

FATIGUE CRACK PROPAGATION RATES FOR TITANIUM ALLOY SHEET

1. INTRODUCTION

Fatigue crack growth behaviour for titanium and titanium alloys is influenced by microstructure, environment, and mechanical loading conditions. This Item presents fatigue crack propagation rate data for sheet specimens of some titanium alloys. Information is given on the effect of grain orientation, stress ratio, R , and heat treatment. Full details of the alloys are provided. The effects of variable loading and environment are not within the scope of this Data Item.

2. 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)	$N/m^{3/2}$	$lbf/in^{3/2}$
ΔK	stress intensity factor range	$N/m^{3/2}$	$lbf/in^{3/2}$
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 correction on stress intensity factor		

2.1 Additional Notation

L–T refers to loading in the longitudinal (rolling) direction with crack propagation occurring in the transverse (width) direction. See Appendix A for details.

T–L refers to loading in the transverse (width) direction with crack propagation occurring in the longitudinal (rolling) direction. See Appendix A for details.

3. NOTES

This Item gives data on the fatigue crack propagation rate in thin sheet titanium alloys. The experimental data analysed were obtained from centre-cracked titanium sheet specimens having thicknesses between 0.46 and 3.2 mm (0.018 and 0.126 in) with a length to width ratio in the range 2.0 to 6.0, although for the majority of specimens that ratio was 3.0.

All tests were carried out under uniaxial constant amplitude tensile loading with frequencies in the range 0.5 to 100 Hz. For each material various values of R in the range 0 to 0.89 were used. All tests were carried out in laboratory air at ambient temperature, specimens were precracked and growing fatigue cracks were established before crack measurements commenced. The majority of tests were conducted on specimens cut in the longitudinal direction. For some materials, data from transverse and longitudinal specimens are shown. Linear elastic fracture mechanics behaviour, as described in Data Item No. 80036*, is assumed to apply.

4. PRESENTATION OF DATA

Figures 1a to 7 show data for the six materials covered by this Item, as detailed by the Index in Table 8.1. All specimens were in the L–T direction unless otherwise stated. Figure 1a details annealed, Figure 1b mill annealed and Figure 1c results from mill annealed T–L specimens. Figure 5a shows curves for L–T specimens, and Figure 5b curves for T–L specimens.

The data in the figures are presented as curves of crack propagation rate versus stress intensity factor range, that is da/dN versus ΔK . Where sufficient data are available a dashed curve has been drawn such that 95 per cent of the data are below it. Each figure is accompanied by a table that details the mechanical properties of the alloy and the frequency and stress ratio used in the test. Values of C and n obtained from the mean crack propagation rate curves for various ranges of ΔK are also tabulated. These values have been calculated from a 'least squares fit' straight line through the data within the given range.

Figures 8 and 9 present the mean curves for all the alloys tested under R values of 0.1 and 0.67, respectively. The data are plotted as da/dN versus ΔK . These figures allow a direct comparison to be made between the alloys.

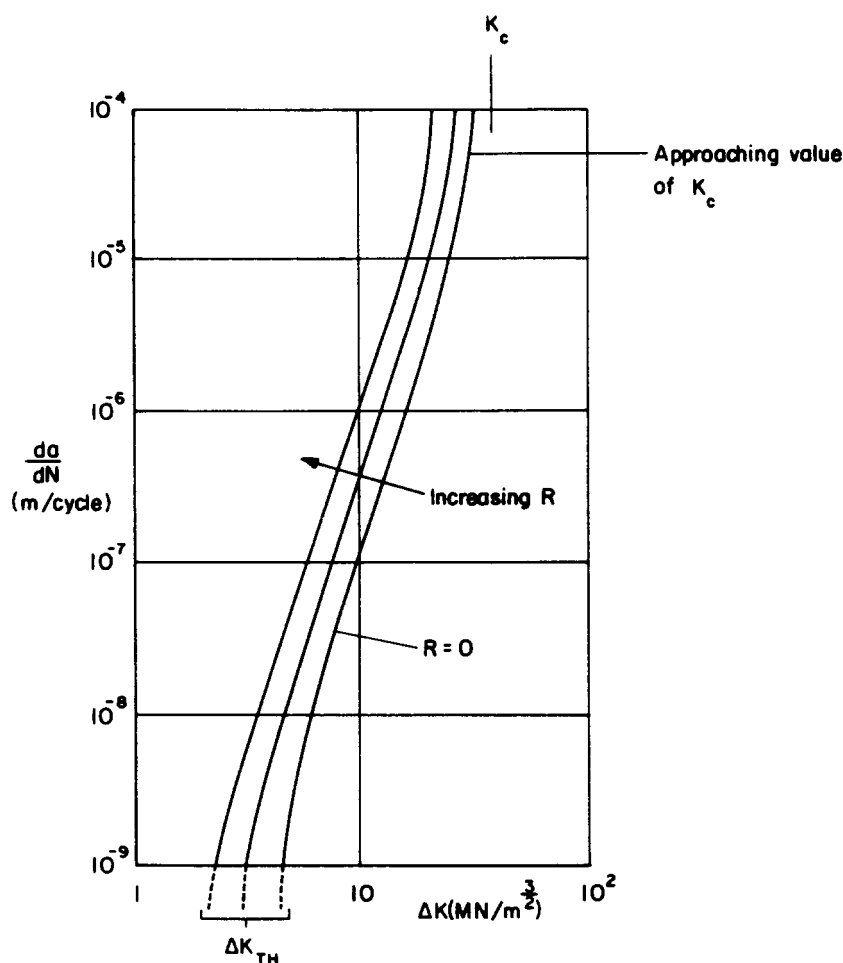
* Data Item No. 80036, 'Introduction to the use of linear elastic fracture mechanics in estimating fatigue crack growth rates and residual strength of components'.

5. DISCUSSION OF DATA

For all alloys the crack growth rate, da/dN , increases with increasing stress intensity factor range, ΔK , until a critical value of ΔK is reached where crack growth becomes unstable. This critical value is not necessarily a true indication of K_c , see Data Item No. 80036, Section 4.2. At low values of ΔK , the curves indicate that a crack propagation rate threshold exists. Figure 7 gives an example of this trend, as highlighted by Sketch 1. However, no data are available below 6.5×10^{-10} m/cycle (2.6×10^{-8} in/cycle) so firm values of ΔK_{TH} are not available. Due to the nature of the data and the form of the curves, extrapolation beyond the curves shown is not recommended. It should also be remembered that these data have been produced from long cracks and that care must be used when applying the results to short cracks. Cracks are generally defined as short when their size is comparable to microstructural features (grain size), or comparable to the scale of local plasticity.

5.1 Effect of Stress Ratio, R

The data presented show that, in general, an increase in R , at a given ΔK value, will lead to an increase in crack growth rate da/dN . Sketch 5.1 illustrates the effect of R on da/dN while Figure 1b provides an example from the data.



Sketch 5.1 Idealised curve of da/dN versus ΔK showing the effect of increasing stress ratio, R .

5.2 Effect of Frequency

Data are presented for tests carried out at various frequencies between 0.5 and 100 Hz. No effect of frequency on the crack propagation rate has been detected.

5.3 Effect of Thickness

Specimen thickness ranged from 0.46 to 3.2 mm (0.018 to 0.126 in), all specimens being cut from full thickness sheet. The data show a slight trend for the crack growth rate, da/dN , to increase with increasing thickness. The effect of thickness is contained within the scatter band of data for a particular material, only being evident by the distribution of the data pertaining to various specimen thicknesses. However, a significant trend is shown by Figure 2 for the $R = 0.1$ curves. The lower curve is for a thickness of 0.46 mm (0.018 in) and the upper curve for a thickness of 1.63 mm (0.064 in). The curves differ by a factor of 10 in growth rate.

5.4 Effect of Specimen Orientation

The effect of orientation on crack growth rate is dependent on the degree of anisotropy of the material tested. For commercially pure titanium, which is sensibly isotropic, the data from T-L specimens agreed with the data from L-T specimens. However, for materials such as Ti-2.5Cu, Figure 6, and Ti-6Al-4V, Figures 1b and 1c, which have some degree of anisotropy, some small effect of orientation can be seen to exist. In general, crack growth rate did not vary significantly with specimen orientation.

5.5 Effect of Heat Treatment

Heat treatment can affect the crack propagation resistance characteristics of some titanium alloys. An example of an improvement can be seen when comparing the data of Figures 2 and 3 for Ti-8Al-1Mo-1V that has been mill annealed and duplex/triplex annealed, respectively.

5.6 Effect of Microstructure

The data presented in this Item cannot be used to ascertain the effect of microstructure on the fatigue crack propagation rate of titanium alloys.

5.7 Comparison of Alloys

Figures 8 and 9 have been included to allow comparison of the crack propagation rates of the alloys covered. Figure 8 is for specimens tested at $R = 0.1$, and Figure 9 for specimens tested at the $R = 0.67$. It can be seen from the curves that the effect of R is similar for all the alloys. For both $R = 0.1$ and $R = 0.67$ the alloy Ti-2.5Cu has the fastest crack propagation rate, and the alloy Ti-8Al-1Mo-1V, both duplex and triplex annealed, has the lowest crack propagation rate for any given ΔK value.

In Figure 8 the curves for Ti-6Al-4V (mill annealed), Ti-8Al-1Mo-1V, and Ti-2.5Cu all appear to be approaching a K_c value in the region of 68 to $80 \text{ MN/m}^{3/2}$ ($62\,000$ to $73\,000 \text{ lbf/in}^{3/2}$).

In Figure 9 the curves for Ti-6Al-4V (mill annealed), Ti-5Al-2.5Sn and commercially pure Ti all appear to be approaching a threshold value in the region of ΔK_{TH} of 3.5 to $4.2 \text{ MN/m}^{3/2}$ (3200 to $3800 \text{ lbf/in}^{3/2}$) although the curves terminate in the region da/dN of 6.5×10^{-10} to $1.5 \times 10^{-9} \text{ m/cycle}$ (2.6×10^{-8} to $6 \times 10^{-8} \text{ in/cycle}$).

6. CALCULATION OF CRACK GROWTH

Crack growth may be predicted by integrating the crack growth rate curves given in Figures 1a to 7 over the linear portion of the curve. This linear portion can be represented by the Paris equation,

$$\frac{da}{dN} = C(\Delta K)^n, \quad (6.1)$$

where n represents the slope and C the ordinate intercept of the straight line. Examples of the use of these curves are given in Data Item Nos 82015, 84001 and 84003*. Equation (6.1) can be integrated analytically, using the method described in Data Item No. 80036, to obtain the number of loading cycles required for a crack to grow a predetermined distance. Note that integration should only be carried out for cracks that are sufficiently long for linear elastic fracture mechanics to apply.

7. DERIVATION AND REFERENCES

7.1 Derivation

This section lists selected sources that have assisted in the preparation of this Item.

- | | | |
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DENTON, K. | The fatigue crack propagation characteristics of titanium and two titanium alloys. NEL Rep. 76, February 1963. |
| 2. | HUDSON, C.M. | Fatigue-crack propagation in several titanium and stainless-steel alloys and one superalloy. NASA tech. Note TN D-2331, October 1964. |
| 3. | HUDSON, C.M. | Studies of fatigue crack growth in alloys suitable for elevated-temperature applications. NASA tech. Note D-2743, April 1965. |
| 4. | HEALY, M.S.
<i>et al.</i> | The fatigue behavior of materials for the supersonic transport. NASA Contractor Rep. CR-215, April 1965. |
| 5. | BINNING, M.S.
GUNN, N.J.F.
LEWIS, G.I. | An evaluation of American manufactured Ti-8Al-1Mo-1V alloy sheets. RAE tech. Rep. 66027, July 1966. |
| 6. | HUDSON, C.M. | Investigation of fatigue crack growth in Ti-8Al-1Mo-1V (duplex-annealed) specimens having various widths. NASA tech. Note D-3879, March 1967. |
| 7. | NOWELL, A. | Some crack propagation characteristics of several sheet materials at room temperature. Rolls-Royce Small Engine Division Research Rep. R311/S1/69, May 1969. |
| 8. | WANHILL, R.J.H.
<i>et al.</i> | Fatigue crack propagation data for titanium sheet alloys. Interim Rep. No. 1: Ti-70 and Ti-6Al-4V. National Aerospace Laboratory NLR TR 72005U, January 1972. |

* Data Item No. 82015, 'Fatigue 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. WANHILL, R.J.H.
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10. WANHILL, R.J.H.
et al. Fatigue crack propagation data for titanium sheet alloys. Interim Rep. No. 3: Ti-5Al-2.5Sn. National Aerospace Laboratory NLR TR 72093U, July 1972.
11. GALLAGHER, J. Damage tolerant design handbook. A compilation of fracture and crack growth data for high strength alloys. Volume 1, Chapter 4. Metals and ceramics information center. Columbus Laboratories, Battelle, Ohio, 1972.
12. – Unpublished work at Hawker Siddeley Aviation Ltd, Woodford, 1973.
13. JONES, R.E. Fatigue crack growth retardation after single-cycle peak overload in Ti-6Al-4V titanium alloy. *Engng Fracture Mech.*, pp. 585-604, Vol. 5, 1973.
14. WANHILL, R.J.H. Environmental fatigue crack propagation in medium strength titanium sheet alloys. *Engng Fracture Mech.*, pp. 681-697, Vol. 6, 1974.
15. WANHILL, R.J.H. Environment and frequency effects during fatigue crack propagation in Ti-2.5Cu (IMI 230) sheet at room temperature. *Corrosion-NACE*, pp. 28-35, Vol. 30, 1974.
16. WANHILL, R.J.H. Environmental fatigue crack propagation in Ti-6Al-4V sheet. *Metallurgical Trans, A*, pp. 1365-1373, Vol. 7A, Part 9, September 1976.

7.2 References

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

17. McCARTNEY, L.N.
COOPER, P. Computerised processing of fatigue crack propagation data. NPL Rep Materials Application 23, October 1972.
18. BENTHEM, J.P.
KOITER, W.T. Asymptotic approximations to crack problems. In *Mechanics of fracture. I. Methods of analysis and solutions of crack problems*, pp. 131-178, Noordhoff International Publishing, Leyden, 1973.

8. TABLES AND FIGURES

TABLE 8.1 INDEX TO FIGURES AND TABLES

<i>Material</i>	<i>Stress ratios covered</i>	<i>Sheet thickness</i>	<i>Figure and table numbers</i>
Ti-6Al-4V (IMI 318) Annealed + Mill annealed	0 to 0.85	Sheet 0.91 → 2.5 mm (0.04 → 0.1 in)	Figs 1a, 1b, 1c Tables 8.2, 8.3, 8.4
Ti-8Al-1Mo-1V Mill annealed	0 to 0.85	Sheet 0.46 → 1.63 mm (0.02 → 0.06 in)	Fig. 2 Table 8.5
Ti-8Al-1Mo-1V Duplex + Triplex annealed	0 to 0.85	Sheet 1.12 → 1.63 mm (0.04 → 0.06 in)	Fig. 3 Table 8.6
Ti-4Al-3Mo-1V Aged	0 to 0.85	Sheet 1.02 mm (0.04 in)	Fig. 4 Table 8.7
Ti-5Al-2.5Sn Annealed	0 to 0.89	Sheet 2.0 → 3.2 mm (0.08 → 0.13 in)	Figs 5a, 5b Tables 8.8, 8.9
Ti-2.5Cu (IMI 230)	0 to 0.67	Sheet 2.0 mm (0.08 in)	Fig. 6 Table 8.10
Ti (Commercially pure) (IMI 130 and Ti 70)	0 to 0.67	Sheet 2.0 mm (0.08 in)	Fig. 7 Table 8.11
All above alloys (except Ti-4Al-3Mo-1V)	0.1	Sheet 0.91 → 3.2 mm (0.04 → 0.13 in)	Fig. 8
All above alloys	0.67	Sheet 0.91 → 3.2 mm (0.04 → 0.13 in)	Fig. 9

TABLE 8.2

MATERIAL		Ti-6Al-4V (IMI 318)				TABLE 8.2 FIGURE 1a			
COMPOSITION NOMINAL ACTUAL		Ti-6Al-4V				HEAT TREATMENT		Annealed. Heat at 700°C ± 10°C for not less than 20 min. Air cool.	
						SPECIMEN ORIENTATION		L-T	
Curve number	Test frequency (Hz)	R	Thickness mm (in)	f_t MN/m ² (10 ³ lbf/in ²)	f_p MN/m ² (10 ³ lbf/in ²)	Number of tests	Range of ΔK MN/m ^{3/2} (lbf/in ^{3/2})	n	C $m(m^{3/2}/MN)^n$ [in(in ^{3/2} /10 ³ lbf) ⁿ]
1	0.5 - 100	0.75	1.63 (0.064)	1012 (147)	896 (130)	4	12 → 27 (11000 → 25000)	2.6	3.0×10^{-10} (1.5×10^{-8})
2	1	0.1	1.60 (0.063)	1012 (147)	896 (130)	2	18 → 37 16000 → 34000	2.4	3.4×10^{-10} (1.7×10^{-8})



TABLE 8.3

MATERIAL		Ti-6Al-4V (IMI 318)				TABLE 8.3 FIGURE 1b			
COMPOSITION NOMINAL ACTUAL		Ti-6Al-4V				HEAT TREATMENT		Mill annealed. Heat between 705°C and 734°C for 1 h. Cool in air	
						SPECIMEN ORIENTATION		L-T	
Curve number	Test frequency (Hz)	R	Thickness mm (in)	f_t^* MN/m ² (10 ³ lbf/in ²)	f_p^* MN/m ² (10 ³ lbf/in ²)	Number of tests	Range of ΔK MN/m ^{3/2} (lbf/in ^{3/2})	n	C m(m ^{3/2} /MN) ⁿ [in(in ^{3/2} /10 ³ lbf) ⁿ]
1	0.5 - 100	0.00	0.91-2.46 [†] (0.036-0.097)	970 (141)	900 (131)	1	45 → 89 (41000 → 81000)	3.2	6.5×10^{-12} (3.5×10^{-10})
2	0.5 - 100	0.10	0.91-2.50 (0.036-0.100)	970 (141)	900 (131)	23	20 → 60 (18000 → 55000)	2.3	2.2×10^{-10} (1.1×10^{-8})
3	0.5 - 100	0.67	2.20-2.50 (0.087-0.100)	970 (141)	900 (131)	14	5 → 16 (5000 → 15000)	3.4	2.0×10^{-11} (1.1×10^{-9})
4	0.5 - 100	0.85	0.91-2.46 [†] (0.036-0.097)	970 (141)	900 (131)	1	4 → 10 (4000 → 9000)	2.9	8.0×10^{-11} (4.2×10^{-9})

* Average taken of test values

† Thickness within range specified