



Fatigue crack propagation rates and threshold stress intensity factor ranges for aluminium alloy sheet

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THE PREPARATION OF THIS DATA ITEM

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FATIGUE CRACK PROPAGATION RATES AND THRESHOLD STRESS INTENSITY FACTOR RANGES FOR ALUMINIUM ALLOY SHEET

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FATIGUE CRACK PROPAGATION RATES AND THRESHOLD STRESS INTENSITY FACTOR RANGES FOR ALUMINIUM ALLOY SHEET

1. NOTATION

a	crack length or crack half-length as defined in Sketch 2.1	m	in
C	coefficient for linear interpolation of crack growth rate curve defined by $da/dN = C(\Delta K)^n$	$m\left(\frac{m}{N}\right)^n$	$in\left(\frac{in}{N}\right)^n$
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 by $S(\pi a)^{1/2}\alpha$	N/m ^{3/2}	lbf/in ^{3/2}
ΔK	stress intensity factor range	N/m ^{3/2}	lbf/in ^{3/2}
ΔK_{TH}	threshold value of ΔK below which fatigue cracks do not grow	N/m ^{3/2}	lbf/in ^{3/2}
N	number of load cycles		
n	characteristic of slope of crack growth rate curve		
R	S_{min}/S_{max}		
r_p	radius of plastic zone	m	in
S	stress based upon cross-sectional area of component	N/m ²	lbf/in ²
α	geometrical factor in stress intensity factor		
γ	index in Equation (3.3)		

1.1 Additional Notation for Test Pieces (Sketch 2.1)

B	thickness of test piece	m	in
b	half-width of test piece type 1	m	in
H	half-depth of test piece type 2	m	in
L	length of test piece type 1	m	in
P	applied direct load for test piece type 2	N	lbf
W	distance from applied load P to back face of test piece type 2	m	in

The crack orientation of the test pieces relative to the grain flow is indicated by the two-letter code system described in Appendix A.

Suffixes

max, *min* indicate maximum or minimum values of stress or stress intensity factor in loading cycle.

1.2 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.

$$1 \text{ MN/m}^{3/2} = 1 \text{ MPa m}^{1/2} = 910.048 \text{ lbf/in}^{3/2}.$$

Note also that

$$1 \text{ MN/m}^{3/2} = 31.623 \text{ N/mm}^{3/2}.$$

2. NOTES

2.1 General

This Item presents fatigue crack propagation rate data (da/dN) in the range 10^{-11} m/cycle to 10^{-3} m/cycle and threshold stress intensity factor ranges, ΔK_{TH} , for aluminium alloy sheet.

The chemical composition, mechanical properties and heat treatment of the materials are given in Table 6.1. The data analysed in the fatigue threshold region have been obtained from tests that provide low crack propagation rates (in the range from 10^{-8} to 10^{-11} m/cycle). Data giving values of ΔK_{TH} only were not considered.

2.2 Test Conditions and Limitations

The data are derived from constant amplitude fatigue tests conducted in laboratory air at room temperature. The loading frequencies of the fatigue machines were in the range 0.1 to 100 Hz, except in one particular case where tests were conducted at frequencies in the range 340 to 1000 Hz (see Figure 2a for details).

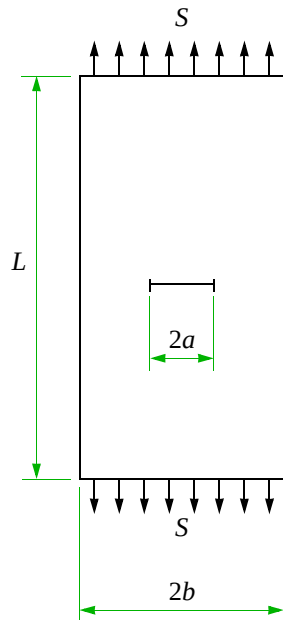
Sketch 2.1 shows the test pieces used together with tabulations of their leading geometric parameters. The thicknesses of the test pieces ranged from 1 mm to 5 mm. Most of the data have been obtained from tests on test pieces of Type 1.

The crack orientation of the test pieces relative to the grain flow was not always given but where known it has been stated in Table 6.1, and on the figures, using the identification system described in Appendix A.

Generally measurements of crack length were made using either optical methods or potential drop techniques. The accuracy of such methods is inevitably limited, particularly where the crack lengths are small, although changes in crack length have been measured down to 0.1 mm at or near the fatigue threshold.

All the tests were stated to have been conducted within the framework of linear elastic fracture mechanics and thus throughout the tests the stresses across the uncracked sections of the test pieces did not exceed the yield strength of the materials and the plastic zone sizes were small compared with crack length (see

Section 1 of ESDU 80036*).

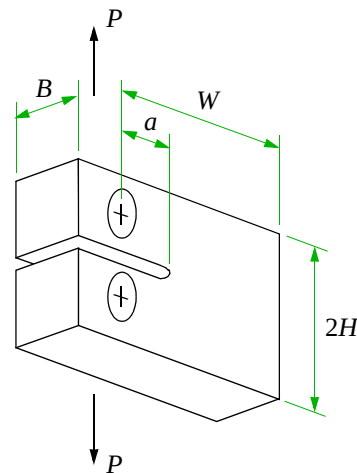


Ratio	Min.	Max.
$2b/L$	0.11	0.65

Central crack in plate or bar (CCT)

Type 1

Ratio	Min.	Max.
a/W	0.15	0.39
H/W	0.6	0.6



Compact tension (CT) or compact K test piece (CKS)

Type 2

Sketch 2.1 Test piece configuration

2.2.1 Applicability of data to short cracks

The data presented in this Item have been obtained from fatigue tests on test pieces that contained machined slots or notches. The minimum length of these machined slots or notches was 2.6 mm. In general the test pieces were fatigue loaded so that small starter cracks, of unstated length, grew from the machined slots or notches before the crack propagation tests began. Therefore all the data presented in this Item have been obtained from test pieces with cracks whose values of $a > 1.3$ mm.

For components containing cracks of lengths < 1 mm the assumption that the material acts as a homogenous continuum in the neighbourhood of the crack tip no longer applies. Also, inaccurate measurement of the lengths of small cracks, because of crack front curvature, leads to wide discrepancies in the estimations of the value of ΔK . Another important parameter to consider in dealing with short cracks is the ratio of the radius of the plastic zone to the crack length, r_p/a . This ratio can be critical if a component is subjected to high stresses such that gross yielding occurs across the net uncracked section and in consequence linear elastic fracture mechanics procedures do not apply.

For components containing short cracks the values of ΔK_{TH} may be much lower than those shown on the figures presented in this Item and the fatigue crack propagation rates may be much higher for a given stress intensity factor range ΔK . Therefore, if the data are applied to components containing short cracks, unsafe estimates may be obtained for values of ΔK_{TH} and for fatigue crack growth life under given loading conditions (References 24, 28, 29, 30 and 32 show some of these effects).

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

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 propagation rates less than 10^{-10} m/cycle were obtained from the tests (which is less than 1 lattice spacing/cycle). For this Item where tests were terminated in the region of $da/dN = 10^{-10}$ m/cycle the crack growth curves have been extrapolated by eye so that values of ΔK_{TH} may be obtained. The values of ΔK_{TH} are considered valid if the crack propagation curves are vertical or very nearly vertical. For most of the materials for which data are presented this condition is taken to be at a da/dN value of 10^{-11} m/cycle.

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 most popular method. Generally testing was terminated, and a value of ΔK_{TH} considered to have been obtained, if there was no visible crack growth after the application of at least 10^6 cycles for a given applied load. In at least two of the tests the cracks were grown at each cyclic load level until their lengths were several times larger than the size of the plastic zone for static loading, before crack measurements were taken (see Equation (3.11) of ESDU 80036). This procedure eliminated the effects of stress history.

2.4 Presentation of Data

Figures 1 to 9 provide crack propagation rate curves, da/dN , plotted against stress intensity factor range, ΔK , for various values of R , including negative values of R for three alloys. Each figure relates to a particular type of alloy or group of alloys of similar composition. Figures 2a, 5a, 6a and 7a provide curves for low crack propagation rates, that is $da/dN \leq 10^{-8}$ m/cycle down to ΔK_{TH} ($da/dN = 10^{-11}$ m/cycle). For many of the alloys considered there are insufficient data available to provide more than one curve, but where sufficient data are available (usually a minimum of five tests are required) a mean curve shown solid and the upper limit of either all or 95 per cent of the data, shown dashed, are presented. For one alloy, 7075-T6 at $R = -1.0$, the curve defining the upper limit of data encloses only 88 per cent of the data (see Figure 5). Also on the figures the thicknesses and, where available, crack orientations relative to the grain flow of the test pieces (see Appendix A) are quoted.

It can be seen that for two of the alloys (2024-T3 and 7075-T6) it was not possible to draw smooth continuous curves between crack propagation rates above and below 10^{-8} m/cycle so that on Figures 2a and 5a there are discontinuities between the curves for high and low values of da/dN . These discontinuities are due to the data having been obtained from completely different populations that were unrelated except for the type of alloy.

Figures 10, 10a and 11 provide summary curves so that the crack propagation rates of the different alloys considered can be compared.

Figure 12 shows how the value of the fatigue threshold stress intensity factor, ΔK_{TH} , varies with the stress ratio, R , for the various alloys.

3. DISCUSSION OF DATA

3.1 Method of Analysis of Test Data

Where the basic crack growth rate data (a , N) were available the crack propagation growth rate has been determined by differentiating the basic crack growth curve obtained using the curve fitting technique described in Reference 22. Basic a , N data were only available for the test pieces of Type 1 of Sketch 2.1.

In the cases where the basic crack growth data were not available, quoted values of da/dN and ΔK have been taken directly from the Derivations.

Equation (4.2) of ESDU 80036 defines ΔK as

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

The values of α used in Equation (3.1) have been taken from either the Derivations directly (where values appropriate to the loading conditions and geometry of the test pieces tested were stated) or, in the cases where the basic a and N data have been analysed as described by Reference 22, from Equation (3.2).

3.1.1 Central crack in a plate loaded in tension (Type 1, Sketch 2.1)

The expression obtained from Reference 23 and used in ESDU 81031*, ESDU 84001* and ESDU 89051* has been used, namely

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

The expression is valid for all values of a/b .

3.1.2 Crack tip plasticity correction in plane stress

The crack propagation rate curves presented in this Item are in terms of a ΔK that ignores the effect of plasticity at the crack tip.

In Section 4.1.1 of ESDU 80036 a method for taking into account the size of the plastic zone under cyclic loading, for materials in a condition of plane stress, is described. It was found that when the method was applied to the data of this Item the increase in the value of ΔK was generally very small, about 1 per cent or less, and for this reason the effect of plasticity on the value of ΔK has been ignored. The two largest increases in the value of ΔK were found to be for the BS L72 alloy (where ΔK increased by 5 per cent at $R = 0.4$) and for the 7075-T6 alloy (where ΔK increased by 6 per cent at $R = -1.0$).

3.2 Effect of Stress Ratio, R

For any given value of ΔK , da/dN depends upon the value of R , and the crack propagation rate curves have been drawn for set values of R in the range -2.0 to 0.9 . The figures show that, for a given value of ΔK , da/dN increases as the value of R becomes more positive. This effect is greatest at low values of da/dN when ΔK approaches the fatigue threshold stress intensity factor. In this region of crack growth the crack propagation rate curves separate with increasing values of R . There is also some evidence that a similar phenomenon occurs at high values of da/dN (approaching failure). The negative values of R give the lowest crack propagation rates for the three materials where data are available. Note that the full stress range has been used when calculating the value of ΔK for the negative R data (that is, the compression part of the load cycle has been included in the calculation).

Figure 12 shows how changes in the value of R affect ΔK_{TH} for various positive values of R . The

* ESDU 81031 "Fatigue crack propagation rates and threshold stress intensity factor ranges for aluminium alloy plate, extruded bar and forgings."

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

ESDU 89051 "Fatigue crack propagation rate of titanium alloy sheets."

presentation allows for four mean lines to be drawn through values of ΔK_{TH} for four alloys. The lower mean line passes through the values of ΔK_{TH} obtained from the 7075-T6 alloys. The upper mean line passes through the data for the 2024-T3 alloy.

For many materials it has been shown that presentation of data in the form of Figure 12 may be represented by the equation

$$\Delta K_{TH} = [(\Delta K_{TH})_{R=0} - (\Delta K_{TH})_{R=1.0}](1-R)^\gamma + (\Delta K_{TH})_{R=1.0}, \quad (3.3)$$

or by an equation of similar form. The index γ varies depending on the type of material and its strength. For the majority of aluminium alloys presented in this Item the data of Figure 12 lie along straight lines so that the index $\gamma \approx 1.0$.

The effects of variations of R , in the crack propagation rate region away from the fatigue threshold area, show the same trends for all the alloys considered.

3.3 Effect of Sheet Thickness

Within the range of thicknesses (1 to 5 mm) for which data are provided the effect of sheet thickness was found to be small. However, the tendency is for the crack growth rate to increase with increasing sheet thickness, although at low values of R this is not always the case.

3.4 Effect of Crack Orientation of Test Piece Relative to Grain Flow

Where possible, the direction of the crack orientation relative to the grain flow is indicated in Table 6.1 and on the figures. The two-letter code system used to identify the crack orientation of the test pieces relative to the grain flow is fully described in Appendix A. Only test pieces with cracks orientated in the L-T and T-L direction are known to have been tested and in these cases the direction of the grain flow did not appear to influence crack propagation rates.

3.5 Effect of Environment

All the test data analysed were obtained from tests conducted in laboratory air at room temperature. It has been shown in other fatigue crack growth tests on sheet specimens (see Reference 27) that as the humidity of air increases at room temperature so does the crack growth rate and this phenomenon may also affect fatigue threshold values. No effects of changes in humidity, and no other environmental factors such as atmosphere, temperature *etc.*, have been considered in this Item.

3.6 Comparison of Alloys

Figures 10, 10a and 11 have been included so that crack propagation rates of the various alloys may be compared. The curves for $R = 0$ to 0.1 from Figures 1 to 9, for the various alloys, have been superimposed on Figure 10. Similarly, the curves for $R = 0.5$ to 0.67 from Figures 1 to 9 have been superimposed on Figure 11.

Figures 10 and 11 show that variation in the value of R does not affect comparative performance since trends are similar on both figures. The figures show that generally the Al-Zn alloys in the T6 condition have the highest crack propagation rates and the Al-Cu alloys in the naturally aged condition have the lowest crack propagation rates.

Figure 10a summarises the low crack propagation rates ($\leq 10^{-8}$ m/cycle down to ΔK_{TH}) for four of the

alloys. The data show that, at $R = 0.05$ to 0.1 , the 2024-T3 alloy has the highest value of ΔK_{TH} , at $3.55 \text{ MN/m}^{3/2}$, although the differences in the values of ΔK_{TH} are small, ranging from 2.6 to $3.55 \text{ MN/m}^{3/2}$.

As discussed in Section 3.6 of ESDU 81031 the microstructure of the alloy can significantly affect crack propagation rates and the transition to the fatigue threshold. References 33 and 34 also discuss some of these effects, but in this Item there are too few results to confirm the trends. Nevertheless, the inflections in the crack propagation curves at slow crack propagation rates shown in Reference 34 are also evident in Figures 2a and 5a of this Item.

4. CALCULATION OF CRACK GROWTH LIFE

4.1 Use of Curves

The complete curves available from the data are presented in Figures 1 to 9. The curves are suitable for use in computer programs that predict crack growth life. Alternatively, simple integration over selected portions of one of the curves will also lead to an estimate of the total crack growth and the associated number of cycles (see ESDU 84001). One method described in ESDU 84001 assumes that the crack propagation rate curves are straight lines over discrete ranges of da/dN and may be described by Equation (4.1) (Reference 21),

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

Suggested values of n and C for given values of R are shown in the tables on the figures. Equation (4.1) cannot be used to describe the full range of crack growth (that is from fatigue threshold to failure). For values of $da/dN < 10^{-10} \text{ m/cycle}$ the crack propagation rate curves become nearly vertical and the value of $n \rightarrow \infty$ so that Equation (4.1) is unusable. If Equation (4.1) is used in the region $da/dN = 10^{-10}$ to 10^{-9} m/cycle it should only be used over small ranges of da/dN .

4.2 Practical Solutions

Simple practical examples using Equation (4.1) are given in ESDU 84001 and 84003* for crack propagation rates $> 10^{-8} \text{ m/cycle}$. Section 6 of ESDU 81031 gives an example of the use of ΔK_{TH} in a practical situation.

Methods of obtaining values of α for cracks in structural components of more complex geometries are outlined in ESDU 80036 and 78036† and may also be obtained directly from sources such as Reference 25.

* ESDU 84003 "Fatigue crack propagation rates and threshold stress intensity factors in high alloy and corrosion resistant (stainless) steel plate."

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

5. DERIVATION AND REFERENCES

Derivation

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