



ESDU 84003

Issued April 1984

With Amendments A and B

February 2012

Supersedes ESDU 79003

Fatigue crack propagation rates and threshold stress intensity factors in high alloy and corrosion resistant (stainless) steel

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THE PREPARATION OF THIS DATA ITEM

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This Item was also accepted for inclusion in the Fatigue – Fracture Mechanics Data Series by the Fatigue Committee which first met in 1955 and now has the following constitution:

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FATIGUE CRACK PROPAGATION RATES AND THRESHOLD STRESS INTENSITY FACTORS IN HIGH ALLOY AND CORROSION RESISTANT (STAINLESS) STEEL

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FATIGUE CRACK PROPAGATION RATES AND THRESHOLD STRESS INTENSITY FACTORS IN HIGH ALLOY AND CORROSION RESISTANT (STAINLESS) STEEL

1. NOTATION

Both SI and British units are quoted.

a	crack length or crack half-length	m	in
b	plate half-width (see Equation (3.2))	m	in
C	coefficient for linear interpolation of crack growth rate curve defined by $da/dN = C(\Delta K)^n$	$m\left(\frac{m^{3/2}}{N}\right)^n$	$in\left(\frac{in^{3/2}}{lbf}\right)^n$
f_p	0.2 per cent proof stress of material	N/m ²	lbf/in ²
f_t	tensile strength of material	N/m ²	lbf/in ²
K	stress intensity factor defined as $S(\pi a)^{1/2}\alpha$	N/m ^{3/2}	lbf/in ^{3/2}
K_{Ic}	plane strain critical stress intensity factor obtained from tests that conformed to BSI or ASTM recommended standards (see Section 2.3.1)	N/m ^{3/2}	lbf/in ^{3/2}
K_{max}	maximum value of K	N/m ^{3/2}	lbf/in ^{3/2}
$(K_{max})_{TH}$	maximum value of K at threshold	N/m ^{3/2}	lbf/in ^{3/2}
K_Q	critical stress intensity factor obtained from tests that did not conform to BSI or ASTM recommended standards (see Section 2.3.1)	N/m ^{3/2}	lbf/in ^{3/2}
ΔK	stress intensity factor range	N/m ^{3/2}	lbf/in ^{3/2}
ΔK_{eff}	effective value of ΔK	N/m ^{3/2}	lbf/in ^{3/2}
ΔK_{TH}	threshold value of ΔK below which fatigue cracks do not exhibit significant growth, typically $< 10^{-11}$ m/cycle ($< 4 \times 10^{-10}$ in/cycle)	N/m ^{3/2}	lbf/in ^{3/2}
N	number of load cycles		
n	index in simple crack growth rate equation, $da/dN = C(\Delta K)^n$		
R	S_{min}/S_{max}		
S	stress based upon gross cross-sectional area	N/m ²	lbf/in ²
S_{max}	maximum value of S in fatigue cycle	N/m ²	lbf/in ²

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S_{min}	minimum value of S in fatigue cycle	N/m^2	lbf/in^2
α	geometrical factor in stress intensity factor		

1.1 Conversion Factors

Stress intensity factors quoted in SI units may be converted into British units using the following conversion factors,

$$1.0 \text{ MN/m}^{3/2} = 910.047 \text{ lbf/in}^{3/2} = 0.910047 \text{ ksi } \sqrt{\text{in}} .$$

Note also that,

$$1.0 \text{ MN/m}^{3/2} = 1.0 \text{ MPa m}^{1/2} = 31.6228 \text{ N/mm}^{3/2} \text{ (that is } 10^{3/2} \text{ N/mm}^{3/2}\text{)}.$$

2. NOTES

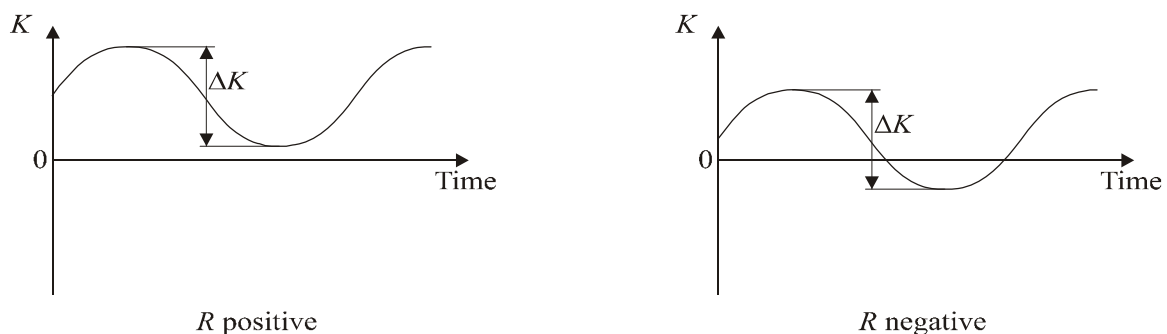
2.1 General

This Data Item presents fatigue crack propagation rate data for several high alloy and corrosion resistant (stainless) steels in the form of plate, sheet, bar, forgings and castings. A high alloy steel is defined in this Item as one containing more than 5 per cent of any one alloying element. Crack propagation rate data for materials in the region of the fatigue threshold stress intensity factor range, ΔK_{TH} , at $da/dN \approx 10^{-11}$ m/cycle ($\approx 4 \times 10^{-10}$ in/cycle) are available for 12 of the steels. The materials covered are indexed with their nominal chemical compositions in Section 7.

2.2 Presentation of Data

Figures 8.1 to 8.18 provide curves of crack propagation rate, da/dN , plotted against the stress intensity factor range, ΔK , for values of stress ratio, R , ranging from -2 to 0.9 . The curves have been drawn through the mean of the data, shown solid, and, where sufficient data are available, around the upper limit of the data, shown dashed.

The curves on the figures referring to tests with negative values of R include both the positive (tensile) and negative (compressive) portions of the fatigue loading cycle in the calculation of ΔK (see Sketch 2.1). The effect of stress ratio is considered in Section 3.3. Tables containing mechanical properties and crack growth data are provided with the relevant figure.



Sketch 2.1

Figure 8.19 summarises the data presented in this Item for values of R between 0 and 0.2. The three envelopes shown enclose the mean curves of three convenient groups of materials. The mean curve for the fourth group, H11 high chromium steel, is shown separately. This figure is discussed in Section 3.2.

Figures 8.20 and 8.21 present curves that show how the values of ΔK_{TH} , taken from Figures 8.1 to 8.16, vary with the stress ratio, R , and with the maximum stress intensity factor at fatigue threshold, $(K_{max})_{TH}$ (see Section 3.3).

2.3 Test Conditions

The data are derived from constant amplitude fatigue tests on various types of commonly used specimens. The thickness of the material from which the specimens were machined is given, where known, in the tables accompanying Figures 8.1 to 8.18. The tests were conducted in laboratory air, with uncontrolled humidities, at room temperature and at loading frequencies in the range 0.2 to 120 Hz.

The majority of the tests were stated to have been conducted within the framework of linear elastic fracture mechanics and thus the stress across the uncracked section of the test piece did not exceed the yield strength of the materials except at the crack tip. The plastic zone sizes were small compared with crack lengths (see Section 3 of ESDU 80036*). The test data have been obtained from specimens that contained cracks several millimetres long. 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 (0.04 in) in length (see Reference 50).

It was not always possible to obtain, from the Derivations, full details of the conditions of the test specimens. For example, the direction of grain flow, heat treatment, microstructure and stress state (particularly at fatigue threshold) were not always given. However, specimens were tested both 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 in the Derivations, were plane strain.

2.3.1 Fracture toughness testing

Some of the materials for which data are presented in this Item were also subjected to fracture toughness tests. The values of fracture toughness have been designated K_{Ic} where they were obtained from tests that conformed to the recommendations of the British Standards Institution (BSI) or the American Society for Testing and Materials (ASTM) criteria (see References 56 and 59). Where the results did not meet the validity criteria or the tests did not conform to these recommendations, they have been designated K_Q .

Values of K_{Ic} for many steels at various temperatures and with various heat treatments may be found in ESDU 83023†.

2.4 Determination of Fatigue Threshold (ΔK_{TH})

There was no 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 exhibit significant growth). The values of ΔK_{TH} are valid if the crack growth rate curves are vertical or very nearly vertical; however, a common definition of ΔK_{TH} is the maximum value of ΔK at which no detectable growth occurs in 10^7 cycles. Since a crack extension of less than about 10^{-4} m (4×10^{-3} in) would remain undetected by conventional crack length monitoring equipment, testing for 10^7 cycles implies a minimum growth rate of 10^{-11} m/cycle (4×10^{-10} in/cycle). Therefore a crack growth rate of $< 10^{-11}$ m/cycle ($< 4 \times 10^{-10}$ in/cycle) has been adopted as the threshold value.

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

† ESDU 83023, "Fracture toughness (K_{Ic}) values of some steels".

Not all the Derivations stated clearly how the testing was conducted at low crack propagation rates but, near the threshold condition, load reduction (or load shedding) was the method most frequently used. In the tests, before crack measurements were taken, the crack was grown at each cyclic load level until it was several times longer (usually 3 or 4 times) than the maximum plastic zone size produced at the previous load level. This procedure is designed to reduce the effects of stress history, but cannot be continued for a crack that has ceased to propagate. By that point in the test, however, the plastic zone size would be negligible.

3. DISCUSSION OF DATA

3.1 Method of Analysis of Test Data

Raw crack growth data (a , N) have been provided in Derivations 2, 3 and 6 from which basic crack growth curves were obtained using the curve fitting technique described in Reference 51. The crack growth rate, obtained by differentiation, is related to values of stress intensity factor range, ΔK , where

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

All the specimens tested in Derivations 2, 3 and 6 were finite width sheets loaded in tension and containing central cracks. Several equations for the value of α for this type of specimen are available. In this Item the following expression, which has been shown to be satisfactory over the whole range of values of a/b for centrally cracked plates, has been used (Reference 53):

$$\alpha = \left[1 - 0.5 \frac{a}{b} + 0.326 \left(\frac{a}{b} \right)^2 \right] \left(1 - \frac{a}{b} \right)^{-1/2}. \quad (3.2)$$

For all the other data presented in this Item the basic crack growth data (a and N values) were not available and the data have therefore been obtained from the published information given in terms of crack propagation rate, da/dN , and stress intensity factor range, ΔK . The values of α in Equation (3.1) that were used in these derivations were appropriate to the loading conditions and geometry of the specimens tested.

3.2 Effect of Alloy Types

The materials for which data are presented in this Item have been divided into the four groups on the basis of alloy types as shown in Figure 8.19. It can be seen that the materials included in Group 1 have the steepest crack growth curves, that is, have a high value of n (in Equation (4.1)). Furthermore, this group of materials has the lowest crack growth rates for values of ΔK less than about $50 \text{ MN/m}^{3/2}$ ($45 \times 10^3 \text{ lbf/in}^{3/2}$) and the highest crack growth rates for values of ΔK greater than about $60 \text{ MN/m}^{3/2}$ ($55 \times 10^3 \text{ lbf/in}^{3/2}$). The Group 3 materials have the lowest crack growth rates for values of ΔK in excess of about $50 \text{ MN/m}^{3/2}$ ($45 \times 10^3 \text{ lbf/in}^{3/2}$). The data for Group 2 and Group 3 materials have the least scatter and there is very little difference in the crack growth rates of the materials within each of these two groups. The data for H11 high chromium steel are shown separately as Group 4.

The envelopes for Groups 2, 3 and 4 have been extended to threshold values. Values of ΔK_{TH} for Group 3 materials are widely spread and do not divide into convenient sub-groups on the basis of alloy type or proof stress.

3.3 Effect of Stress Ratio, R

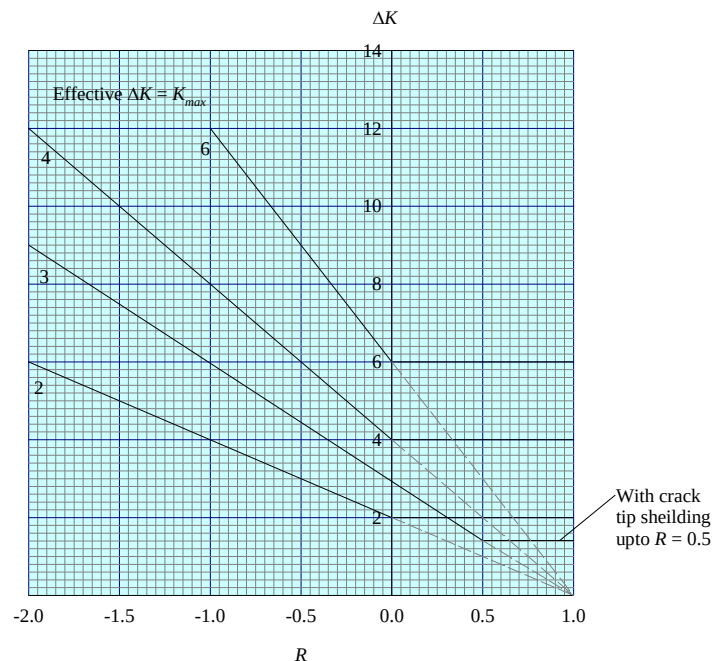
The effect of variations in the value of R on crack growth rates exceeding 10^{-9} m/cycle (4×10^{-8} in/cycle) for steel specimens is small and in many cases may be swamped by experimental scatter. Nevertheless, the data presented show a tendency for increased crack growth rate with increasing R . The influence of R on da/dN is largely explained by crack tip shielding phenomena (often referred to as crack closure), see ESDU ESDU 80036. Below crack growth rates of 10^{-9} m/cycle (4×10^{-8} in/cycle) there is a pronounced dependence on R and the values of ΔK_{TH} are reduced considerably with increased R , as shown on Figure 8.20. A simple explanation of this is that the crack is not open for part of the loading cycle. When R is negative, the crack is closed during the time that K is compressive, and open while K is tensile. Hence the effective value of ΔK , ΔK_{eff} , is given by

$$\Delta K_{eff} = K_{max} = \frac{\Delta K}{1-R}. \quad (3.3)$$

When R is positive, $\Delta K_{eff} = \Delta K$. If Equation (3.3) is plotted on a graph of the form used for Figure 8.20 as $\Delta K = (1-R)K_{max}$ for values of $K_{max} = 2, 3, 4$ and 5 , it appears as shown in Sketch 3.1. However, it has been suggested (Reference 52) that at threshold, the effect of increasing or decreasing R on the value of ΔK_{TH} is related to crack tip shielding phenomena. At low values of R the crack faces do not actually open until the load is somewhat greater than zero, thus reducing the effect of the applied stress intensity and apparently increasing the value of ΔK_{TH} . This effect is illustrated in Figure 8.21, where ΔK_{TH} is plotted against $(K_{max})_{TH}$. Straight lines of constant R are drawn on the figure, derived from Equation (3.4), which has been adapted from Equation (4.8) of ESDU 80036,

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

It can be seen that if R is greater than about 0.5, ΔK_{TH} remains roughly constant for a given material which could be explained by the crack faces remaining open throughout the cycle. This is shown by the near horizontal portion of Figure 8.21. At lower values of R , however, crack closure occurs and although the effective value of ΔK probably remains the same, the applied value of ΔK corresponding to ΔK_{TH} as given in this Item, increases. This is illustrated by the near vertical data plots of Figure 8.21, which show that ΔK_{TH} is approximately proportional to $(1-R)$ and independent of $(K_{max})_{TH}$.



Sketch 3.1 Effect of Stress Ratio R on ΔK for Tensile Loads

3.4 Effect of Specimen Size and Thickness

In the crack growth data analysed, no consistent effect of specimen size and thickness was apparent. The precipitation hardened steels and the maraging steels covered a very wide range of specimen thicknesses (0.51 to 50.8 mm, 0.02 to 2 in) and no effect of change in thickness on crack growth rate was observed for these materials at values of R from 0 to 0.2.

3.5 Effect of Material Proof Stress

Unlike low alloy steels, there appeared to be no consistent effect of material proof stress on crack growth rate for these materials. Furthermore, changes in the values of the ratio of proof stress to tensile strength, f_p/f_t , do not appear to have affected crack growth rate. Annealed corrosion resistant steel specimens have low values of f_p/f_t and precipitation hardened corrosion resistant steels have high values of f_p/f_t , yet these materials can have very similar crack growth rates. The effect of varying the proof stress of a particular alloy through different heat treatments is discussed in Section 3.7.

3.6 Effect of Environment and Frequency

All the test data analysed were obtained from tests conducted at room temperature and in laboratory air, with uncontrolled humidities and a wide range of testing frequencies. Within the range of frequencies (0.2 to 120 Hz) covered by the data in this Item, no effect of frequency can be seen. Data referring to corrosive environments may be found in Derivations 7, 14, 36 and 38.

The variation of crack growth rate with temperature does not conform to a simple pattern. The form of the growth rate curve may be altered so that in all cases reference should be made to tests carried out at the relevant temperature. It should also be noted that an increased crack growth rate does not necessarily imply a reduced value of ΔK_{TH} . Temperature effects are cited in Derivations 2, 3, 11, 17, 28 and 34 and Reference 57.

3.7 Effect of Heat Treatment

The effect of heat treatment on the fatigue crack propagation characteristics of the steels considered in this Item can be important. The effect is particularly noticeable when considering the data for the precipitation hardened corrosion resistant steels which can have widely differing heat treatments. The 17-4 PH and PH 15-7 Mo data have the largest scatter, which may be due to the effect of the different heat treatments of the specimens tested. The data for AISI 403 martensitic corrosion resistant steel refer to specimens subjected to three different heat treatments. Heat treatment 1, as defined in the table accompanying Figure 8.4, gives the lowest crack propagation rate but there is very little difference in the crack growth characteristics resulting from heat treatments 2 and 3. Data for both annealed and aged 18Ni maraging steels are presented on Figure 8.14 but there appears to be no difference in the fatigue crack growth rates for these two heat treatment conditions. Any effects of heat treatment on crack growth rates are likely to be more pronounced at threshold.

Changes in grain size may be responsible for changes in crack growth rate but any correlation is usually masked by corresponding changes in proof stress. An increased grain size (or a corresponding decrease in proof stress) has been shown to decrease crack growth rates and increase threshold values in low alloy, low strength steels, but a similar effect cannot be seen in the steels presented in this Item. The work cited in Reference 58 has shown that threshold values depend on the parameter $f_p \times (\text{grain size})^{1/2}$, but has only confirmed this hypothesis for stress ratios between 0 and 0.1. Owing to lack of data concerning grain size, this relationship cannot be confirmed for the materials presented here.

4. CALCULATION OF CRACK GROWTH

4.1 Use of Curves

The complete curves available from the data are presented in Figures 8.1 to 8.18. The curves are suitable for use in computer programs that predict crack growth life as described in Section 4.2 of ESDU 80036. Alternatively, integration over selected portions of one of the curves will lead to an estimate of crack growth over a number of cycles. Because of the shape of the curve it is usually necessary to employ a numerical integration procedure in which da/dN is assumed to be constant over a small increment of crack growth. The accuracy of crack growth prediction based on such procedures will depend upon the size of the increments used. Alternatively, if portions of the curve may be considered straight on the logarithmic presentation then the slope of the curve may be represented by an index, n , and its ordinate intercept by the coefficient, C , so that over such portions of the curves the expression

$$\frac{da}{dN} = C(\Delta K)^n \quad (4.1)$$

is applicable (see Reference 48). Equation (4.1) can be integrated analytically, using the method described in ESDU 80036 (demonstrated in Section 6.1 of this Item and in ESDU 81011* and 85019†), to obtain the total number of loading cycles required for a crack to reach a particular length. For convenience, suggested values of n and C , obtained from the mean crack propagation rate curves for various ranges of da/dN for the appropriate value of R , are given on the tables accompanying Figures 8.1 to 8.18. It should be noted that considerable variations in the values of n and C may be expected over even quite small ranges of da/dN if the crack growth rate curves are not absolutely straight. In such cases, the values given in the tables should only be used for rough predictions of crack life. For values of da/dN less than 10^{-10} m/cycle (4×10^{-9} in/cycle), the crack growth rate curves become nearly vertical and the value of n tends to infinity, so that in this region Equation (4.1) is not valid. If this equation is used in the crack growth rate region 10^{-10} to 10^{-9} m/cycle (4×10^{-9} to 4×10^{-8} in/cycle) it should only be used over small ranges of da/dN .

Note that the threshold crack size, beyond which cracks will propagate, is dependent upon the **square** of the value of ΔK_{TH} (see Equation (6.4)). This implies that any errors in ΔK_{TH} will be approximately doubled when calculating the associated crack size.

4.2 Practical Solution

Simple practical examples are given in Section 6 of this Item and in ESDU 81011 and 85019 in which Equation (4.1) is integrated analytically to obtain an estimate of the number of load cycles needed for a crack to grow to an unacceptable length. Methods of obtaining values of α for cracks in structural components of more complex geometries are outlined in ESDU 78036‡ and 80036 or may be obtained directly from sources such as Reference 53. The user should note that if, when applying crack growth data to practical situations, the loading distribution in the structure is altered by the effect of the growing crack, it may be necessary to take this effect into account in the calculations.

The use of ΔK_{TH} in practical situations is illustrated in the worked examples presented in Section 6.2 of this Item and in ESDU 81012**.

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

† ESDU 85019, "Fatigue crack propagation rates and threshold stress intensity factors in high strength low alloy steel plate, bar and forgings".

‡ ESDU 78036, "The compounding method of estimating stress intensity factors for cracks in complex configurations using solutions from simple configurations".

** ESDU 81012, "Fatigue threshold stress intensity factors and slow crack propagation rates in low and medium strength low alloy steel".

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5.1 Derivation

This section lists selected sources that have assisted in the preparation of this Item.

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5.2 References

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6. WORKED EXAMPLES

6.1 Example 1

A wide plate, 6 mm (0.24 in) thick and manufactured from annealed austenitic corrosion resistant steel to AISI 304, is subjected to cyclic fatigue loading. The cycle varies from zero to a constant, maximum stress, S_{max} , the value of which is difficult to estimate. During a regular inspection, a crack with a half-length of 10 mm (0.39 in) was discovered and a method of prediction of the growth of the crack with further loading cycles was required. Since the value of S_{max} is unknown it was decided to monitor the growth of the crack. This showed that the crack grew a further 10 mm as a result of 500 000 load cycles.

A method of prediction requires a value of S_{max} and this is first estimated from the data revealed by monitoring crack growth (see Section 6.1.1). The equation for predicting crack growth is derived in Section 6.1.2 and, as an example, the number of cycles required to extend the crack a further 10 mm is calculated.

Two assumptions will be made in the analysis: that the gross stress distribution is unaffected by the crack and that the plate is sufficiently wide to be considered infinite so that the geometrical factor, α , may be taken to be unity.

Crack growth data for this plate material are found on Figure 8.1 and its accompanying table. This loading cycle has a stress ratio of zero, so the data for $R = 0$ to 0.07 are appropriate.

6.1.1 Estimation of applied gross stress, S_{max}

The value of S_{max} may be inferred from the rate of growth of the crack over the period for which it was monitored. Assuming for the moment that the crack growth is linear over this interval, then the growth rate is

$$\begin{aligned}\frac{da}{dN} &= \frac{\text{change in crack length}}{\text{number of cycles}} \\ &= \frac{10 \times 10^{-3}}{500\,000} = 2 \times 10^{-8} \text{ m/cycle.}\end{aligned}$$

Referring to Table 8.1, values of n and C are given for two ranges of crack growth rate near 2×10^{-8} m/cycle; da/dN between 10^{-8} and 10^{-7} m/cycle and between 10^{-7} and 10^{-6} m/cycle. The crack growth equation for the curve is thus given by either

$$(a) \quad \frac{da}{dN} = 3 \times 10^{-12} \times (\Delta K)^{3.1} \quad \text{for } da/dN \text{ in the range } 10^{-8} \text{ to } 10^{-7} \text{ m/cycle or}$$

$$(b) \quad \frac{da}{dN} = 5 \times 10^{-12} \times (\Delta K)^{3.0} \quad \text{for } da/dN \text{ in the range } 10^{-7} \text{ to } 10^{-6} \text{ m/cycle.}$$

Both values of da/dN will be used in the ensuing calculation in order to find which value yields the closest approximation to the crack growth curve of Figure 8.1.

6.1.1.1 Estimation of S_{max} using Equation (a)

First, known values are substituted into the fatigue crack growth equation (Equation (6.5) of ESDU 81011 and Equation (4.6) of ESDU 84001*) which is presented as Equation (6.1) below.

$$\left[N \right]_{N_r}^{N_{r+1}} = \frac{1}{CQ} \left\{ \frac{a^{[1-n/2]}}{1-n/2} \right\}_{a_r}^{a_{r+1}}, \quad (6.1)$$

where $Q = \left[\alpha (S_{max} - S_{min}) \pi^{1/2} \right]^n, \quad (6.2)$

so that Equation (6.1) becomes

$$0.5 \times 10^6 = \frac{1}{3 \times 10^{-12} Q} \left\{ \frac{1}{1-3.1/2} \times \left[0.02^{[1-3.1/2]} - 0.01^{[1-3.1/2]} \right] \right\},$$

and hence $Q = \frac{7.256}{1.5 \times 10^{-6}} = 4.837 \times 10^6 \text{ (MN/m}^2\text{)}^{3.1}.$

This value of Q is substituted into Equation (6.2) and, remembering that $\alpha = 1$ and $S_{min} = 0$,

$$4.837 \times 10^6 = \left[S_{max} \pi^{1/2} \right]^{3.1}$$

and hence $S_{max} = \frac{\left[4.837 \times 10^6 \right]^{1/3.1}}{\pi^{1/2}} = 80.9 \text{ MN/m}^2.$

Substituting this value of S_{max} into Equation (3.1) and using the values of a at the two observed crack lengths to obtain values of ΔK yields

$$\Delta K_1 = 80.9 \times (\pi \times 0.01)^{1/2} \times 1.0 = 14.3 \text{ MN/m}^{3/2}$$

and $\Delta K_2 = 80.9 \times (\pi \times 0.02)^{1/2} \times 1.0 = 20.3 \text{ MN/m}^{3/2}.$

These values of ΔK are then substituted into Equation (4.1) to obtain a crack growth curve that can be compared with the mean curve of Figure 8.1.

At ΔK_1 , $da/dN = 3 \times 10^{-12} \times 14.3^{3.1} = 1.14 \times 10^{-8} \text{ m/cycle}$

and at ΔK_2 , $da/dN = 3 \times 10^{-12} \times 20.3^{3.1} = 3.39 \times 10^{-8} \text{ m/cycle}.$

* ESDU 84001, "Growth of cracks under constant amplitude fatigue loading: example calculations".

6.1.1.2 Estimation of S_{max} using Equation (b)

The calculation procedure can now be repeated but using the crack growth Equation (b). Hence

$$Q = \frac{5.858}{2.5 \times 10^{-6}} = 2.343 \times 10^6 (\text{MN/m}^2)^{3.0}$$

and therefore, from Equation (6.2),

$$S_{max} = \frac{(2.343 \times 10^6)^{1/3.0}}{\pi^{1/2}} = 74.9 \text{ MN/m}^2.$$

Substituting this value of S_{max} into Equation (3.1) as before to obtain values of ΔK_1 and ΔK_2 gives

$$\Delta K_1 = 74.9 \times (\pi \times 0.01)^{1/2} \times 1.0 = 13.3 \text{ MN/m}^{3/2}$$

and
$$\Delta K_2 = 74.9 \times (\pi \times 0.02)^{1/2} \times 1.0 = 18.8 \text{ MN/m}^{3/2}.$$

Again, these values are substituted into Equation (4.1) to obtain a crack growth curve that can be compared with the mean curve of Figure 8.1.

At ΔK_1 ,
$$da/dN = 5 \times 10^{-12} \times 13.3^{3.0} = 1.18 \times 10^{-8} \text{ m/cycle}$$

and at ΔK_2 ,
$$da/dN = 5 \times 10^{-12} \times 18.8^{3.0} = 3.32 \times 10^{-8} \text{ m/cycle}.$$

The da/dN values obtained from the crack growth law of (a) give an overall curve that is closer to the mean curve for $R = 0$ to 0.07 of Figure 8.1 and therefore the value of $S_{max} = 80.9 \text{ MN/m}^2$ is probably nearer to the applied fatigue loading maximum stress.

6.1.2 Estimation of number of load cycles to reach 30 mm

Now an estimate is made of the number of load cycles needed to make the crack grow to a length of 30 mm assuming that the gross stress range is equal to 80.9 MN/m^2 . Crack lengths of 20 mm and 30 mm are substituted into Equation (6.1), after calculating a value of Q from Equation (6.2).

$$Q = \left[80.9 \times \pi^{1/2} \right]^{3.1} = 4.84 \times 10^6 (\text{MN/m}^2)^{3.1}.$$

Substituting the crack lengths into Equation (6.1) gives

$$\Delta N = \frac{1}{3 \times 10^{-12} \times 4.84 \times 10^6} \left\{ \frac{1}{1 - 3.1/2} \times \left[0.03^{[1 - 3.1/2]} - 0.02^{[1 - 3.1/2]} \right] \right\},$$

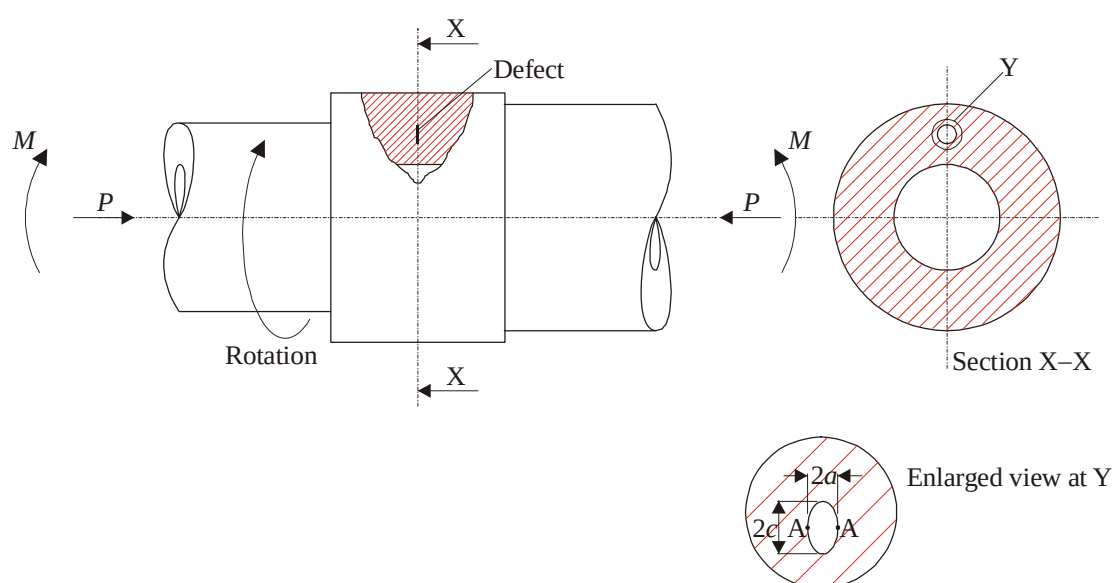
$$\Delta N = 215 \text{ 000 cycles}.$$

Note that this value of ΔN is only about half of the value of ΔN required to grow the crack from 10 to 20 mm.

6.2 Example 2

Non-destructive testing (NDT) is often carried out on components subject to cyclic loading to check for flaws that were they to remain undetected might cause the propagation of fatigue cracks. A fracture mechanics analysis of such a component enables a schedule to be drawn up detailing the maximum tolerable size of particular shapes of crack at various positions in the component and on its surfaces. Any defects discovered by the NDT examination may then be assessed using this schedule to ensure that they are not large enough to propagate fatigue cracks.

In this example, the calculation procedure involved in producing such a schedule is given for a hollow shaft machined from a 13Cr martensitic corrosion resistant casting. The shaft rotates in a non-corrosive environment at about room temperature and carries both a compressive load, P , and a bending moment, M . For the purposes of this example, the case of an elliptical crack below the surface of the shaft will be investigated (see Sketch 6.1).



Sketch 6.1

To carry out this investigation, data are required in three areas:

- (1) the stress field in the region of the flaw (see Section 6.2.1),
- (2) a solution for the stress intensity factor induced by the presence of the flaw (see Section 6.2.2) and
- (3) the value of threshold stress intensity factor for the material below which cracks will not propagate (see Section 6.2.3).

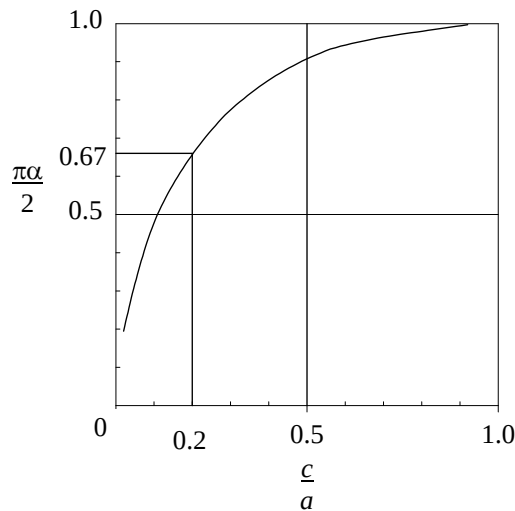
6.2.1 Stress analysis

Details of the required stress calculations are beyond the scope of this Item and will not be presented here. The compressive stress induced by the load, P , has been calculated as -50 MN/m^2 , on which is superimposed a rotating bending stress due to the moment, M . The latter stress varies across the section of the shaft and is, of course, a maximum at the outer surface. The crack in this example is assumed to exist below the surface at a point where the bending stress alternates between $\pm 150 \text{ MN/m}^2$. Combining the bending and

compressive stresses gives $S_{max} = 100 \text{ MN/m}^2$ and $S_{min} = -200 \text{ MN/m}^2$. The stress ratio, $R = -200/100 = -2$. It is assumed that the variation in stress across the crack is negligible, since the crack length is small in relation to the diameter of the shaft.

6.2.2 Stress intensity factor solution

A solution to the stress intensity factor for an elliptical flaw buried beneath the surface may be found on Figure 179 of Reference 54. This relates the stress intensity factor at different points on the circumference of an elliptical crack to the ratio c/a (see Sketch 6.1). Note that a is the crack half-length. The maximum stress intensity factor occurs at points A, shown on that sketch. This maximum value is plotted against c/a on Sketch 6.2.



Sketch 6.2

Two types of elliptical crack will now be considered, one with a ratio $c/a = 1$ (that is a circular crack) for which $\alpha = 2/\pi$ and a long elliptical crack with $c/a = 0.2$ for which $\alpha = 2 \times 0.67/\pi = 1.34/\pi$.

The stress intensity factor range (from Equation (3.1)) is given by

$$\Delta K = (S_{max} - S_{min})(\pi a)^{1/2} \alpha. \quad (6.3)$$

The maximum crack half-length permissible before the crack will propagate is a_{max} and occurs when $\Delta K = \Delta K_{TH}$. Equation (6.3) may be rearranged to give the value of a_{max} .

$$a_{max} = \left[\frac{\Delta K_{TH}}{(S_{max} - S_{min})\pi^{1/2} \alpha} \right]^2. \quad (6.4)$$

6.2.3 Threshold stress intensity factor determination

Threshold stress intensity factors for this steel may be found on Figure 8.4. With $R = -2$, $\Delta K_{TH} = 17 \text{ MN/m}^{3/2}$ ($14.6 \times 10^3 \text{ lbf/in}^{3/2}$). Substituting the values of S_{max} , S_{min} , ΔK_{TH} and α into Equation (6.4) gives, for the circular crack,

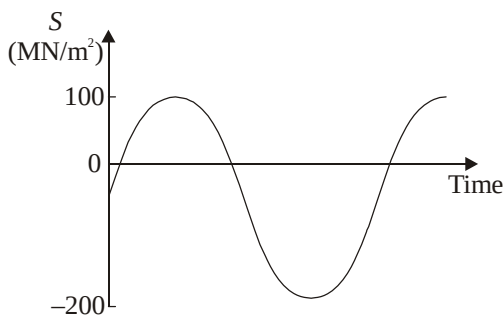
$$a_{max} = \left[\frac{17}{(100 - (-200)) \times \pi^{1/2} \times 2/\pi} \right]^2 = 2.2 \text{ mm (0.087 in)}$$

and for the elliptical crack,

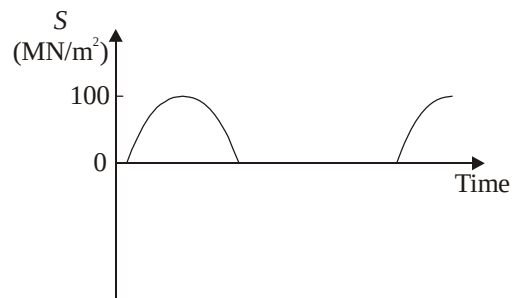
$$a_{max} = \left[\frac{17}{(100 - (-200)) \times \pi^{1/2} \times 1.34/\pi} \right]^2 = 5.0 \text{ mm (0.197 in)}.$$

Thus, remembering that a refers to the crack half-length, circular flaws with diameters greater than 4.4 mm (0.173 in) are liable to propagate cracks in this portion of the shaft, as are elliptical cracks of the geometry described longer than 10 mm (0.394 in). An NDT examination should be able to detect cracks of this size although allowances should of course be made for inaccuracies in measurement. It should be noted that the values taken from the curves are mean values and in practice a conservative, lower, value of ΔK_{TH} would be used.

If data are not available for $R = -2$, an approximate solution may still be obtained by assuming the crack is only open during the tensile portion of the fatigue cycle and using data for $R = 0$. Errors are likely to arise, though, due to crack closure effects. This example will now be recalculated assuming that no $R = -2$ data are available. The assumed stress cycle is shown in Sketch 6.3.



Actual cycle, $R = -2$



Assumed cycle, $R = 0$

Sketch 6.3

The value of S_{max} is still 100 MN/m^2 but now S_{min} is zero. The stress ratio, R , is thus zero, and so, from Figure 8.4 with $R = 0$, $\Delta K_{TH} = 6.3 \text{ MN/m}^{3/2}$ ($5.7 \times 10^3 \text{ lbf/in}^{3/2}$).

Substituting these values into Equation (6.4) gives, for the circular crack,

$$a_{max} = \left[\frac{6.3}{(100 - 0) \times \pi^{1/2} \times 2/\pi} \right]^2 = 3.1 \text{ mm (0.122 in)}.$$