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Fatigue threshold stress intensity factors and slow crack propagation rates in low and medium strength low alloy steel

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FATIGUE THRESHOLD STRESS INTENSITY FACTORS AND SLOW CRACK PROPAGATION RATES IN LOW AND MEDIUM STRENGTH LOW ALLOY STEEL

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1. NOTATION

a	crack length or crack half-length as defined in Sketch 7.1	m	in
b	panel half-width	m	in
B	thickness of specimen (see Sketch 7.1 and Table 7.1)	m	in
C	coefficient for linear interpolation of crack growth rate curve defined by $\mathrm{d}a/\mathrm{d}N = C(\Delta K)^n$	$\mathrm{m}\left(\frac{\mathrm{m}^{3/2}}{\mathrm{N}}\right)^n$	$\mathrm{in}\left(\frac{\mathrm{in}^{3/2}}{\mathrm{lbf}}\right)^n$
f_p	0.2 per cent proof stress of material	$\mathrm{N/m^2}$	$\mathrm{lbf/in^2}$
f_t	tensile strength of material	$\mathrm{N/m^2}$	$\mathrm{lbf/in^2}$
H	half-depth of specimens types 3, 4 and 5 (see Sketch 7.1)	m	in
K	stress intensity factor defined by $S(\pi a)^{1/2}\alpha$	$\mathrm{N/m^{3/2}}$	$\mathrm{lbf/in^{3/2}}$
$(K_{max})_{TH}$	maximum value of K at fatigue threshold	$\mathrm{N/m^{3/2}}$	$\mathrm{lbf/in^{3/2}}$
ΔK	stress intensity factor range	$\mathrm{N/m^{3/2}}$	$\mathrm{lbf/in^{3/2}}$
ΔK_{TH}	threshold value of ΔK below which fatigue cracks do not grow	$\mathrm{N/m^{3/2}}$	$\mathrm{lbf/in^{3/2}}$
L	length of specimens types 1, 2 and 3 (see Sketch 7.1)	m	in
N	number of load cycles		
n	characteristic of slope of crack growth rate curve		
P	applied direct load for specimens types 3, 4 and 5 (see Sketch 7.1)	N	lbf
R	S_{min}/S_{max}		
S	stress based upon gross cross-sectional area of specimen	$\mathrm{N/m^2}$	$\mathrm{lbf/in^2}$
W	distance from applied load P to edge of specimens types 3, 4 and 5 (see Sketch 7.1)	m	in
α	geometrical factor in stress intensity factor		
γ	index in Equation (3.2)		

Suffixes

max, min	indicate the maximum and minimum values of stress or stress intensity factor in loading cycle

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1.1 Conversion Factors

Both SI and British units are shown in the notation. The data are presented in terms of SI units and the following conversion factor for British units applies

$$1\ \text{MN/m}^{3/2} = 1\ \text{MPa}\sqrt{\text{m}} = 910.047\ \text{lbf/in}^{3/2}.$$

Note also that

$$1\ \text{MN/m}^{3/2} = 31.6228\ \text{N/mm}^{3/2}.$$

2. NOTES

2.1 General

This Item presents slow fatigue crack propagation rate data $\mathrm{d}a/\mathrm{d}N$ in the range 10^{-8} m/cycle to 10^{-11} m/cycle) and threshold stress intensity factors, ΔK_{TH}. The data are presented in terms of linear elastic fracture mechanics as described in ESDU 80036*. The Item is complementary to ESDU 81011† which deals with crack propagation rates from 10^{-9} up to approximately 10^{-5} m/cycle; both Items present data for materials of similar specification, and there is a certain amount of overlapping of the crack propagation rate curves presented in the two Items. In this particular Item data are presented on the rate of growth of fatigue cracks in a wide variety of low and medium strength ($f_t < 850$ MN/m^2) low alloy steels, in plate form, and for a forged material. A low alloy steel is defined in this case as one where any single alloying element constitutes less than 5 per cent. The chemical composition and mechanical properties of the materials are given in Table 7.1 and are tabulated in order of increasing values of their 0.2 per cent proof stresses.

The data analysed have been taken only from tests that provide slow crack growth rates approaching a fatigue threshold value of stress intensity, ΔK_{TH}. Data giving ΔK_{TH} values only were not considered except when presenting the upper and lower lines in Figures 6 and 7.

2.2 Test Conditions

The data are derived from constant amplitude fatigue tests on specimens of the five types shown in Sketch 7.1; their dimensions are given in Table 7.1 and their thicknesses were between 5.1 mm and 70 mm. The tests were conducted in laboratory air at room temperature and the loading frequencies of the fatigue testing machines were in the range 0.25 Hz to 160 Hz.

All the tests were stated to be conducted within the framework of linear elastic fracture mechanics and thus throughout the tests the stresses across the uncracked sections of the specimens did not exceed the yield strength of materials and the plastic zone sizes were small compared with crack length, see Section 1 of ESDU 80036. Also, the test data presented in this Item have been obtained from specimens that contained fairly long cracks. The value of the threshold stress intensity factor would probably be much lower if the tests were conducted on specimens with cracks less than 1 mm in length.

It was not possible to obtain from the derivations the full details of the condition of the test specimens prior to testing. For instance, conditions such as the direction of grain flow, heat treatment, microstructure and stress state (particularly at fatigue threshold) were not always stated. However, specimens were tested both

* ESDU 80036, "Introduction to the use of linear elastic fracture mechanics in estimating fatigue crack growth rates and residual strength of components".

† ESDU 81011, "Fatigue crack propagation in low and medium strength low alloy steel plate, bar and forgings".

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where the crack propagated in the direction of the grain flow and where it propagated across the grain flow. The stress conditions of the specimens at fatigue threshold, where stated, were plane strain.

Microstructure and heat treatment of materials have been shown to affect crack propagation rates and the fatigue threshold values of stress intensity. The data analysed and presented in this Item are for a wide variety of steels with differing types of microstructures: for instance the C-Mn steels (presented in Figures 1, 2 and 3) had various ferritic-pearlitic microstructures and these steels were quite different from the quenched and tempered steels, presented in Figure 4. For this reason, and because in many cases the details of microstructure and heat treatment were unavailable (in many cases it was said that the steels were tested in the "as-received" condition), the data are presented for engineering purposes in terms of strength parameters for which the material yield strength, f_p, and the ratio of yield strength to ultimate tensile strength, f_p/f_t, are the most convenient parameters to use.

2.3 Determination of Fatigue Threshold (ΔK_{TH})

There was no clear and consistent convention used in the derivations for determining the threshold value of the stress intensity factor range, ΔK_{TH} (that is the value of ΔK below which fatigue cracks will not grow). In the majority of the derivations fatigue crack growth rates less than 10^{-10} m/cycle were obtained from the tests (which is very much less than 1 lattice spacing/cycle). In this Item the values of ΔK_{TH} are considered valid if the crack growth rate curves are vertical or very nearly vertical. For most of the materials for which data are presented, the condition is taken to be at a growth rate of about 2×10^{-11} m/cycle.

In most tests before crack measurements were taken the crack was grown, at any one cyclic load level, until it was several times longer (usually 3 or 4 times) than the maximum steady plastic zone size. This procedure eliminates the effects of stress history. The steady plastic zone size in conditions of plane strain may be calculated using Equation (3.13) of ESDU 80036, that is

$$r_p = \frac{1}{6\pi}\left(\frac{K}{f_y}\right)^2 . \tag{2.1}$$

Not all the derivations stated clearly how the testing was conducted at slow crack growth rates, but near the threshold condition load reduction (or load shedding) was the most popular method. In general, if the crack had not grown after the application of at least 5×10^6 cycles for a given applied load then a valid value of ΔK_{TH} was considered to have been obtained and testing was stopped.

2.4 Presentation of Data

Figures 1 to 5 provide curves of mean crack propagation rate, da/dN, plotted against the stress intensity factor range, ΔK, for various values of R. Each of Figures 1 to 4 is presented for a different range of material yield strengths. The material yield strength is taken to be the 0.2 per cent proof stress of the material, designated f_p in the Notation. The data also correlate with the ratio f_p/f_t and this effect is also shown on the figures. Figure 1 presents data for materials where $255 \le f_p < 340$ MN/m^2 and for values of f_p/f_t between 0.42 and 0.67. Figure 2 presents data for materials where $360 \le f_p < 435$ MN/m^2 and for f_p/f_t = 0.53 to 0.69. Figures 3 and 4 present data for materials where $430 \le f_p \le 530$ MN/m^2, f_p/f_t = 0.76 to 0.81, and where $590 \le f_p \le 795$ MN/m^2, f_p/f_t = 0.8 to 0.96, respectively. On each figure over 90 per cent of the data lie within the dashed lines which indicate the limit of the scatter of the crack propagation rate data. The curves between these limits have been drawn by eye to represent mean curves for the crack propagation rate data. Figure 5 summarises the curves of Figures 1 to 4 by super-imposing the mean curves for the four yield strength groups and five f_p/f_t ratios so that a comparison of the effect of the material yield strength on crack propagation rate can be made, for two ranges for R.

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Where possible an indication of the limits of the scatter of the data at the threshold value of stress intensity is given on the figures. Note that these limits of scatter are not necessarily equally displaced about the mean line of the data presented.

Figures 6 and 7 present curves that show how values of ΔK_{TH} vary with the stress ratio, R, and the maximum stress intensity factor, at fatigue threshold $(K_{max})_{TH}$ respectively. The data points presented on these figures are values of ΔK_{TH} taken from Figures 1 to 4 for $\mathrm{d}a/\mathrm{d}N = 2 \times 10^{-11}$ m/cycle. The curves of Figure 6 are presented for various ratios of f_p/f_t and have been derived from the empirical equation given in Section 3.2. These curves have been replotted on Figure 7 in terms of $(K_{max})_{TH}$, according to the relationship described by Equation (3.3) (see Section 3.5). Also presented on Figures 6 and 7, for comparison, are upper and lower bound lines (broken lines) obtained from other published data, where details of the material were not always given. The ΔK_{TH} curves obtained from the slow crack growth rate curves of Figures 1 to 4 fall within these bounds.

3. DISCUSSION OF DATA

3.1 Method of Analysis of Test Data

In the derivations, basic crack growth data (a, N values) were obtained from the fatigue crack growth tests. Smooth curves were drawn through these data using appropriate curve fitting methods and these smoothed curves were differentiated to obtain the crack propagation rate, $\mathrm{d}a/\mathrm{d}N$, for a given value of stress intensity factor range, ΔK. Equation (4.2) of ESDU 80036 defines ΔK as

$$\Delta K = (S_{max} - S_{min})(\pi a)^{1/2}\alpha . \tag{3.1}$$

All the data analysed in this Item have been obtained from $\mathrm{d}a/\mathrm{d}N$ and ΔK data given in the derivations. The values of α in Equation (3.1) that were used in the derivations were values appropriate to the loading conditions and geometry of the specimens tested.

Allowances for the effects of plasticity at the crack tip on the value of ΔK were not made because at these load levels the size of the fatigue plastic zone is negligibly small.

3.2 Effect of Mean Stress

The effect of the mean stress is presented in terms of the stress ratio R. Unlike the data analysed in ESDU 81011, that is, data for crack growth rates greater than 10^{-9} m/cycle, the effect of mean stress on slow propagation rates (less than 10^{-9} m/cycle) is very significant and as the value of R increases towards 1.0 so the crack growth rate increases for a given value of ΔK. At threshold, the value of ΔK_{TH} for a material is reduced considerably as R increases as shown on Figure 6. Data for negative values of R were not analysed. The curves of Figure 6 have been derived so that they pass through, or close to, the data points taken from Figures 1 to 4 at threshold and have been obtained using the following empirical equation,

$$\Delta K_{TH} = [(\Delta K_{TH})_{R=0} - (\Delta K_{TH})_{R=1.0}](1 - R)^{\gamma} + (\Delta K_{TH})_{R=1.0} , \tag{3.2}$$

where $(\Delta K_{TH})_{R=0}$ is the apparent limit as R tends to 1.0 and is obtained by extrapolation. The values of the index γ used in the above equation and quoted on Figure 6 are mean values that have been obtained from initial curves that were drawn by eye through the data points at threshold, for four ranges of values of f_p/f_t. The effect of the parameter γ on the stress intensity factor at threshold is further discussed in Section 3.4.

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3.3 Effect of Specimen Size, Thickness and Crack Orientation

In the crack growth data analysed no significant effect of specimen size for a given thickness could be seen. Crack growth rate may be affected by specimen thickness and orientation, with respect to load direction and grain flow. These effects are discussed in the derivations but no consistent trend in the results has been discerned.

3.4 Effect of Material Yield Strength and f_p/f_t

The data show that a material with a higher yield strength exhibits a higher crack propagation rate for a given value of ΔK, below values of $\mathrm{d}a/\mathrm{d}N < 10^{-9}$ m/cycle. At values of $f_p/f_t \geq 0.76$, however, there is a certain amount of overlapping of the crack growth curves, see Figure 5. As the crack growth rate curves move away from the threshold region (at $\mathrm{d}a/\mathrm{d}N < 10^{-9}$ m/cycle) the effects of R and f_p/f_t are less dominant and the data merge as they approach the region that may be described by Equation (4.1) (at $\mathrm{d}a/\mathrm{d}N > 10^{-8}$ m/cycle).

At threshold the value of ΔK_{TH} has been shown to be affected by changes in the ratio f_p/f_t and this is reflected by the value of the index γ in Equation (3.2). The value of γ is dependent on the ratio of f_p/f_t and the curves of Figure 6 show that as the value of f_p/f_t increases, so does the value of γ. The exception to this trend is shown in the data obtained from materials whose $f_p/f_t = 0.88$ to 0.96. These particular materials have a ΔK_{TH} to R relationship that approximates to a straight line and $\gamma \approx 1.0$, which is less than the value of γ for materials whose f_p/f_t ratios are between 0.53 and 0.81.

3.5 Effect of K_{max}

The relationship between K_{max}, ΔK and R is given by the expression

$$K_{max} = \frac{\Delta K}{(1 - R)}, \tag{3.3}$$

so that for the particular case at fatigue threshold Equation (3.3) may be written

$$(K_{max})_{TH} = \frac{\Delta K_{TH}}{(1 - R)}. \tag{3.4}$$

The straight lines shown in Figure 7 present this equation in graphical form.

It has been proposed in Reference 24 that at threshold the effects of increasing or decreasing R (and hence K_{max}) on the apparent value of ΔK_{TH} may be caused by crack closure effects. At low values of R the crack faces probably do not open until the load is very much above K_{min} thus reducing the effect of the applied stress intensity factor, and the apparent value of ΔK_{TH} is increased. This is shown in the near vertical data plots of Figure 7 for $R < 0.6$ where K_{max} appears to be constant for increasing ΔK_{TH}. If, on the other hand, R is high enough to keep the crack open throughout the fatigue cycle, say for $R > 0.6$, then a constant apparent level of ΔK_{TH} is obtained, for increasing values of K_{max}, as shown in the near horizontal portions of Figure 7. This effect has also been illustrated in Derivation 19.

3.6 Environmental Effects

All the test data analysed were obtained from tests conducted at room temperature and in laboratory air, with uncontrolled humidities. Therefore no effects of changes in environment on the fatigue crack growth characteristics of steel specimens have been considered in this Item.

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