

FATIGUE CRACK PROPAGATION RATES OF EXPERIMENTAL ALUMINIUM LITHIUM SHEET AND PLATE 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, $da/dN = C(\Delta K)^n$	$m(m^{3/2}/N)^n$	$in(in^{3/2}/lbf)^n$
E	modulus of elasticity of material	N/m^2	lbf/in^2
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_c	critical value of stress intensity factor (also plane stress fracture toughness)	$N/m^{3/2}$	$lbf/in^{3/2}$
K_{Ic}	plane strain fracture toughness in Mode I	$N/m^{3/2}$	$lbf/in^{3/2}$
K_{max}	maximum value of K in fatigue cycle	$N/m^{3/2}$	$lbf/in^{3/2}$
ΔK	stress intensity factor range defined as $(S_{max} - S_{min})(\pi a)^{1/2}\alpha$	$N/m^{3/2}$	$lbf/in^{3/2}$
ΔK_{TH}	threshold value of ΔK	$N/m^{3/2}$	$lbf/in^{3/2}$
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 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 General

This Data Item presents constant amplitude fatigue crack propagation rate (da/dN) data for a collection of experimental aluminium lithium alloys in unclad sheet or plate form. Data are presented for the alloys in various heat treated conditions in a range of environments. Mode I linear elastic fracture mechanics behaviour is assumed throughout (as described in Data Item No. 80036^{*}).

Aluminium lithium alloys have two major advantages over many conventional, national specification aluminium alloys in widespread usage; these are a higher elastic modulus and a lower density. These advantages are particularly valuable in aerospace applications and other applications where weight is critical. As aluminium lithium alloys are still in development, this Item presents data on experimental alloys for which, at the time of publication, full specifications do not exist. Therefore, the specifications to which the materials have been prepared are subject to change and, where nominally the same, may in fact differ from one set of data to another. For example, the production route of 8090-T6 may not be the same for batches produced at different sources. The production of these alloys continues to be a subject of research and the degree to which consistently repeatable properties may be obtained will vary. Experimental versions of alloys are often obtained from small batches that are heat treated under laboratory control conditions. The resulting properties may or may not be achievable in mass production. Therefore, the properties of material used in the tests from which the data in this Item are derived may, in some cases, differ from those of material that is nominally the same. Nevertheless, the data provided in this Item give useful information on the crack propagation behaviour of aluminium lithium alloys currently in development.

Most of the data are from tests performed in dry air. However, data are provided for other environments. The chemical composition and mechanical properties of the materials, where these are given in the derivations, are set out in the table of mechanical data in Table 6.2. A complete list of the materials and environments for which data are provided and their locations is given in the index to the figures in Table 6.1. Difficulty may arise in relating these laboratory environments to real conditions.

2.2 Presentation of Data

Data on experimental versions of four aluminium lithium alloys are presented in Figures 1 to 18. All the data are for specimens with long cracks subject to constant amplitude loading. 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 source. None of the curves has been extrapolated beyond the range of the available data. A table providing details on relevant testing conditions accompanies each figure. The conventions 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 ΔK (see Sketch 2.1). Therefore, ΔK is given by:

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

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



Sketch 2.1 Illustration of ΔK used in Figures 1 to 18

Some sources, for example where the tests are carried out to BS 6835, use only the tensile part of the fatigue cycle in the calculation of ΔK for the tests with a negative stress ratio value:

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

When comparing data from other sources with negative stress ratio values with the data presented in this Item, care must be taken to ensure that the ΔK values are calculated using the same method. The effect of the stress ratio is discussed in Section 3.3.

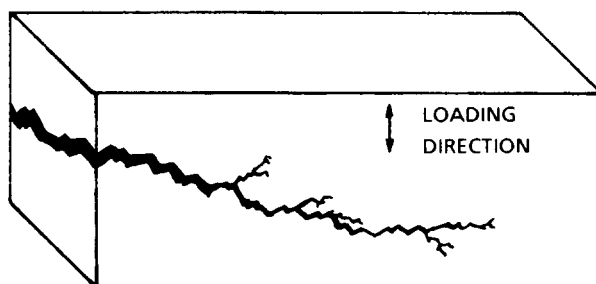
It should be noted that the number of specimens used to generate the data for the curves differs; some curves are based on data from a single test specimen. No estimates of scatter between tests or batch-to-batch variability of material have been possible. Small differences between curves should be treated with caution. The curves should not necessarily be considered exact mean curves.

3. NOTES ON CRACK GROWTH RATE IN ALUMINIUM LITHIUM ALLOYS

3.1 General

Constant amplitude crack propagation rates in the aluminium lithium alloys investigated compare favourably with the rates found in conventional aluminium alloys (see Data Item Nos. 83007 and 88007*). At low values of stress ratio, R , and low to intermediate values of stress intensity factor range, ΔK , the crack propagation rates of aluminium lithium alloys are often markedly lower than those of conventional aluminium alloys. The relatively low Mode I crack propagation rates of the aluminium lithium alloys are due largely to the fact that at the microscopic level cracks deviate and form branching crack paths as shown in Sketch 3.1. Because of the deviating crack paths, cracks grow under mixed loading. However, most analyses treat the crack growth as Mode I and in this Item all the data are based on assumed Mode I behaviour. The tortuous crack paths and the high levels of fracture debris produce higher levels of crack closure than those found in conventional aluminium alloys. The high level of crack closure reduces the effective ΔK and thus reduces the crack propagation rate.

* Data Item No. 83007 "Fatigue crack propagation rates and threshold stress intensity factor ranges for aluminium alloy sheet".
Data Item No. 88007 "Effect of environment on fatigue crack propagation in aluminium alloy sheet and plate".



Sketch 3.1 View of a typical fatigue crack in an aluminium lithium alloy

3.2 Effect of Microstructure

It is not possible to quantify accurately the effect of microstructure on crack propagation rates in aluminium lithium alloys. But it should be noted that features such as texture, degree of recrystallisation, degree and type of precipitate and grain size can all significantly alter the crack propagation rate. Figure 17, for example, shows how altering the heat treatment and hence the microstructure can affect the crack propagation rate for one particular aluminium lithium alloy.

3.3 Effect of Stress Ratio, R

As is the case for other aluminium alloys, increasing the stress ratio, R , for any given value of ΔK , results in higher crack propagation rates in aluminium lithium alloys (see for example Figure 10). Raising the mean stress level reduces the amount of crack closure and therefore reduces the effect of crack closure on the crack propagation rates in aluminium lithium alloys.

3.4 Effect of Environment

Lithium is a very reactive element. But tests have shown that the corrosion resistance of the aluminium lithium alloys 2090, 2091 and 8090 can be at least equivalent to that of 2024 and 7075 with a similar temper (which are the alloys most likely to be in competition with the aluminium lithium alloys). [Stress corrosion resistance can be low in certain cases, notably in the short transverse direction of thick T651 plate. Aluminium lithium alloys appear to be more susceptible to pitting corrosion than are conventional aluminium alloys (see Reference 25).]

4. CALCULATION OF CRACK GROWTH

The growth of a crack over a number of cycles may be estimated by integrating the crack growth rate curves given in Figures 1 to 18. This may easily be done over the linear portion of the curve which may be represented by the simple crack growth equation

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

As an example, values of C and n have been provided in the table accompanying Figure 18. These values are only valid for the specified range of ΔK . Some curves may have no portion which may be usefully approximated linearly. The user's attention is drawn again to the fact that the curves presented are only for experimental alloys.

Examples of the use of this method are given in Data Items 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 estimate 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 selected sources that have been of assistance in the preparation of this Data Item.

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* 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 calculation".
Data Item No. 84003 "Fatigue crack propagation rates and threshold stress intensity factors in high alloy and corrosion resistant (stainless) steel".

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5.2 References

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

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6. TABLES AND FIGURES

TABLE 6.1 INDEX TO FIGURES

<i>Material</i>	<i>Temper designation</i>	<i>Material form *</i>	<i>Environment</i>	<i>Figure number (Curve number)</i>	<i>Derivation number</i>
2090	T8E41	sheet	laboratory air	1 (1, 2, 3)	14
			air	2 (1, 2, 3)	20
2090	T8E41	plate	air	3 (1)	2
			salt water	3 (2)	2
2090	T83	sheet	high humidity air, relative humidity = 90%	4 (1)	20
2090	T81	plate	high humidity air, relative humidity = 90%	4 (2)	20
2091	T8	sheet	air	5 (1, 2, 3)	19
				6 (1, 2)	19
				7 (1)	19
				7 (3)	22
				8 (1, 2, 3)	19
2091	T3	sheet	air	7 (2)	22
2091	T8X	sheet	air	7 (4)	22
8090	T651	plate	air	9 (1, 2, 3, 4, 5)	4
				10 (1, 2)	4
				11 (1, 2, 3, 4)	23
				16 (2)	4
				17 (2)	4
8090	T6	sheet	air	12 (1, 2)	19
8090	T6	plate	3.5% NaCl solution	13 (1, 2, 3, 4)	7
			air	14 (1, 2, 3, 4)	7
8090	peak aged	plate	air	15 (1)	6
8090	overaged	plate	air	15 (2, 3)	6
				16 (3)	4
				17 (3)	4
8090	underaged	plate	air	16 (1)	4
				17 (1)	4
CP271	T651	plate	dry argon	18 (3)	8
			laboratory air	18 (1, 4, 5)	8
			distilled water	18 (2)	8

* All sheet is unclad.



TABLE 6.2 GUIDE TO MATERIALS

Material	Temper designation	Form	Chemical composition per cent by weight										Properties			Figure number (Curve number) [Derivation number]
			Cu	Li	Mg	Mn	Fe	Si	Zn	Ti	Zr	Cr	f_t (MN/m ²) (10 ³ lbf/in ²)	f_p (MN/m ²) (10 ³ lbf/in ²)	E (GN/m ²) (10 ⁶ lbf/in ²)	
2090	T8E41	sheet	3.0	2.6	0.25	0.05	0.12	0.1	0.1	0.15	0.15	0.05	580 (84)	525 (76)	-	1 (1, 2, 3) [14]
2090	T8E41	sheet	2.4 - 3.0	1.9 - 2.6	0.25	0.05	0.12	0.08	0.1	0.15	0.08 - 0.16	0.05	-	-	-	2 (1, 2, 3) [20]
2090	T8E41	plate	2.4 - 3.0	1.9 - 2.6	0.25 max	0.05 max	0.12 max	0.1 max	0.1	0.15 max	0.08 - 0.15	-	554 (L) (80) 551 (T) (80)	517 (L) (75) 518 (T) (75)	78.6 (L) (1139) 78.9 (T) (1144)	3 (1, 2) [2]
2090	T83	sheet	-	-	-	-	-	-	-	-	-	-	-	-	-	4 (1) [20]
2090	T81	plate	-	-	-	-	-	-	-	-	-	-	-	-	-	4 (2) [20]
2091	T8	sheet	1.8 - 2.5	1.7 - 2.3	1.1 - 1.9	0.1	0.3	0.2	0.25	0.1	0.04 - 0.16	0.1	-	-	-	5 (1, 2, 3) [19] 6 (1, 2) 7 (1) 8 (1, 2, 3)
2091	T8	sheet	1.8 - 2.5	1.7 - 2.3	1.1 - 1.9	0.1 max	0.3 max	0.2 max	0.25 max	0.1 max	0.04 - 0.16	0.1 max	450 (L) (65) 462 (T) (67)	351 (L) (51) 325 (T) (47)	-	7 (3) [22]
2091	T3	sheet	1.8 - 2.5	1.7 - 2.3	1.1 - 1.9	0.1 max	0.3 max	0.2 max	0.25 max	0.1 max	0.04 - 0.16	0.1 max	431 (L) (63) 447 (T) (65)	337 (L) (49) 301 (T) (44)	-	7 (2) [22]
2091	T8X	sheet	2.1	1.8	1.6	-	0.04	0.03	-	0.02	0.07	-	462 (L) (67) 450 (T) (62)	331 (L) (48) 314 (T) (46)	-	7 (4) [22]
8090	T651	plate	-	-	-	-	-	-	-	-	-	-	-	-	-	9 (1, 2, 3, 4, 5) [4] 10 (1, 2) 16 (2) 17 (2)

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TABLE 6.2 GUIDE TO MATERIALS

Material	Temper designation	Form	Chemical composition per cent by weight										Properties			Figure number (Curve number) [Derivation number]
			Cu	Li	Mg	Mn	Fe	Si	Zn	Ti	Zr	Cr	f_t (MN/m ²) (10 ³ lbf/in ²)	f_p (MN/m ²) (10 ³ lbf/in ²)	E (GN/m ²) (10 ⁶ lbf/in ²)	
8090	T651	plate ¹	-	-	-	-	-	-	-	-	-	-	469 (L) (68) 474 (T) (69)	417 (L) (60) 389 (T) (56)	-	11 (1, 2, 3, 4) [23]
		plate ²	-	-	-	-	-	-	-	-	-	-	514 (L) (75) 526 (T) (76)	474 (L) (69) 469 (T) (68)	-	11 (1, 2, 3, 4) [23]
8090	T6	sheet	1.0 - 1.4	2.3 - 2.6	0.5 - 0.9	0.10	0.3	0.2	0.25	0.1	0.10 - 0.14	0.1	-	-	-	12 (1, 2) [19]
8090	T6	plate	1.19	2.5	0.67	-	-	-	-	-	0.1	-	442 (L) (64) 458 (T) (66)	345 (L) (50) 369 (T) (54)	-	13 (1, 2, 3, 4) [7] 14 (1, 2, 3, 4)
8090	peak aged	plate	1.1 - 1.7	2.2 - 2.8	0.7 - 1.3	-	0.3 max	-	-	-	0.08 - 0.16	-	548 (79)	512 (74)	-	15 (1) [6]
8090	underaged	plate	-	-	-	-	-	-	-	-	-	-	-	-	-	16 (1) [4] 17 (1)
8090	overaged	plate	-	-	-	-	-	-	-	-	-	-	-	-	-	16 (3) [4] 17 (3)
8090	overaged	plate	1.1 - 1.7	2.2 - 2.8	0.7 - 1.3	-	0.3 max	-	-	-	0.08 - 0.16	-	499 (72)	430 (62)	-	15 (2, 3) [6]
CP271	T651	plate	1.3	2.5	1.0	-	0.02	-	0.25 max	-	0.09	-	-	-	-	18 (1, 2, 3, 4, 5) [8]

Notes

All values in this table are taken from the derivations. A dash indicates no values are specified. (L) indicates a longitudinal value and (T) indicates a transverse value.

1 surface specimens.

2 core specimens.

TABLE 6.3 GUIDE TO FIGURE 1

Material: 2090						
<i>Curve number</i>	<i>Derivation number</i>	<i>Stress ratio, R</i>	<i>Environment</i>	<i>Temper designation</i>	<i>Material form</i>	<i>Orientation</i>
1	14	0	laboratory air	T8E41	2.3 mm (0.09 in) sheet	L – T
2	14	–1	laboratory air	T8E41	2.3 mm (0.09 in) sheet	L – T
3	14	–2	laboratory air	T8E41	2.3 mm (0.09 in) sheet	L – T

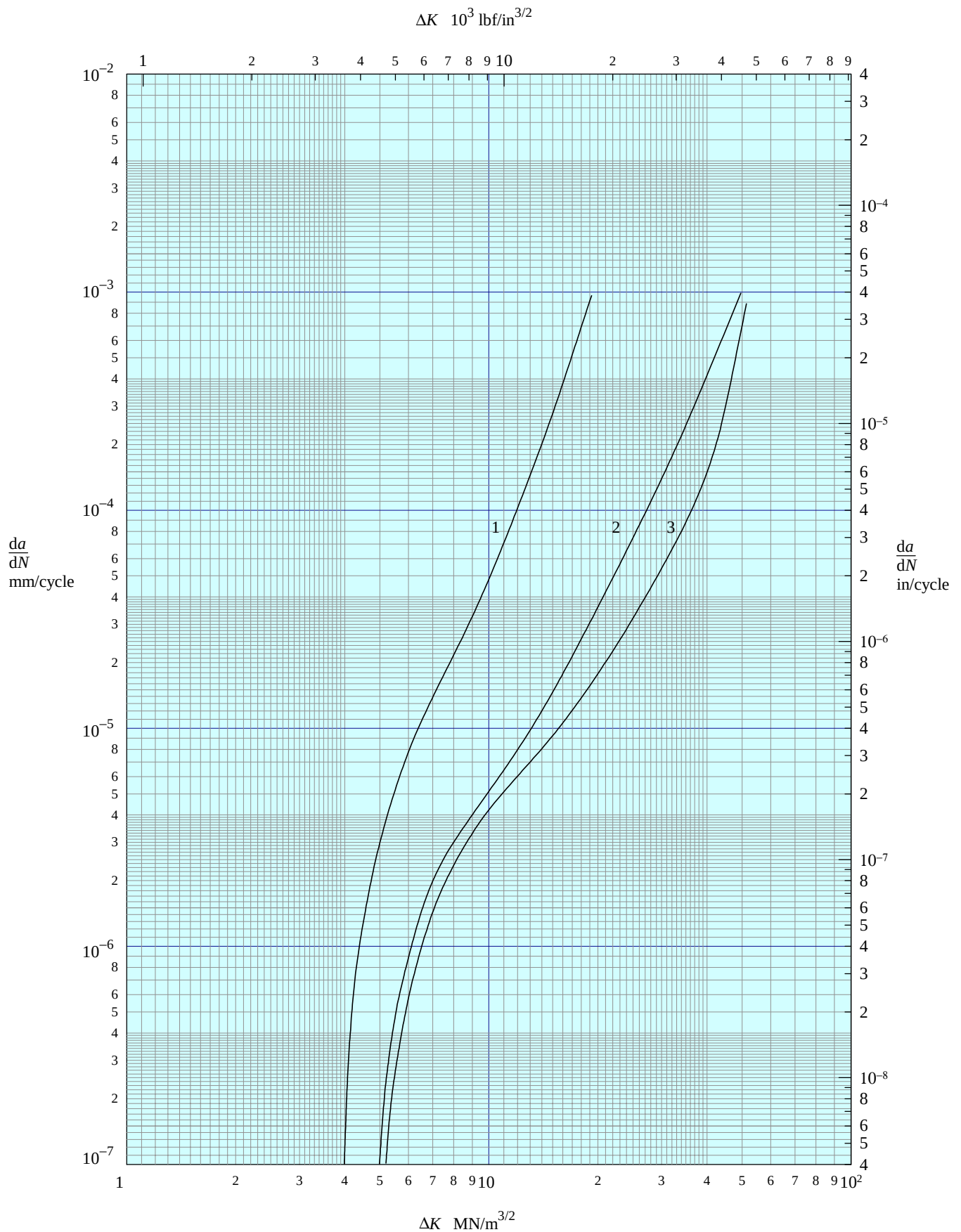


FIGURE 1 2090-T8E41 SHEET

TABLE 6.4 GUIDE TO FIGURE 2

Material: 2090						
Curve number	Derivation number	Stress ratio, R	Environment	Temper designation	Material Form	Orientation
1	20	0.1	air	T8E41	1.6 mm (0.06 in) sheet	L – T
2	20	0.2	air	T8E41	1.6 mm (0.06 in) sheet	L – T
3	20	0.4	air	T8E41	1.6 mm (0.06 in) sheet	L – T

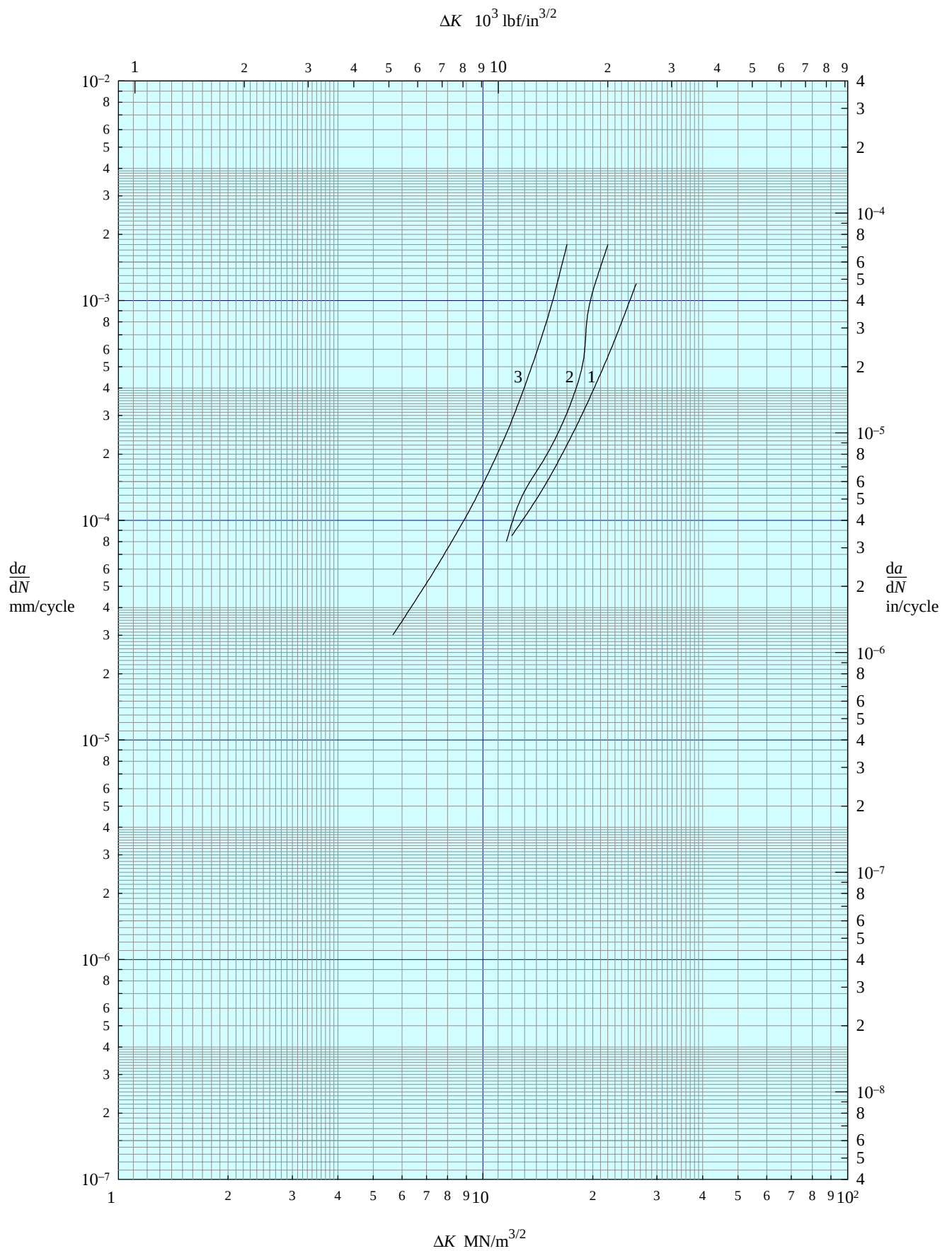


FIGURE 2 2090-T8E41 SHEET

TABLE 6.5 GUIDE TO FIGURE 3

Material: 2090						
Curve number	Derivation number	Stress ratio, R	Environment	Temper designation	Material Form	Orientation
1	2	0.1	air	T8E41	12.7 mm (0.5 in) plate	L – T
2	2	0.1	salt water	T8E41	12.7 mm (0.5 in) plate	L – T