

FATIGUE PROPAGATION BEHAVIOUR OF SHORT CRACKS IN ALUMINIUM ALLOYS

1. NOTATION

Both SI and British units are quoted.

a	crack length or crack half-length	m	in
C	coefficient in simple crack growth rate equation, $da/dN = C(\Delta K)^n$	$m(m^{3/2}/N)^n$	$in(in^{3/2}/lbf)^n$
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
f_y	yield stress	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_{cl}	stress intensity factor value at crack closure	N/m ^{3/2}	lbf/in ^{3/2}
K_{max}	maximum value of K in fatigue cycle	N/m ^{3/2}	lbf/in ^{3/2}
K_{min}	minimum value of K in fatigue cycle	N/m ^{3/2}	lbf/in ^{3/2}
ΔK	stress intensity factor range defined as $(S_{max} - S_{min}) (\pi a)^{1/2} \alpha = K_{max} - K_{min}$	N/m ^{3/2}	lbf/in ^{3/2}
ΔK_{eff}	effective stress intensity factor range defined as $K_{max} - K_{cl}$	N/m ^{3/2}	lbf/in ^{3/2}
ΔK_{TH}	threshold value of ΔK for long cracks	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	stress ratio defined as S_{min}/S_{max}		
S	stress based upon gross cross-sectional area	N/m ²	lbf/in ²
S_{max}	maximum stress in fatigue cycle	N/m ²	lbf/in ²
S_{min}	minimum stress in fatigue cycle	N/m ²	lbf/in ²
α	geometrical factor in stress intensity factor expression		

2. NOTES

2.1 Introduction

This Data Item presents propagation rate data for short cracks in aluminium alloys. Some long crack propagation rate data are also presented to illustrate the differences that can exist between the propagation rates of long and short cracks. These differences in propagation can exist for cracks as long as 1–2 mm (0.04–0.08 in) in aluminium alloys. A short crack may be microstructurally small (having a length close to the dominant microstructural dimension) and/or mechanically small (not substantially larger than the plastic zone at the crack tip). When employing linear elastic fracture mechanics (described in Data Item No. 80036*) to analyse both long and short cracks significant differences in propagation behaviour are revealed. The purposes of this Data Item are to illustrate the need for short crack data in some designs and to highlight the danger of using long crack data where they are inappropriate.

2.2 The Short Crack Effect

When crack propagation rates are plotted against ΔK , as determined by linear elastic fracture mechanics, and compared, significant differences between the behaviour of long and short cracks are apparent. Long cracks display a threshold value of stress intensity factor range, ΔK_{TH} , below which they do not propagate. However, short cracks will often not appear to have a threshold value of ΔK and can grow at values of ΔK below the long crack threshold value, ΔK_{TH} . Also, the crack propagation rates of short cracks, as determined by linear elastic fracture mechanics, are often significantly higher than the crack propagation rates of long cracks at the same values of ΔK and R . The differences in crack propagation rates are usually most pronounced at low to medium values of ΔK and at negative stress ratios, R . In situations where a difference in crack propagation rates is observed, the difference between the rates tends to decrease with increasing ΔK until both the long and the short cracks have the same propagation rate. These differences in crack propagation behaviour are illustrated in Sketch 2.1.

Crack tip shielding, and in particular crack closure effects, are probably the most significant factors in explaining the differences in crack propagation behaviour between long and short cracks. Long cracks often experience premature crack closure, that is effective closure of the crack prior to the complete removal of the tensile load during the fatigue cycle. Premature crack closure can occur in a variety of ways. Deflected crack paths or rough crack sides can result in the sides of the crack sliding over each other and the crack becoming wedged at values of K greater than K_{min} . Debris inside a crack can also cause wedging and premature closure. These factors are largely dependent on the crack being of sufficient length and hence are usually more effective in long cracks than short cracks. The effect of premature crack closure is to shield the crack tip from the effects of the full load cycle so that it only experiences the effective stress intensity factor range, ΔK_{eff} .

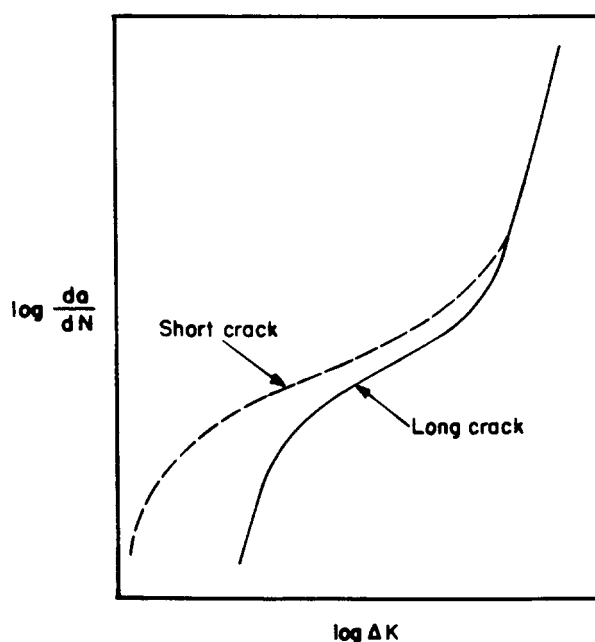
This reduction in stress intensity factor range will only be experienced when K_{min} is less than K_{cl} . Therefore, the effects of premature crack closure will be most significant when load cycles have a large compressive portion. Short cracks are unlikely to experience premature crack closure. Short cracks often remain open at K values less than zero giving rise to negative K_{cl} values which increase the value of K_{eff} at the crack tip. As a short crack grows its K_{cl} value will usually increase resulting in a decrease in the value of ΔK_{eff} and in some cases this reduction may be larger than the increase in ΔK_{eff} due to the increase in crack length. Hence, as the crack grows there is a decrease in the value of ΔK_{eff} and the crack propagation rate is reduced when plotted against ΔK , as defined in the notation.

* Data Item No. 80036. "Introduction to the use of linear elastic fracture mechanics in estimating fatigue crack growth rates and residual strength of components".

This is shown in curves 1-4 in Figure 5 where increases in ΔK result in decreases in crack propagation rate. A large amount of scatter is apparent when the rates of different cracks are plotted together for the purpose of finding the mean rate, particularly where ΔK is less than ΔK_{TH} .

For short cracks the assumptions of linear elastic fracture mechanics are not strictly valid. However, it is convenient to use the same method of analysis for both long and short cracks, particularly in a damage tolerance analysis where a short crack is assumed to be the initial defect. It is therefore necessary to allow for the short crack effect since, if only long crack data are used, inaccurate and non-conservative endurance will be obtained.

It is extremely difficult to calculate K accurately for short cracks. A shape function must be assumed for the crack. As the crack grows it may change shape requiring a change in the shape function. If the shape function is taken to be constant, large errors in K can result. The calculated stress intensity values, K , are only valid for specific regions of the crack, for example, at the point of maximum depth in a semi-elliptical surface crack. Short cracks are very susceptible to local stress fields which may differ from the assumed stress field, for example, a short surface crack may experience a stress field resulting from surface treatment or machining that is very different from the nominal stress field. The stress field around the short crack can also be modified by a plastic zone that is large relative to the crack. Short cracks often propagate along favoured crystallographic planes and the orientation of these planes can change from one grain to another. Thus, short cracks will often propagate along a plane that is inclined to the plane normal to the loading (for uniaxial loading). In such a case the short crack will be subjected to mixed mode loading. This is particularly likely in Al-Li alloys (Figures 7 to 12) which are noted for their deviating and branching fatigue crack paths. Fatigue cracks in Al-Li alloys also experience higher levels of premature crack closure than those in conventional aluminium alloys. It is difficult to measure the curvature of the crack tip and its orientation with respect to the plane normal to the loading. These factors are not usually fully allowed for in the calculation of ΔK and Mode I loading only is usually assumed. The measurement of short cracks is more difficult than long cracks and the procedures involved are more complex. In some cases a length is calculated based on the surface length of the crack and an assumed shape function.



Sketch 2.1 Comparison of the crack propagation rates of typical long and short cracks at a common value of stress ratio, R

2.3 Presentation of Data

Most of the crack propagation rate data are taken from constant amplitude tests in air. However, some data are presented for other environments. The data are presented as curves of crack propagation rate against stress intensity factor range, that is da/dN against ΔK . Mean curves have been drawn by eye, using all the data points provided in the relevant derivation. None of the curves has been extrapolated beyond the range of the available data. A table providing details on the testing conditions accompanies each figure. Material data are set out in Table 6.1. The convention used for denoting crack orientation is shown in Appendix A.

All the curves on the figures that refer to tests with negative stress ratio values, R , include both the tensile (positive) and compressive (negative) portions of the fatigue cycle in the calculation of the stress intensity factor range, ΔK (see Sketch 2.2). Therefore, ΔK is given by:

$$\Delta K = (S_{max} - S_{min})(\pi a)^{1/2} \alpha. \quad (2.1)$$



Sketch 2.2 Illustration of ΔK used in Figures 1 to 12

Some published papers, for example where the tests were carried out to BS 6835, use only the tensile part of the fatigue cycle in the calculation of the stress intensity factor range, ΔK , for tests with negative stress ratio values:

$$\Delta K = S_{max}(\pi a)^{1/2} \alpha. \quad (2.2)$$

When comparing data from other sources having negative stress ratio values with the data presented in this Item, care must be taken to ensure that the ΔK values have been calculated using the same method. The difficulties associated with the calculation of K for short cracks, as discussed in Section 2.2, should be noted. It should also be noted that the individual da/dN values are average values of the measured increase in crack length over a number of cycles.

In the tests from which the presented data are taken, two approaches have been taken to the generation of the cracks. In most of the tests a notch has been used to provide a stress concentration in a particular area which serves as the origin for naturally occurring short cracks. The second approach is to generate short cracks artificially from long cracks. In this case a specimen containing a long crack is machined to leave just the tip of the long crack. The propagation of this artificial short crack is then measured. However, the plastic zone at the tip of this short crack will be that of the long crack and this will affect the subsequent propagation of the crack. This is illustrated in Figure 5 and is similar to a repair situation where a defect or crack is incompletely machined out.

3. NOTES ON FIGURES

Figures 1 to 12 present propagation rate curves for short cracks in aluminium alloys. Most of the curves present data from more than one test. Each of curves 1 to 4 in Figure 5 presents propagation rate data for an individual crack. For comparison some figures show propagation rate curves for long cracks. All the curves have been drawn by eye.

Figure 1 illustrates short cracks propagating below ΔK_{TH} and propagating at a higher rate than the long cracks in 2024-T3. The short crack propagation rate approaches the long crack propagation rate at ΔK values above ΔK_{TH} .

Figure 2 shows the short crack propagation rates in overaged and underaged 7010. At low values of ΔK the short cracks propagate at a higher rate in the overaged material than in the underaged material. As ΔK increases, this difference in crack propagation rates becomes negligible.

In Figure 3 the propagation rate of short cracks in 7075-T651 in moist air is much higher than in vacuum over the entire range of ΔK for which data are presented. The propagation rates of short cracks in 7075-T7351 in moist air, nitrogen and in vacuum are presented in Figure 4.

Curves 1 to 4 in Figure 5 are propagation rate curves for individual short cracks in 2124. Under the testing conditions, the short crack propagation rates decrease as the cracks grow. In curves 1 to 3 the propagation of the cracks is arrested. For curve 4, where ΔK approaches ΔK_{TH} the short crack propagation rate reaches a minimum and then begins to increase with increasing ΔK and eventually follows approximately the propagation rate curve of the long cracks. The differences observed could be related to the method of formation of the short cracks as discussed in Section 2.3. Testing with different stress levels, different curves might have been obtained.

In both Figures 6 and 7 for RR58 and an Al-Li alloy respectively the propagation rates of short cracks are higher than the propagation rates of long cracks. Also, the short cracks propagate at the lowest value of ΔK for which data are presented. As ΔK increases the differences between the long and short crack propagation rates become smaller.

Figures 8, 9 and 10 present data for short and long cracks in 2090-T8E41 at R values of 0, -1 and -2 respectively. In all three cases and over the entire range of ΔK for which data are presented the short cracks propagate at higher rates than the long cracks. It can be seen that the effect of stress ratio, R , is different at high and low ΔK values.

Figures 11 and 12 present short and long crack propagation rates for 8090 and 8091 respectively. In both figures the short cracks propagate at a significantly higher rate than the long cracks over the entire range of ΔK for which data are presented.

4. CALCULATION OF CRACK GROWTH

The growth of a crack over a number of cycles may be predicted by integrating the crack growth rate curves given in Figures 1 to 12. This may be easily done over any portion of the curve that may be adequately represented by the simple linear Paris equation:

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

Similarly, curved portions may be represented by a series of straight lines. Examples of the use of these

curves are given in Data Item Nos 82015, 84001 and 84003*. Since the curves are presented on a logarithmic scale, n represents the slope and C the ordinate intercept of the straight line. Equation (4.1) can be integrated analytically, using the method described in Data Item No. 80036, to obtain an estimate of the total number of loading cycles required for a crack to grow from one length to another.

5. DERIVATION AND REFERENCES

5.1 Derivation

This section lists sources of information which have been of assistance in the preparation of this Item.

1. HICKS, M.A.
BROWN, C.W. A comparison of short crack growth behaviour in engineering alloys. In: Fatigue '84. Engineering Materials Advisory Service, Conference Proceedings, 1984.
2. BROWN, C.W.
KING, J.E. The relevance of microstructural influences in the short crack regime to overall fatigue resistance. In: Small fatigue cracks. Proceedings of the 2nd International Conference/Workshop, Santa Barbara, California, January 5-10, 1986.
3. RITCHIE, R.O.
YU, W. Short crack effect in fatigue: a consequence of crack tip shielding. In: Small fatigue cracks. Proceedings of the 2nd International Conference/Workshop, Santa Barbara, California, January 5-10, 1986.
4. PINEAU, A. Short fatigue crack behaviour in relation to three-dimensional aspects and crack closure effect. In: Small fatigue cracks. Proceedings of the 2nd International Conference/Workshop, Santa Barbara, California, January 5-10, 1986.
5. ZEGHLOUL, A.
PETIT, J. ΔK_{eff} rationalization of short crack behaviour: environmental and microstructural influence. In: Small fatigue cracks. Proceedings of the 2nd International Conference/Workshop, Santa Barbara, California, January 5-10, 1986.
6. GANGLOFF, R.P.
WEI, R.P. Small crack-environment interactions: the hydrogen embrittlement perspective. In: Small fatigue cracks. Proceedings of the 2nd International Conference/Workshop, Santa Barbara, California, January 5-10, 1986.
7. HOWLAND, C.
HICKS, M.A.
JEAL, R.H. The relevance of short crack behaviour to the integrity of major rotating aero engine components. In: Small fatigue cracks. Proceedings of the 2nd International Conference/Workshop, Santa Barbara, California, January 5-10, 1986.
8. BOLLINGBROKE, R.K.
KING, J.E. A comparison of long and short fatigue crack growth in a high strength aluminium alloy. In: *The behaviour of short fatigue cracks*. Mechanical Engineering Publications, 1986.

* Data Item No. 82015 "Fatigue crack propagation rates and threshold stress intensity factor ranges for titanium alloy plate, bar and forgings".
Data Item No. 84001 "Growth of cracks under constant amplitude fatigue loading: example calculations".
Data Item No. 84003 "Fatigue crack propagation rates and threshold stress intensity factors in high alloy and corrosion resistant (stainless) steel".

9. PETIT, J.
ZEGHOUL, A. On the effect of environment on short crack growth behaviour and threshold. In: *The behaviour of short fatigue cracks*. Mechanical Engineering Publications, 1986.
10. NEWMAN, J.C. Jr.
EDWARDS, P.R. Short crack growth behaviour in an aluminium alloy - an AGARD cooperative test programme. AGARD-R-732, 1988.
11. EDWARDS, P.R.
NEWMAN, J.C. Jr. An AGARD supplemental test programme on the behaviour of short cracks under constant amplitude and aircraft spectrum loading. In: AGARD-R-767. Short-crack growth behaviour in various aircraft materials. 1990.
12. MAZUR, C.J.
RUDD, J.L. Determination of the short crack effect in 2090-T8E41 aluminium lithium. In: AGARD-R-767. Short-crack growth behaviour in various aircraft materials. 1990.
13. SWAIN, M.H.
et al. The growth of short cracks in 4340 steel and aluminium lithium 2090. In: AGARD-R-767. Short-crack growth behaviour in various aircraft materials. 1990.
14. NICHOLLS, D.J.
MARTIN, J.W. Small crack growth in the aluminium-lithium alloys 8090 and 8091. *Fatigue and Fracture of Engineering Materials and Structures*, Vol. 13, No. 1, pp. 83-94, 1990.
15. WANHILL, R.J.H. Durability analysis using short and long fatigue crack growth data. NLR TP 91120 L. 1991.

5.2 References

This section gives recommended sources of information supplementary to that in this Item.

16. LANKFORD, J.
DAVIDSON, C. The role of metallurgical factors in controlling the growth of small fatigue cracks. In: *Small fatigue cracks*. Proceedings of the 2nd International Conference/Workshop, Santa Barbara, California, January 5-10, 1986.
17. MURAKAMI, Y. *The stress intensity factor handbook*. Volumes 1 and 2, Pergamon Press, 1987.
18. BSI British standard method for determination of the rate of fatigue crack growth in metallic materials. British Standards Institution BS 6835, 1988.
19. BLOM, A.F. Short fatigue crack growth behaviour in Al2024 and Al7475. In: *The behaviour of short fatigue cracks*. EGF Pub. 1, Mechanical Engineering Publications, 1986.

6. TABLES AND FIGURES

TABLE 6.1 GUIDE TO MATERIALS

Material	Composition* (percentage by weight)	Heat Treatment*	Mechanical Properties*			Figure No.
			f_t MN/m ² (10 ³ lbf/in ²)	f_y MN/m ² (10 ³ lbf/in ²)	f_p MN/m ² (10 ³ lbf/in ²)	
2024	Al-4.61Cu-1.51Mg -0.57Mn-0.33Fe -0.16Si	T3	495 (71.8)	details not provided	355 (51.5)	1
7010	Al-6.2Zn-2.5Mg -1.7Cu-0.05Cr -0.14Zr-0.07Si -0.11Fe-0.10Mn	underaged	details not provided	490 (71.1)	details not provided	2
		overaged	details not provided	495 (71.8)	details not provided	2
7075	Al-1.52Cu-6.0Zn -2.44Mg-0.20Cr -0.16Fe-0.07Si-0.04Ti	T651	details not provided	527 (76.4)	details not provided	3
		T7351	details not provided	470 (68.2)	details not provided	4
2124	Al-4.50Cu-0.25Zn -1.5Mg-0.50Mn -0.30Fe-0.20Si -0.15Ti-0.10Cr	T351	488 (70.8)	360 (52.2)	details not provided	5
RR58	Al-2.4Cu-1.5Mg -1.2Ni-1Fe-0.125Si	details not provided	450 (65.3)	details not provided	370 (53.7)	6
Al-Li alloy	Al-2.45Li-1.2Cu -0.7Mg-0.12Zn	details not provided	490 (71.1)	details not provided	400 (58.0)	7
2090	Al-2.60Li-3.00Cu -0.25Cr-0.15Ti -0.15Zr-0.12Fe -0.10Zn-0.10Si -0.05Mn	T8E41	580 (84.1)	details not provided	525 (76.1)	8, 9, 10
8090	details not provided	peak aged	details not provided	details not provided	details not provided	11
8091	details not provided	peak aged	details not provided	details not provided	details not provided	12

* As quoted in the relevant derivation.

TABLE 6.2 GUIDE TO FIGURE 1

Material: 2024-T3 2.3 mm (0.09 in) sheet						
Curve No. (Symbol)	Derivation No.	Stress ratio, R	Environment	Orientation	Crack type	Notes
1 (O)	15	0	air	L-T	short [shorter than 2 mm (0.08 in)]	single edge notched tensile specimens, either a semi elliptical surface crack at the centre of the notch or a quarter elliptical corner crack at an edge was assumed, crack growth measured using the plastic replica method
2 (x)	15	0	air	L-T	long [longer than 2 mm (0.08 in)]	centre crack tension specimens

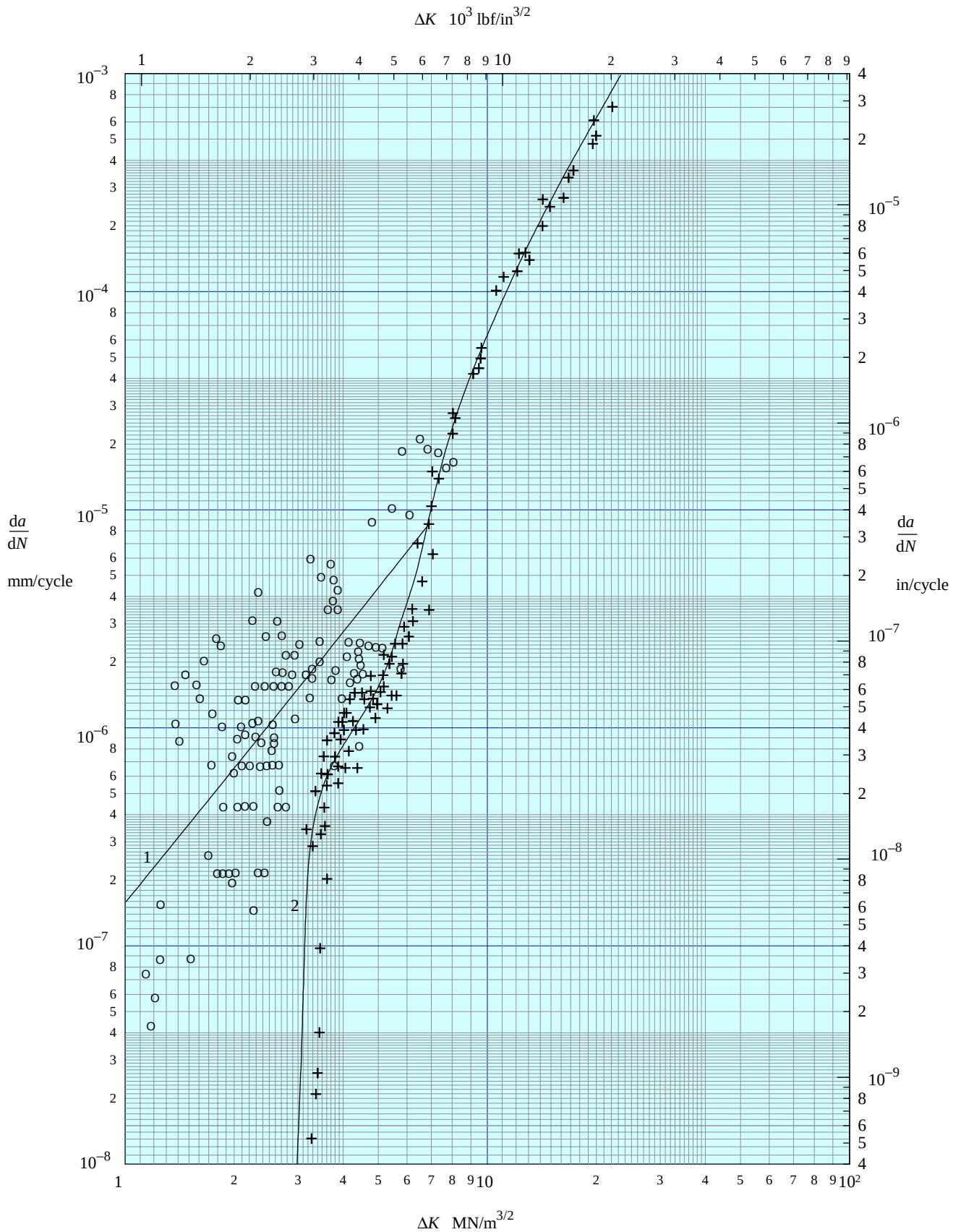


FIGURE 1 2024

TABLE 6.3 GUIDE TO FIGURE 2

Material: 7010 (underaged or overaged) rolled plate						
Curve No. (Symbol)	Derivation No.	Stress ratio, R	Environment	Orientation	Crack type	Notes
1 (O)	8	0.1	air	L-T	short	overaged, square section bar specimen, four point bend loading, semi elliptical cracks assumed, crack growth measured using plastic replica technique
2 (●)	8	0.1	air	L-T	short	underaged, square section bar specimen, four point bend loading, semi elliptical cracks assumed, crack growth measured using plastic replica technique