{CL} = R_c/(1-R_c)\ \Delta K_c \quad (4)$$

The average value of K_{CL} for the 12 mm thickness is 6.3 $MN/m^{3/2}$. Using a similar procedure, a value of K_{CL} = 3.1 $MN/m^{3/2}$ was obtained for the 24 mm thickness. Tests for the 50 mm thickness are now in hand (Fig. 8).

Using equation (4), the value of $R_{c,th}$ at the threshold can be obtained from:

$$R_{c,th} = \frac{K_{CL}}{K_{CL} + \Delta K_{c,th}} \tag{5}$$

These values are 0.68 and 0.51 for the 12 mm and 24 mm thicknesses, respectively (Fig. 8). The data for ΔK_{th} versus R, for $R \leqslant R_{c,th}$, can be represented by a straight line in the form:

$$\Delta K_{th} = A\,R + B \tag{6}$$

and after substitution: $$\Delta K_{th} = K_{CL}\,(1 - R/R_c) + \Delta K_{c,th} \tag{7}$$

The present results in NaCl solution show that at R = 0.7, ΔK_{th} was not significantly affected (Fig. 2). However, at low values of R, such as R = 0.08, ΔK_{th} increased from 5.5 $MN/m^{3/2}$ in air to about 10 $MN/m^{3/2}$ in a corrosion test. It was found that an introduction of salt water into the crack, previously growing in air at ΔK values below 10 $MN/m^{3/2}$ and at R = 0.08, caused a rather unexpected crack arrest [5,7]. The crack stopped very suddenly or, in some instances, after a short growth. This behaviour is being investigated in more detail and under different conditions.

Although only limited data are available on fatigue crack growth in steels in salt water at low ΔK values [2,5,8-10], the present results at R = 0.7 seem to support the general view that ΔK_{th} is not strongly affected by the corrodent. However, exceptions have been reported [2,8,10] and these require further analysis.

The dependence of ΔK_{th} on stress ratio, usually observed in air but not in a vacuum, has been attributed to the environmental effects of water vapour in air [17]. Assuming that similar environmental effects operate in salt water, which is a more corrosive environment than air, ΔK_{th} should be lower in salt water than in air.

The value of ΔK_{th} is dependent on the condition and test method used for its determination; some comment may be appropriate here. In order to obtain the 'true' threshold not affected by load history effects [18], it is necessary to apply suitably small load reductions and run the tests for reasonable periods. The value of ΔK_{th} depends on the level of growth rates at which the apparent crack growth ceases. The thresholds are usually quoted at values of ΔK corresponding to growth rates in the range 10^{-8} to 10^{-6} mm/cycle.

It was suggested by Pook [2] that the minimum crack growth per cycle is of the order of one lattice spacing. For most materials, this would account for the rates of the order of $3\text{-}5 \times 10^{-7}$ mm/cycle. While accepting this lower limit as fairly conservative for most engineering applications, it could prove dangerously large for long lives of the order of 10^{10} to 10^{12} cycles. Since growth rates lower than the atomic spacing are not unknown [10,19], it would be likely that cracks will reach critical dimensions during the design life of a structure. It is also known that the crack growth mechanism near the threshold can change from a continuous crack front advance to a discontinuous ledge nucleation and growth [19], highly sensitive to any change in ΔK. Here again, further investigation of these

extremely slow processes is needed, but the present definition of thresholds at growth rates of the order of 10^{-8} mm/cycle is considered adequate.

CONCLUSIONS

The effects of stress ratio, thickness and environment on threshold values, ΔK_{th}, in 30 Hz fatigue of low alloy steel BS4360-50D have been investigated and the following conclusions drawn:

1. The effect of positive stress ratio is thickness dependent; it is most pronounced for 12 mm, but almost insignificant for the 50 mm thick plates.

2. ΔK_{th} decreases with increasing stress ratio to a minimum value, $\Delta K_{c,th}$, of about 3 $MN/m^{3/2}$ at $R \to 1$.

3. ΔK_{th} can be related to R by the following expressions using the crack closure concept:

$$\Delta K_{th} = K_{CL}\,(1 - R/R_{c,th}) + \Delta K_{c,th} \quad \text{for } R \leqslant R_{c,th}$$

and: $$\Delta K_{th} = \Delta K_{c,th} \quad \text{for } R \geqslant R_{c,th}$$

where K_{CL} is the crack closure stress intensity factor and $R_{c,th}$ is the value of R at which ΔK_{th} reduces to $\Delta K_{c,th}$. Values of K_{CL} of 6.3 $MN/m^{3/2}$ and 3.1 $MN/m^{3/2}$ were obtained for the 12 mm and 24 mm thick plates. $R_{c,th}$ depends on thickness and amounts to 0.68 and 0.51 for the 12 mm and 24 mm.

4. 3.5% NaCl **solution** does not affect ΔK_{th} at high R values, but an increase of ΔK_{th} at low stress ratios was observed as compared with the data in air.

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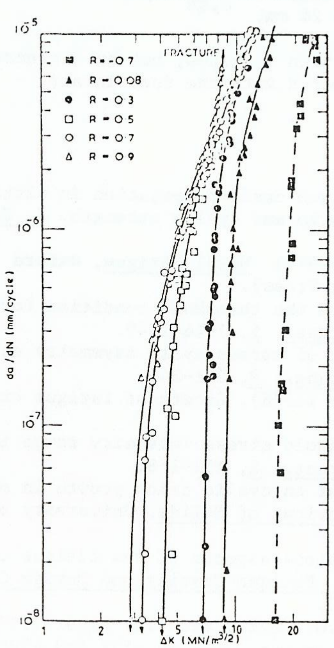

Fig. 1 *da/dN* vs ΔK, B = 12 mm, in air

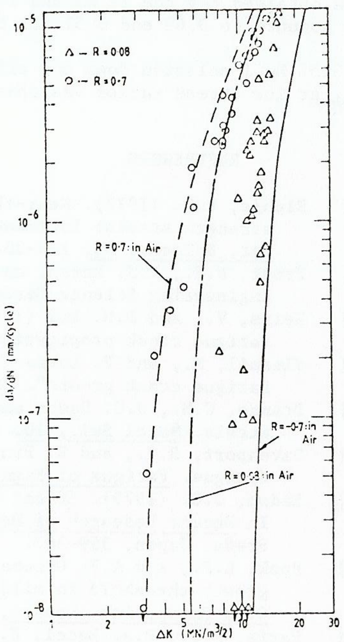

Fig. 2 *da/dN* vs ΔK, B = 24 mm, in 3.5% NaCl solution

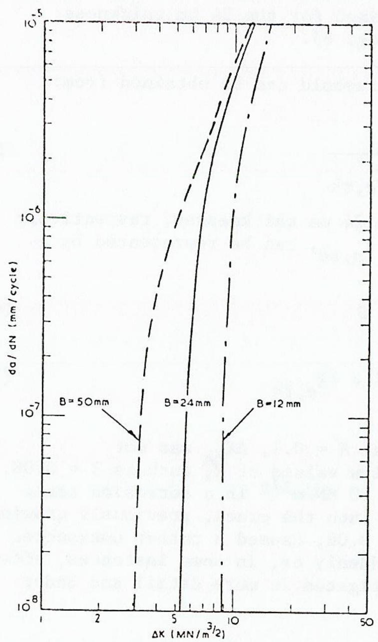

Fig. 3 Effect of thickness on *da/dN* vs ΔK, R = 0.08, in air

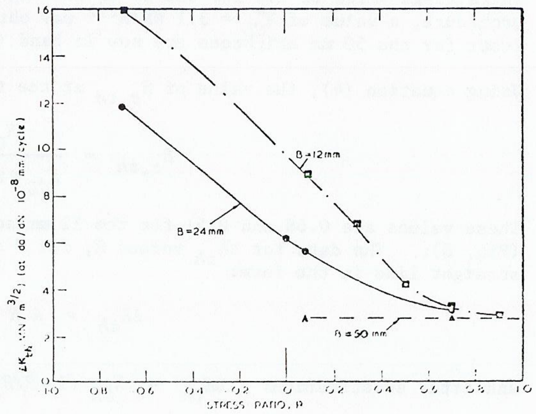

Fig. 4 Effect of R on ΔK_{th}

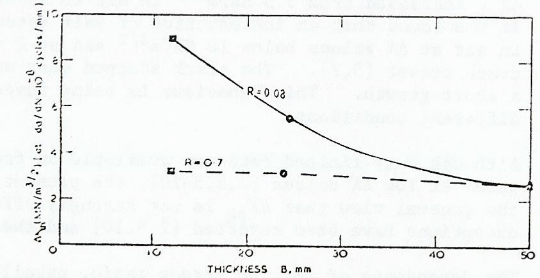

Fig. 5 Effect of thickness on ΔK_{th}

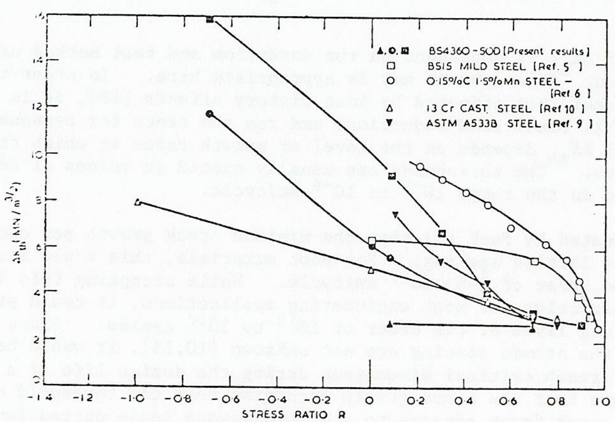

Fig. 6 ΔK_{th} vs R for different steels

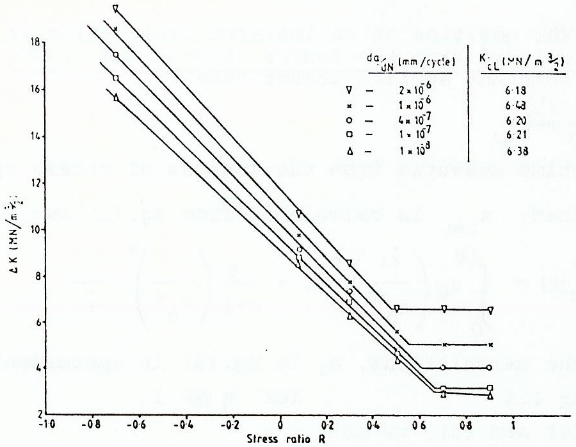

Fig. 7 Estimation of K_{CL} from da/dN vs ΔK data, B = 12 mm

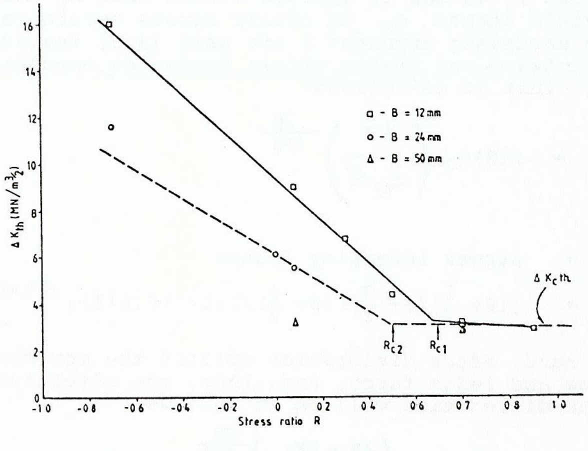

Fig. 8 Correlation of ΔK_{th} with R