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Fatigue crack propagation in low and medium strength low alloy steel plate, bar and forgings

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FATIGUE CRACK PROPAGATION IN LOW AND MEDIUM STRENGTH LOW ALLOY STEEL PLATE, BAR AND FORGINGS

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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 4 and 5 (see Sketch 7.1)	m	in
K	stress intensity factor defined by $S(\pi a)^{½}\alpha$	$\mathrm{N/m^{3/2}}$	$\mathrm{lbf/in^{3/2}}$
ΔK	stress intensity factor range	$\mathrm{N/m^{3/2}}$	$\mathrm{lbf/in^{3/2}}$
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 4 and 5 (see Sketch 7.1)	N	lbf
Q	coefficient defined by Equation (6.3)	$(\mathrm{N/m^2})^n$	$(\mathrm{lbf/in^2})^n$
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 4 and 5 (see Sketch 7.1)	m	in
α	geometrical factor in stress intensity factor		

Suffixes

r	denotes step number used when calculating crack growth using equation $\mathrm{d}a/\mathrm{d}N = C(\Delta K)^n$ (see Section 6, Example, Table 6.1)
max, min	indicate the maximum and minimum values of stress or stress intensity factor in loading cycle

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1.1 Conversion Factor

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 fatigue crack propagation rate data in the range $\mathrm{d}a/\mathrm{d}N \geq 10^{-9}$ m/cycle to approximately $\mathrm{d}a/\mathrm{d}N = 10^{-5}$ m/cycle. The data are presented in terms of linear elastic fracture mechanics as described in ESDU 80036*. The Item is complementary to ESDU 81012† which deals with crack propagation rates $< 10^{-9}$ m/cycle down to the threshold value of stress intensity factor; it presents 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 low and medium strength ($f_t < 850$ MN/m^2) low alloy steel plate, bar and forgings. 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 material are given in Table 7.1 and are tabulated in order of increasing values of their 0.2 per cent proof stresses.

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 mm and 76 mm. The tests were conducted in laboratory air at room temperature and the loading frequencies of the fatigue testing machines (where known) were in the range 0.1 Hz to 130 Hz.

All the tests were stated to be conducted within the framework of linear elastic fracture mechanics and thus by implication the tests were terminated before the stresses across the uncracked section of the specimens exceeded the yield strength of the materials, see ESDU 80036.

It was not always clear from the derivations whether or not the specimens failed in conditions of plane stress or plane strain. In a few cases the shapes of fractures that occurred during the fatigue process were described and both oblique (plane stress) and flat (plane strain) fractures occurred. The shape of fractures for individual specimens could not be identified and therefore the data are presented irrespective of the stress condition.

Microstructure and heat treatment of materials have been shown to affect crack propagation rates. The data analysed and presented in this Item are for a wide variety of steels with differing types of microstructure: for instance the C-Mn steels (presented in Figures 1 and 2) had various ferritic-pearlitic microstructures and these steels were quite different from the quenched and tempered steels, presented in Figure 3. For this

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

† ESDU 81012, "Threshold stress intensity factors and slow fatigue crack propagation rates in low and medium strength low alloy steel".

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reason and because in many cases the details of microstructure and heat treatment were unavailable (in many cases the steels were tested in the 'as-received' condition), the data are presented for engineering purposes in terms of the material yield strength, f_p.

2.3 Presentation of Data

Figures 1 to 4 provide curves of mean crack propagation rate, $\mathrm{d}a/\mathrm{d}N$, plotted against the stress intensity factor range, ΔK. Each of Figures 1 to 3 is presented for a different range of material yield strength. The material yield strength is taken to be the 0.2 per cent proof stress of the material, designated f_p in the Notation. Figure 1 presents data for materials where, $f_p < 345$ MN/m^2 and Figures 2 and 3 present data for $345 \le f_p < 550$ MN/m^2 and for $550 \le f_p < 795$ MN/m^2 respectively. On each figure over 90 per cent of the data lie within the dashed lines which indicate the limits of the scatter of the crack propagation rate data. The continuous curves have been drawn by eye between these scatter bands to represent a mean curve for the crack propagation rate data. Figure 4 summarises the curves of Figures 1 to 3 by super-imposing the mean curves of the three yield strength groups so that a comparison of the effect of the material yield strength on crack propagation rate can be made.

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. Typical values of α for the various specimen types have been tabulated on Sketch 7.1 for two values of a/b or a/W. In some cases the equation used for α was found to be questionable, but the change in the value of ΔK obtained using a more accurate equation for α was negligibly small, at about 1.5 per cent.

Allowances for the effects of plasticity at the crack tip on the value of ΔK were generally not made. Where allowances have been made the difference between the value of ΔK with and without a plasticity correction was negligibly small, at about one per cent.

3.2 Effect of Mean Stress

The effect of the mean stress is presented in terms of the stress ratio R. The majority of the data analysed were obtained for low values of R ($R = 0$ to 0.1). Only in a few tests were higher values of R investigated (up to $R = 0.7$) and in only two cases could the effect of R be distinguished. In these cases high values of R tended to lie towards the top curve of the scatter bands. It is generally acknowledged that the effect of variations in the value of R in fatigue crack growth tests on steel specimens is small and is usually swamped by the experimental scatter. Nevertheless, fatigue crack propagation rate data in steel specimens have been shown to be sensitive to variations in the value of R at low values of stress intensity factor and very low crack propagation rates, see ESDU 81012. Data for negative values of R were not analysed.

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3.3 Effect of Specimen Size and Thickness

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 were discussed in the literature but no consistent trend in the results could be discerned.

3.4 Effect of Material Yield Strength

The data show that, for $\mathrm{d}a/\mathrm{d}N > 2 \times 10^{-8}$ m/cycle, increasing the yield strength of a material lowers the crack propagation rate for a given value of ΔK (see Figure 4). At values of $\mathrm{d}a/\mathrm{d}N > 2 \times 10^{-8}$ m/cycle differences in material yield strength seem to have little effect on crack growth rate although there is a tendency for the higher yield strength materials to have higher crack growth rate as the crack growth rate approaches the threshold region (see also ESDU 81012). Comparing Figure 3 with Figures 1 and 2 it can be seen that the higher yield strength materials produce the largest experimental scatter, nearly one order of magnitude in crack propagation rate for a given value of ΔK.

3.5 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.

4. CALCULATION OF CRACK GROWTH LIFE

4.1 Use of Curves

As described in ESDU 80036, integration over a selected portion of the crack growth rate curves, Figures 1 to 3 of this Item, will lead to an estimate of the total crack growth and associated number of cycles. In the absence of any suitable equation to cover the full range of $\mathrm{d}a/\mathrm{d}N$, the complete curves available from the data are presented. Values read from these curves are suitable for use in computer programs that predict crack growth life; the accuracy of such predictions will be dependent upon the number of values provided. Alternatively, a simple integration over selected portions of the curves will also lead to an estimate of the total crack growth and the associated number of cycles. Over discrete ranges of the curve the expression

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C(\Delta K)^n \tag{4.1}$$

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