

EFFECT OF ENVIRONMENT ON FATIGUE CRACK PROPAGATION RATE IN TITANIUM ALLOY SHEET AND PLATE

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
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 a fatigue cycle	N/m ^{3/2}	lbf/in ^{3/2}
ΔK	stress intensity factor range	N/m ^{3/2}	lbf/in ^{3/2}
ΔK_{SCC}	value of ΔK at onset of cyclic stress corrosion	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 value of S in fatigue cycle	N/m ²	lbf/in ²
S_{min}	minimum value of S in fatigue cycle	N/m ²	lbf/in ²
α	geometrical factor in stress intensity factor expression		

1.1 Additional Notation for Test Specimens

SEN	single edge notched
WOL	wedge opening loaded

2. NOTES

2.1 General

This Data Item presents fatigue crack propagation rate (da/dN) data for titanium alloys in a variety of environmental conditions. Linear elastic fracture mechanics behaviour is assumed, as described in Data Item No. 80036*. The data presented refer to titanium alloy sheet and plate. The most common test environments for which data are provided are vacuum, dry argon, ambient air, distilled water and salt water. Limited data are also presented for aqueous KBr solutions and aqueous methanol-HCl solutions. A complete list of all the materials and environments for which data are presented and their location is given in Table 6.2

Difficulty may arise in relating these laboratory environments to real conditions. In many applications the laboratory environments represent overly harsh conditions. Thus, the fatigue crack propagation curves, presented in this Item, may predict higher crack growth rates (and hence shorter crack growth lives) than those that may be obtained in service.

In the uncracked state, the fatigue strengths of titanium alloys are, in general, unaffected by environment, due to the formation of protective oxide films (passivation). However, in environments such as a methonal-HCl solution where these films become degraded and provide less protection, the fatigue strengths of titanium alloys are markedly reduced. The environment can have a significant influence on fatigue crack propagation rates of cracked titanium alloy specimens. The magnitude of this environmental effect depends upon many factors including the environment, the alloy type and the applied loading. The main environments, for which data are presented in this Item, can be ranked in terms of increasing severity, and hence increasing crack growth rates, as follows:

vacuum,
air,
distilled water and
salt water.

2.2 Presentation of Data

Data on 6 alloys subject to constant amplitude loading in various environments are presented in Figures 1 to 19. In all the tests the loading cycle was a sine wave. In some cases data are provided for several heat treatments of one alloy. The data are presented as curves of crack propagation rate against stress intensity factor range, that is da/dN against ΔK . These 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. The values of stress ratio, R , and loading frequency are noted. A table providing details on relevant testing conditions accompanies each figure.

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

It should be noted that the number of test specimens used to generate the data for the curves differs; some curves are based on data from a single test specimen. No estimate has been made of the scatter between tests or of the batch-to-batch variability of material. For these reasons, small apparent differences between curves should be treated with caution and the curves should not be considered mean curves for the material.

3. NOTES ON CRACK GROWTH RATE

3.1 Frequency Effects

Titanium alloys subjected to constant amplitude loading display three distinct types of environmental fatigue crack propagation rate behaviour. The first type of behaviour (Sketch 3.1a) is frequency independent and is associated with relatively inert environments such as argon, vacuum and dry air.

The second type of behaviour (Sketch 3.1b) is frequency dependent. The crack growth rate increases with decreasing frequency. The degree of frequency dependence is largely influenced by the environment. In distilled water, crack propagation rates are not changed greatly by changes in loading frequency (see Figure 17) but in methanol-HCl solutions a strong dependence on the loading frequency is evident (see Figure 16).

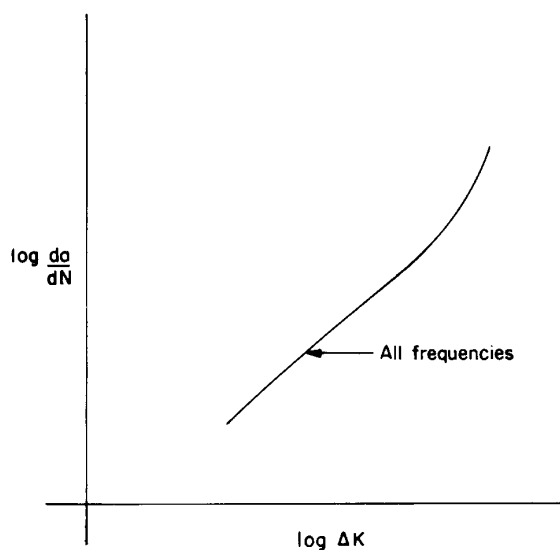
The third type of behaviour (Sketches 3.1c and d) is associated with cyclic stress corrosion and is also frequency dependent. At high values of ΔK the frequency dependence is the same as that of the second type of behaviour, that is, the crack growth rate increases with decreasing frequency. At intermediate values of ΔK there is a reversal of frequency dependence. This reversed frequency dependence is either maintained to low ΔK values (Sketch 3.1c) or changes to frequency independence (Sketch 3.1d). This transition in frequency dependence is associated with the onset of cyclic stress corrosion cracking. The value of ΔK at which this occurs is denoted ΔK_{SCC} and in some cases (particularly at low frequencies) is marked by an abrupt change in crack growth rate. This type of crack growth behaviour is found in aggressive aqueous environments such as NaCl and KBr solutions (see Figure 3).

At low ΔK values in aggressive aqueous environments, the resistance to fatigue crack propagation is largely determined by the rate of passivation of the freshly exposed metal. At low frequencies, the passivation of exposed metal tends to be more complete than at high frequencies where there is insufficient time for complete passivation of the freshly exposed metal to occur. Therefore, at low ΔK values fatigue crack propagation rates at high frequencies may be higher than those at low frequencies. At values of ΔK greater than ΔK_{SCC} , stress corrosion cracking tends to dominate the rate of fatigue crack propagation. At low frequencies, there is a larger increment of stress corrosion cracking per cycle than at high frequencies. Therefore, when ΔK is greater than ΔK_{SCC} the fatigue crack propagation rates at low frequencies tend to be higher than those at high frequencies. At values of ΔK such that K_{max} approaches the fracture toughness of the material the influence of environment on fatigue crack growth rates is significantly reduced (see for example Figures 9 and 14).

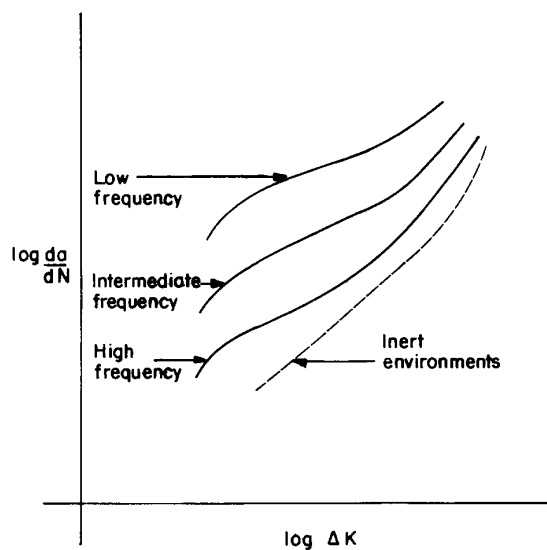
3.2 Stress Ratio and Grain Orientation Effects

The data show that increasing the stress ratio, R , has the same general effect in corrosive environments as in inert environments; it raises the crack propagation rate for a given value of ΔK . Within the region of environmental sensitivity, environmental effects are more pronounced at high values of R .

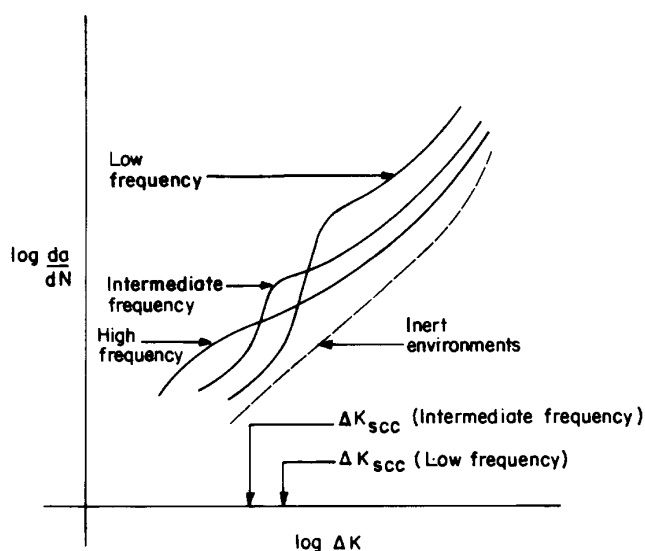
The effect of grain orientation varies among the various alloys. Specimens of Ti-6Al-4V, tested in a 3.5 per cent NaCl aqueous solution, show large variations in crack growth rate between the T–L orientation and the L–T orientation (Figure 2). Transverse and longitudinal specimens of IMI 130, tested in a 3.5 per cent NaCl aqueous solution, do not show significant differences in crack growth rates (Figures 12 and 13). No data are presented for specimens stressed in the short transverse orientation. Variations in the crack growth rates in different orientations may be related to the differences in modulus values in the different orientations and to the texture. For a given specimen, loading in the direction of the highest elastic modulus will usually produce the lowest crack growth rates. Large grain sizes can reduce the fatigue crack growth rates in many situations. It has been shown that β -annealing (which results in a Widmanstätten microstructure) produces a texture that is particularly resistant to fatigue crack growth (References 7, 9 and 11).



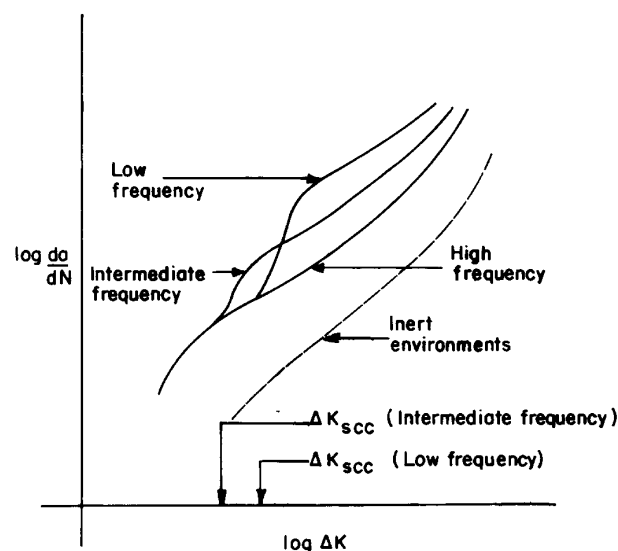
(a) Inert environments



(b) Mildly aggressive environments



(c) Aggressive aqueous environments



(d) Aggressive aqueous environments

The stress ratio, R , is the same value for all curves.

Sketch 3.1 Idealised Fatigue Crack Propagation Behaviour for Titanium Alloys

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 19. This may be easily done over the linear portion of the curve which may be represented by the Paris equation

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

Where possible, values of C and n have been provided in the tables accompanying the figures. These values are only valid for the specified range of ΔK . Some of the curves have no portion which may be usefully approximated linearly.

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 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 assisted in the preparation of this Data Item.

1. PIPER, D.E. Corrosion fatigue and stress corrosion cracking in aqueous environments. *Met. Eng. Quart.*, pp. 50 – 63, ASM, August 1968.
SMITH, S.H.
CARTER, R.V.
2. WANHILL, R.J.H. Environment and frequency effects during fatigue crack propagation in Ti-2.5Cu (IMI 230) sheet at room temperature. *Corrosion*, Vol. 30, No. 1, January 1974.
3. DAWSON, D.B. Corrosion fatigue crack growth of titanium alloys in aqueous environments. *Metall. Trans*, Vol. 5, pp. 723-731, March 1974.
PELLOUX, R.M.
4. WANHILL, R.J.H. Environmental fatigue crack propagation in medium strength titanium sheet alloys. *Engng fracture Mech.*, Vol. 6, pp. 681-697, 1974.
5. WANHILL, R.J.H. Environmental fatigue crack propagation in Ti-6Al-4V sheet. *Metall. Trans A.*, Vol. 7A, pp. 1365-1373, September 1976.
6. DÖKER, H. Influence of environment on the fatigue crack propagation of two titanium alloys. In: *The Influence of Environment on Fatigue*, pp. 123-130, I. Mech. E. Conference publications, 1977.
MUNZ, D.
7. WANHILL, R.J.H. The Influence of texture on environmental fatigue crack propagation in titanium alloys. In: *Textures of Materials*, Vol II, Aachen, Germany, 28 - 31 March 1978. Berlin – Heidelberg, 1978.

* 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)'.

8. WANHILL, R.J.H. Corrosion fatigue in titanium alloys. Seeco '79, Proc. Society of Environmental Engineers Conference, Vol. 5, pp. 104-127, London, May 1979.
9. YODER, G.R.
COOLEY, L.A.
CROOKER, T.W. Improvement of environmental crack propagation resistance in Ti-8Al-1Mo-1V through microstructural modifications. In: Advances in Material Technology in the Americas, Vol. 2, Materials Processing and Performance, ASME, 1980.
10. DAWSON, D.B. Fatigue crack growth behaviour of Ti-6Al-6V-2Sn in methanol and methanol-water solutions. *Metall. Trans A.*, Vol. 12A, pp 791-800, May 1981.
11. YODER, G.R.
COOLEY, L.A.
CROOKER, T.W. Effects of microstructure and frequency on corrosion-fatigue crack growth in Ti-8Al-1Mo-1V and Ti-6Al-4V. *Corrosion fatigue : mechanics, metallurgy, electrochemistry, and engineering*. ASTM STP 801, pp. 159-174, 1985.

5.2 References

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

12. PARIS, P.
ERDOGAN, F. A critical analysis of crack propagation laws. *Trans. am. Soc. mech. Engrs, J. bas. Engng*, Vol. 85, Series D, No. 4, 1963.
13. PARIS, P. The fracture mechanics approach to fatigue. In: *Fatigue an interdisciplinary approach*, Syracuse University Press, New York, USA, 1964.
14. MEYN, D.A. An analysis of frequency and amplitude effects on corrosion fatigue crack propagation in Ti-8Al-1Mo-1V. *Metall. Trans*, Vol. 2, pp. 853-865, March 1971.
15. RITCHIE, R.O. Role of the environment in near-threshold fatigue crack growth in engineering materials. In: *Environment-sensitive Fracture of Engineering Materials*. Proc. Conf. Chicago, October 1977.

6. TABLES AND FIGURES

TABLE 6.1 GUIDE TO MATERIAL PROPERTIES*

<i>Alloy</i>	<i>Orientation</i>	f_p MN/m ² (lbf/in ²)	f_t MN/m ² (lbf/in ²)	E GN/m ² (lbf/in ²)
Ti-6Al-4V sheet	Transverse	1043 (151 × 10 ³)	1110 (161 × 10 ³)	133 (192 × 10 ⁵)
	Longitudinal	846 (123 × 10 ³)	919 (133 × 10 ³)	103 (149 × 10 ⁵)
Ti-6Al-4V plate (β-anneal)	Transverse	869 (126 × 10 ³)	958 (139 × 10 ³)	117 (170 × 10 ⁵)
Ti-6Al-4V plate (Mill anneal)	Transverse	1007 (146 × 10 ³)	1034 (150 × 10 ³)	130 (189 × 10 ⁵)
Ti-8Al-1Mo-1V plate (Duplex anneal)	Transverse	958 (139 × 10 ³)	1025 (149 × 10 ³)	136 (197 × 10 ⁵)
	Longitudinal	943 (138 × 10 ³)	986 (143 × 10 ³)	not specified
Ti-8Al-1Mo-1V plate (β-anneal)	Transverse	794 (115 × 10 ³)	894 (130 × 10 ³)	128 (186 × 10 ⁵)
	Longitudinal	803 (116 × 10 ³)	901 (131 × 10 ³)	not specified
Ti-70 [†] sheet	Transverse	510 (74 × 10 ³)	617 (89 × 10 ³)	111 (161 × 10 ⁵)
	Longitudinal	498 (72 × 10 ³)	616 (89 × 10 ³)	107 (155 × 10 ⁵)
IMI 130 [‡] sheet	Transverse	400 (58 × 10 ³)	518 (75 × 10 ³)	106 (154 × 10 ⁵)
	Longitudinal	392 (57 × 10 ³)	530 (77 × 10 ³)	106 (154 × 10 ⁵)
Ti-6Al-6V-2Sn sheet	Transverse	1100 (160 × 10 ³)	1170 (169 × 10 ³)	not specified
Ti-2.5Cu sheet	Transverse	692 (100 × 10 ³)	757 (110 × 10 ³)	111 (161 × 10 ⁵)
	Longitudinal	646 (94 × 10 ³)	757 (110 × 10 ³)	106 (154 × 10 ⁵)

* The values quoted are those given in the derivations.

† Commercially pure titanium with high oxygen content.

‡ Commercially pure titanium with low oxygen content.

TABLE 6.2 INDEX TO FIGURES

<i>Alloy</i>	<i>Heat treatment</i>	<i>Orientation</i>	<i>Environment</i>	<i>Figure no. (curve no.)</i>
Ti-6Al-4V sheet	High ($\alpha + \beta$) anneal, air cool	L – T	vacuum	1 (1)
			air	1 (3)
	High ($\alpha + \beta$) anneal, water quenched and aged	L – T	vacuum	1 (2)
			air	1 (4)
	Mill anneal	T – L	distilled water	2 (1)
			aqueous NaCl solution	2 (3)
		L – T	distilled water	2 (2)
			aqueous NaCl solution	2 (4)
		T – L	aqueous NaCl solution	3 (1, 2, 3)
Ti-6Al-4V plate	β -anneal	T – L	aqueous NaCl solution	4 (1, 2)
	Mill anneal	T – L	vacuum	5 (1)
			air	5 (2)
			aqueous NaCl solution	5 (3, 4)
Ti-8Al-1Mo-1V plate	β -anneal	T – L	air	6 (1)
			aqueous NaCl solution	6 (2, 3), 8 (1, 2)
	Duplex anneal	T – L	vacuum	7 (1)
			air	7 (2, 3)
			aqueous NaCl solution	7 (4, 5), 8 (3, 4)
Ti-70 sheet		L – T	dry argon	9 (1), 10 (1)
			air	9 (2), 10 (2)
			distilled water	9 (3), 10 (3)
			aqueous NaCl solution	9 (4, 5), 10 (4), 11 (1, 2, 3)

TABLE 6.2 INDEX TO FIGURES

IMI 130 sheet		L – T	air	12 (1)
			distilled water	12 (2)
			aqueous NaCl solution	12 (3, 4, 5)
		T – L	air	13 (1)
			distilled water	13 (2)
			aqueous NaCl solution	13 (3, 4, 5)
Ti-6Al-6V-2Sn sheet	Mill-anneal and 760°C anneal	T – L	aqueous NaCl solution	14 (1, 2, 3, 4, 5)
	Mill anneal	T – L	aqueous KBr solution	15 (1, 2)
			aqueous (methanol + 0.5% HCl) solution	16 (1, 2, 3)
Ti-2.5Cu sheet	Solution treated and aged	L – T	air	17 (1)
			distilled water	17 (2, 3)
			aqueous NaCl solution	18 (1, 2, 3, 4)
		T – L	air	19 (1)
			distilled water	19 (2)



TABLE 6.3 GUIDE TO FIGURE 1

MATERIAL: Ti-6Al-4V, 10 mm (0.394 in) thick sheet, high ($\alpha + \beta$) anneal								
Curve No.	Derivation number	Stress ratio, R	Environment	Test frequency (Hz)	Range of ΔK $\text{MN}/\text{m}^{3/2}$ $(10^3 \text{ lbf}/\text{in}^{3/2})$	n	$\frac{C}{m(m^{3/2}/\text{MN})^n}$ $[\text{in}(\text{in}^{3/2}/10^3 \text{ lbf})^n]$	Notes
1	7	0.35	Vacuum (1.33 mPa)	100	$7.8 \rightarrow 8.4$ $(7.1 \rightarrow 7.6)$	40	2.8×10^{-45} (5.0×10^{-42})	Air cool, L – T orientation
2	7	0.35	Vacuum (1.33 mPa)	100	$6.6 \rightarrow 8$ $(6.0 \rightarrow 7.3)$	14	1.4×10^{-18} (1.7×10^{-16})	Water quench and age, L – T orientation
3	7	0.35	Air	100	–	–	–	Air cool, L – T orientation
4	7	0.35	Air	100	–	–	–	Water quench and age, L – T orientation

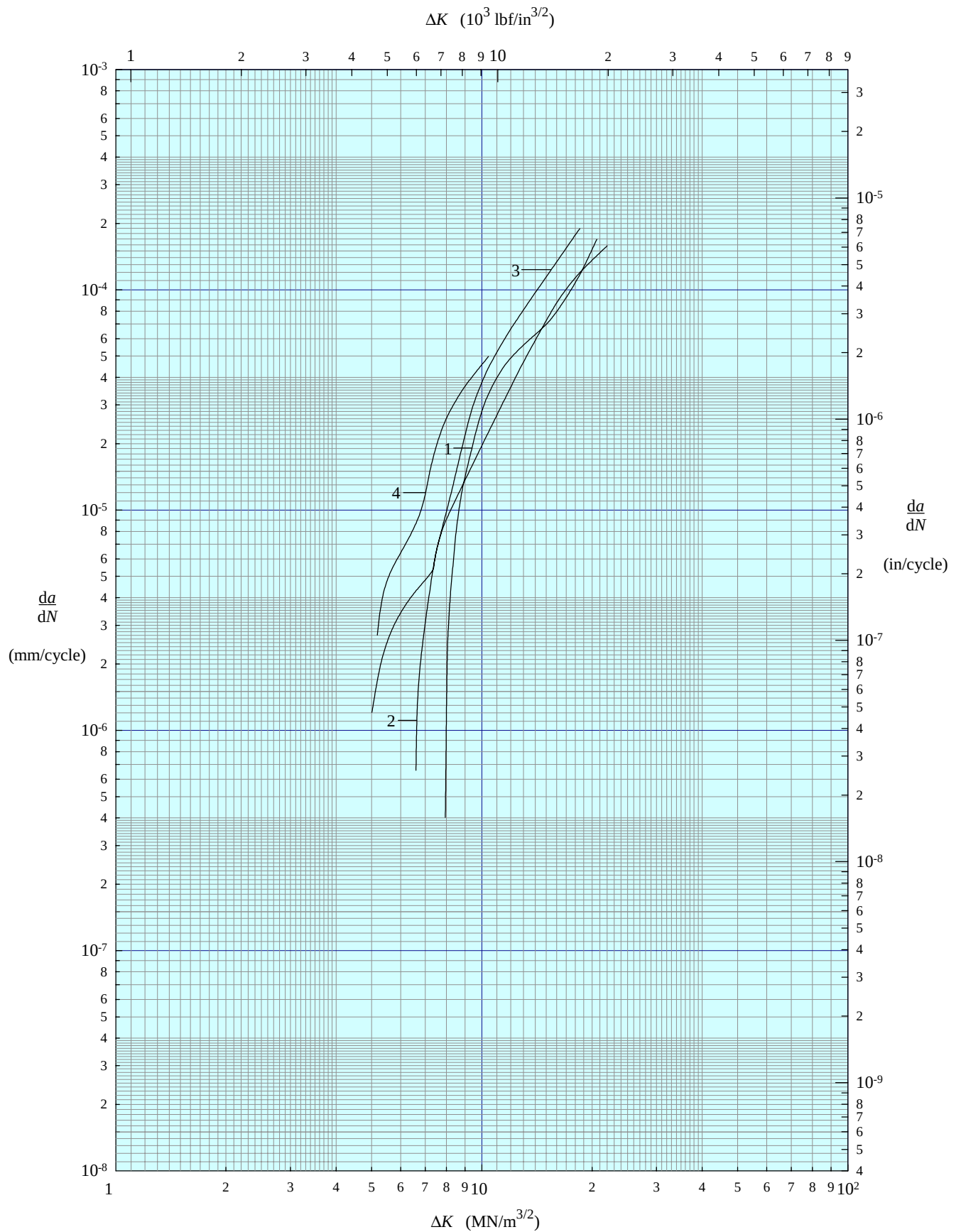


FIGURE 1 Ti-6Al-4V, ($\alpha + \beta$) ANNEALED SHEET



90028

TABLE 6.4 GUIDE TO FIGURE 2

MATERIAL: Ti-6Al-4V, 2.2 mm (0.087 in) thick sheet, mill anneal								
Curve No.	Derivation number	Stress ratio, R	Environment	Test frequency (Hz)	Range of ΔK $\text{MN/m}^{3/2}$ $(10^3 \text{ lbf/in}^{3/2})$	n	$\frac{C}{m(m^{3/2}/\text{MN})^n}$ $[\text{in}(\text{in}^{3/2}/10^3 \text{ lbf})^n]$	Notes
1	7	0.667	Distilled water	50	$5 \rightarrow 17$ $(4.6 \rightarrow 15.5)$	2.6	2.1×10^{-10} (1.1×10^{-8})	T – L orientation
2	7	0.667	Distilled water	50	–	–	–	L – T orientation
3	7	0.667	3.5% NaCl aqueous solution	50	–	–	–	T – L orientation
4	7	0.667	3.5% NaCl aqueous solution	50	$6.1 \rightarrow 12$ $(5.6 \rightarrow 10.9)$	6.1	1.8×10^{-13} (1.2×10^{-11})	L – T orientation

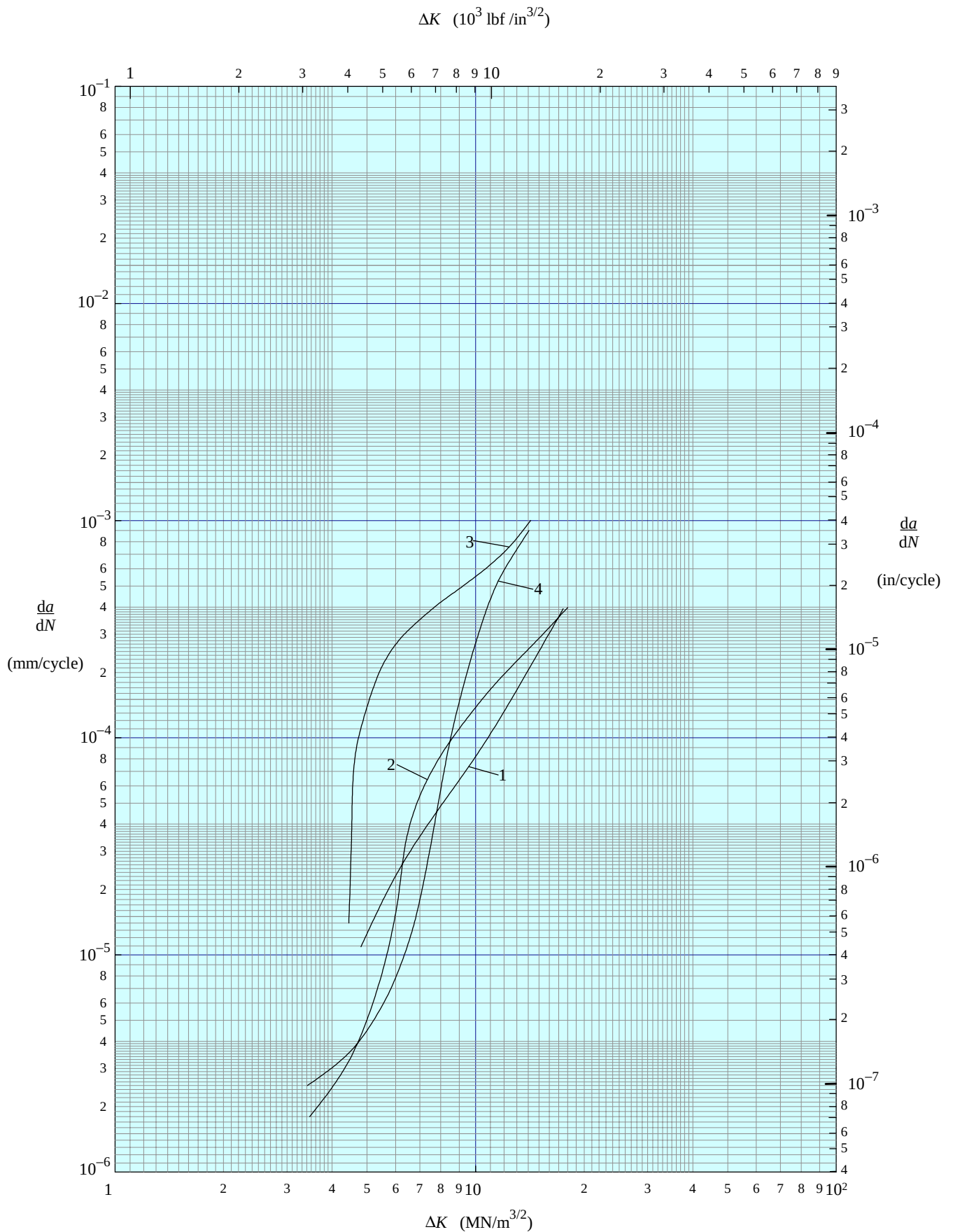


FIGURE 2 Ti-6Al-4V, MILL ANNEALED SHEET



TABLE 6.5 GUIDE TO FIGURE 3

MATERIAL: Ti-6Al-4V, 3.2 mm (0.126 in) thick sheet, mill anneal								
Curve No.	Derivation number	Stress ratio, R	Environment	Test frequency (Hz)	Range of ΔK $\text{MN/m}^{3/2}$ $(10^3 \text{ lbf/in}^{3/2})$	n	C $m(m^{3/2}/\text{MN})^n$ $[\text{in}(\text{in}^{3/2}/10^3 \text{ lbf})^n]$	Notes
1	3	0.1	0.6 M NaCl aqueous solution*	10	10 → 20 (9.1 → 18.2)	4.3	2.4×10^{-12} (1.4×10^{-10})	SEN test, T – L orientation
					20 → 60 (18.2 → 54.6)	2.7	2.8×10^{-10} (1.4×10^{-8})	
2	3	0.1	0.6 M NaCl aqueous solution*	5	10 → 15 (9.1 → 13.7)	7.4	1.2×10^{-15} (9.7×10^{-14})	SEN test, T – L orientation
					18 → 64 (16.4 → 58.2)	2.7	4.3×10^{-10} (2.2×10^{-8})	
3	3	0.1	0.6 M NaCl aqueous solution*	1	17 → 21 (15.5 → 19.1)	13	3.4×10^{-23} (4.5×10^{-21})	SEN test, T – L orientation
					22 → 54 (20 → 49.1)	2.6	1.4×10^{-9} (7.2×10^{-8})	

* 35×10^{-3} kg NaCl/litre of water