

FATIGUE PROPAGATION BEHAVIOUR OF SHORT CRACKS IN TITANIUM 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	$N/m^{3/2}$	$lbf/in^{3/2}$
K_t	elastic stress concentration factor		
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		

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2. NOTES

2.1 Introduction

This Data Item presents propagation rate data for short cracks in titanium 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. 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, that difference 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.

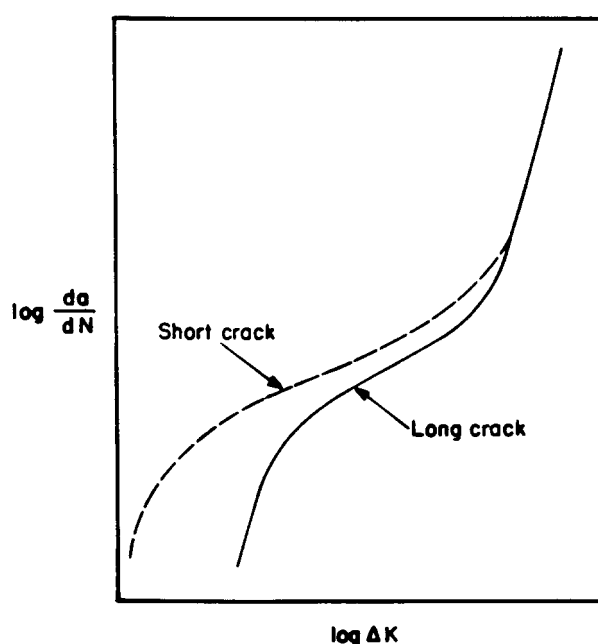
Crack tip shielding, and in particular crack closure effects, are probably the most significant factors in explaining the differences in crack propagation behaviour between long and short cracks. Long cracks often experience premature crack closure, that is effective closure of the crack prior to the 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. They 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 net decrease in the value of ΔK_{eff} and the crack propagation rate is reduced when plotted against ΔK , as defined in the notation. This erratic behaviour is shown in Figures 2 and 11 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} .

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

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 values 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 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. 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. Measurement of short cracks is more difficult than for 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

The crack propagation rate data are taken from constant amplitude tests in air. The data are presented in terms of crack propagation rate against stress intensity factor range, that is da/dN against ΔK . Where mean curves are provided these 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 conventions used for denoting orientation are 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 11

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.

3. NOTES ON FIGURES

Figures 1 to 11 present propagation rate data for short cracks in titanium alloys. Figures 2 and 11 each presents propagation rate data for individual cracks. For comparison some figures show propagation rate curves for long cracks.

Figure 1 shows short cracks propagating at a higher rate and at lower ΔK values than long cracks in IMI 318. The short cracks propagate at ΔK values below the threshold value, ΔK_{TH} , of the long cracks.

Propagation rate data for an individual short crack in IMI 318 are shown in Figure 2. It can be seen that an increase in ΔK does not necessarily result in an increase in propagation rate. The propagation rate is very erratic at low ΔK values (varying by a factor of four) but becomes smoother at higher ΔK values.

Figures 3 and 4 present propagation rate curves for short and long cracks in Ti-6Al-4V at stress ratios, R , of zero and -1 , respectively. At a stress ratio, R , of zero (Figure 3) the long cracks propagate at a higher rate than the short cracks except at low ΔK values. At a stress ratio, R , of -1 the short cracks propagate at a higher rate except at high values of ΔK .

Figures 5 and 6 present propagation rate curves for short cracks in Ti-6Al-4V and Ti-4Al, respectively. It should be noted that the Ti-6Al-4V has been heat treated to an abnormally high strength.

Propagation rate curves of short and long cracks in IMI 685 are presented in Figure 7. The short cracks propagate at much higher rates than the long cracks over the entire range of ΔK for which data are provided.

A propagation rate curve for short cracks in Ti-6Al-2Sn-4Zr-6Mo is presented in Figure 8.

Propagation rate curves for short cracks in Ti-8Al at stress ratios, R , of 0.1 and 0.5 are presented in Figure 9. The crack propagation rate is higher at the higher value of stress ratio, R .

A propagation rate curve for short cracks in Ti-8.6Al is presented in Figure 10.

Figure 11 presents propagation rate data for two individual short cracks in Ti-8.6Al. It should be noted that the propagation rate does not increase steadily with increase in ΔK .

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 11. 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. BROWN, C.W. A study of short fatigue crack growth behaviour in titanium IMI 685.
HICKS, M.A. *Fatigue Engng Materials Struct*, Vol. 6, No. 1, pp. 67-76, 1983.

* 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".

2. GERDES, C.
et al. Propagation of small surface cracks in Ti-alloys. In: Fatigue crack growth threshold concepts. TMS–AIME, 1984.
3. 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.
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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.
5. BOLLINGBROKE, R.K.
KING, J.E. The growth of short fatigue cracks in titanium alloys IMI 550 and IMI 318. In: Small Fatigue Cracks. Proceedings of the 2nd International Conference/Workshop, Santa Barbara, California, January 5-10, 1986.
6. WAGNER, L.
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7. HOWLAND, C.
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8. LARSEN, J.M.
JIRA, J.R. Small-crack closure measurements in titanium alloys. In: International Congress on Experimental Mechanics, Portland, Oregon, June 6-10, Proceedings Volume 2, pp. 873-880, 1988.
9. LARSEN, J.M.
et al. Crack closure effects on the growth of small surface cracks in titanium-aluminum alloys. In: Mechanics of fatigue crack closure. ASTM STP 982, ASTM, 1988.
10. LANCIOTTI, A.
GALATOLO, R. Short crack observations in Ti-6Al-4V under constant amplitude loadings. In: Short-crack growth behaviour in various aircraft materials. AGARD-R-767, 1990.

5.2 References

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

11. 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.
12. MURAKAMI, Y. *The stress intensity factor handbook*. Volumes 1 and 2, Pergamon Press, 1987.
13. BSI British standard method for determination of the rate of fatigue crack growth in metallic materials. British Standards Institution BS 6835, 1988.

14. NEWMAN, J.C. Jr. Short-crack growth behaviour in an aluminum alloy – an AGARD
EDWARDS, P.R. cooperative test programme. AGARD-R-732, 1988.

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_b MN/m ² (10 ³ lbf/in ²)	
IMI 318	Ti-6Al-4V -0.17O -0.15Fe	Details not provided	960 (139)	890 (129)	Details not provided	1
	Ti-6.43Al-4.02V -0.19Fe-0.01C -0.205O-0.007Sn -0.002H	Mill annealed at 700°C and air cooled	Details not provided	898 (130)	Details not provided	2
Ti-6Al-4V	Ti-6Al-4V-0.3Fe -0.1C	Annealed	970 (141)	920 (133)	Details not provided	3, 4
	Ti-6.3Al-4.2V -0.2O-0.145Fe -0.02C-0.017N -0.005H	Recrystallised, water quenched, aged for 12 h at 500°C, machined and aged for 12 h	1590 (231)	Details not provided	1063 (154)	5
Ti-4Al	Ti-4.18Al	Details not provided	625 (90.6)	548 (79.5)	Details not provided	6
IMI 685	Ti-6Al-5Zr -0.5Mo-0.25Si -0.1Fe	Details not provided	800 (116)	780 (113)	Details not provided	7
Ti-6Al-2Sn-4Zr-6Mo	Ti-6.63Al -2.07Sn-3.93Zr -5.76Mo	Details not provided	1232 (179)	1160 (168)	Details not provided	8
Ti-8Al	Ti-7.7Al	Solution treated and quenched	759 (110)	673 (97.6)	Details not provided	9
Ti-8.6Al	Ti-8.6Al-0.07O -0.07Fe-0.02C -0.017H-0.01N	Recrystallised, water quenched, aged for 5 h at 500°C, machined, aged for 5 h	973 (141)	Details not provided	777 (113)	10, 11

* As quoted in the relevant derivation.

TABLE 6.2 GUIDE TO FIGURE 1

Material: IMI 318					
Curve No. (Symbol)	Derivation No.	Stress ratio, R	Orientation	Crack type	Notes
1 (X)	3	0.1	—	Short	10 mm (0.39 in) square smooth bars loaded in four point bending with maximum load between 80 and 100 per cent of monotonic 0.2 per cent proof strength, semi-circular cracks, crack length monitored by plastic replica technique
2 (O)	3	0.1	—	Long	Deep notched specimens, crack length measured using direct current potential drop technique

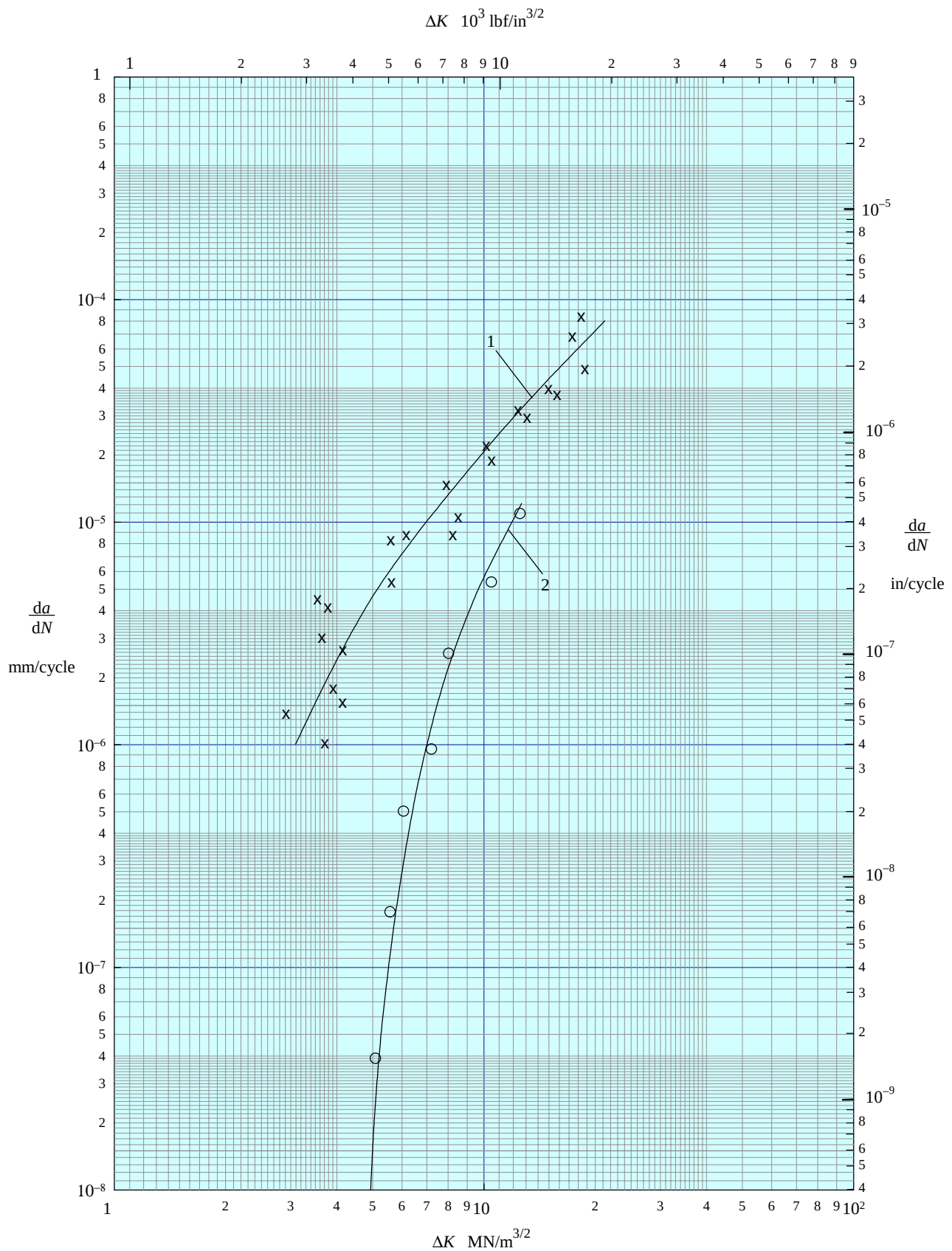


FIGURE 1 IMI 318