

FATIGUE CRACK PROPAGATION RATES AND THRESHOLD STRESS INTENSITY FACTOR RANGES FOR TITANIUM ALLOY PLATE, BAR AND FORGINGS

1. NOTATION

Both SI and British units are quoted.

a	crack length or crack half-length as defined in Sketch 6.1	m	in
B	thickness of test pieces	m	in
b	half-width of test pieces types 1 and 2	m	in
C	coefficient for linear interpolation of crack growth rate curve defined by $da/dN = C(\Delta K)^n$	$m\left(\frac{m}{N}\right)^{3/2}$	$in\left(\frac{in}{lbf}\right)^{3/2}$
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
H	half-depth of test pieces types 3 and 4	m	in
K	stress intensity factor defined as $S(\pi a)^{1/2}\alpha$	N/m ^{3/2}	lbf/in ^{3/2}
K_{Ic}	plane strain critical stress intensity factor obtained from test pieces that conform to BSI or ASTM recommended standards (see Section 2.3)	N/m ^{3/2}	lbf/in ^{3/2}
K_Q	critical stress intensity factor obtained from tests that do not conform to BSI or ASTM recommended standards (see Section 2.3)	N/m ^{3/2}	lbf/in ^{3/2}
$K_{(max)TH}$	maximum value of K at threshold	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 below which fatigue cracks do not exhibit significant growth, typically $< 10^{-11}$ m/cycle	N/m ^{3/2}	lbf/in ^{3/2}
L	length of test pieces types 1 and 2	m	in
N	number of load cycles		
n	characteristic of slope of crack growth rate curve		
P	applied direct load for test pieces types 3 and 4	N	lbf
R	S_{min}/S_{max}		
r	radius of Type 5 test piece	m	in

r_p	size of plastic zone*	m	in
S	stress based upon gross cross-sectional area of component	N/m ²	lbf/in ²
W	distance from applied load P to back face of test pieces types 3 and 4	m	in
α	geometrical factor in stress intensity factor		

* See Data Item No. 80036 "Use of linear elastic fracture mechanics in estimating fatigue crack growth rates and residual strength of components".

The orientation of the grain flow within the test pieces is indicated by the two-letter code system described in Appendix A.

Suffixes

max, min indicate maximum or minimum values respectively of stress or stress intensity factor in loading cycle.

1.1 Conversion Factors

The data are presented in terms of SI units and the following conversion factors for British units apply.

$$1 \text{ MN/m}^{3/2} = 1 \text{ MPa m}^{1/2} = 910.047 \text{ lbf/in}^{3/2}.$$

Note also that

$$1 \text{ MN/m}^{3/2} = 31.6228 \text{ N/mm}^{3/2}.$$

2. NOTES

2.1 General

This Data Item presents fatigue crack propagation rate data for several titanium alloys in plate, bar and forging forms. The major chemical elements and mechanical properties of the materials are given in Table 6.1, together with the heat treatment applied and the test piece geometries. Crack propagation rate data for the materials are provided over a wide range of stress intensity factors. Crack propagation rate data in the region of the fatigue threshold stress intensity factor range, ΔK_{TH} , (at $da/dN \approx 10^{-11}$ m/cycle) are available for four of the alloys, namely Ti-6Al-4V, Ti-4Al-4Mo-2Sn-0.5Si, Ti-8Al-Mo-1V and Ti-10V-2Fe-3Al.

2.2 Test Conditions and Limitations

The data are derived from constant amplitude fatigue tests conducted in air at room temperature with, in most cases, uncontrolled humidity. The loading frequencies of the fatigue machines were generally in the range of 0.1 to 100 Hz, although some of the data, see Derivations 9 and 14, were obtained from tests conducted at 1000 Hz. Tests were conducted on test pieces of the types shown in Sketch 6.1; the thicknesses of the test pieces ranged from 1.3 to 25.4 mm. The orientation of the grain flow within the test piece was not always given but, where known, it is stated in Table 6.1 and on the figures, using the identification system described in Appendix A. Generally, measurements of crack length were made using either optical methods or potential drop techniques.

All the tests were stated to have been conducted within the framework of linear elastic fracture mechanics and thus, throughout each of the tests the stress across the uncracked section of the test piece did not exceed the yield strength of the material except at the crack tip. The plastic zone sizes were small compared with crack length (see Section 1 of Data Item No. 80036*).

2.2.1 Applicability of data to short cracks

The data presented in this Data Item have been obtained from fatigue tests on test pieces that contained machined slots or notches. The minimum length of these machined slots or notches was 3 mm. In general the test pieces were fatigue loaded so that small starter cracks, of unstated length, grew from the machined slots or notches before the crack propagation tests began. Therefore all the data presented in this Data Item have been obtained from test pieces with cracks a greater than 3 mm in length.

For components containing short cracks, the values of ΔK_{TH} may be much lower than those shown on the figures presented in this Data Item and the fatigue crack propagation rates may be much higher, for a given stress intensity factor range, ΔK . Therefore, if the data are applied to components containing short cracks, unsafe estimates may be obtained for values of ΔK_{TH} and for fatigue crack growth life under given loading conditions (References 44, 54, 55 and 56 show some of these effects). As the crack propagation rate increases, however, the long crack data may overestimate fatigue crack growth rate because components containing short cracks generally have higher values of apparent fracture toughness than components containing long cracks. Another paper that discusses the significance of ΔK_{TH} and short cracks in aircraft structures is Reference 59.

For components containing cracks of lengths less than 1 mm, inaccurate measurements of the lengths of small cracks, because of crack front curvature, lead to wide discrepancies in the estimations of the value of ΔK . Another important parameter to consider when dealing with short cracks is r_p/a , the ratio of the radius of the plastic zone to the crack length. This ratio can be critical if a component is subjected to high

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

stresses such that gross yielding occurs across the net uncracked section and in consequence linear elastic fracture mechanics procedures do not apply. A similar situation can occur locally at the root of a notch in the presence of local yielding. Where crack lengths are of a similar size to the microstructural unit size (*e.g.* grain size or other significant features) the assumption that the material acts as a homogeneous continuum in the neighbourhood of the crack tip no longer applies.

2.3 Presentation of Data

Figures 1 to 16 provide curves of crack propagation rate, da/dN , plotted against stress intensity factor range, ΔK , for various values of R . Data are presented for $\alpha + \beta$ alloys, which are widely used for airframe components, on Figures 1 to 15, and for some near α alloys, used for engine components, on Figure 16. Details of the materials and their form are given in Table 6.1. Figures 2a, 3a, 4a, 5a and 8a provide data for low crack propagation rates, that is $da/dN \leq 10^{-7}$ m/cycle down to ΔK_{TH} ($da/dN = 10^{-11}$ m/cycle). Many of the low crack propagation rate curves have been obtained by extrapolating down to the region of the fatigue threshold at 10^{-11} m/cycle (dash-dot curves). For many of the alloys considered there were insufficient data available to provide more than one curve but, where sufficient data were available, a mean curve, shown solid, and the upper limit of 95 per cent of the data, shown dashed, are presented.

Figures 17, 18 and 18a provide summary curves so that crack propagation rates for the different alloys and heat treatments can be compared. Figure 18a compares low crack propagation rate data for the Ti-6Al-4V alloy, for two ranges of values of R .

Figure 19 shows how the value of the fatigue threshold stress intensity factor, ΔK_{TH} , varies with the stress ratio, R , for the Ti-6Al-4V alloy.

The test piece thicknesses and, where available, the orientation of grain flow within the test pieces are quoted on the figures. The values of fracture toughness obtained from tests for each material grade, as given in the Derivations, are quoted in Table 6.1 and are also indicated on the figures. The values of fracture toughness have been designated K_{IC} where they were obtained from tests that conformed to the recommendations of the British Standards Institution (BSI) or the American Society for Testing and Materials (ASTM) criteria (see References 50 and 61). Where the results did not meet the validity criteria or the tests did not conform to these recommendations, they have been designated K_Q .

3. DISCUSSION OF DATA

3.1 Method of Analysis of Test Data

In all but one case (that of Derivation 29) the data analysed and presented in this Data Item have been obtained from da/dN and ΔK data given in the Derivations.

Equation (4.2) of Item No. 80036 defines ΔK as

$$\Delta K = (S_{max} - S_{min})(\pi a)^{1/2} \alpha . \quad (3.1)$$

The values of α in Equation (3.1) used in the Derivations were values appropriate to the loading conditions and geometry of the test pieces. It was not generally known whether or not allowances were made for the effects of plasticity at the crack tip on the value of ΔK , although the effect of this is unlikely to be significant within the range of data available.

3.1.1 Analysis of data from Derivation 29

The data available from Derivation 29 were in the form of basic fatigue crack growth test results (a , N) and the crack growth rate has been determined by differentiating the basic crack growth curve obtained using the curve fitting technique described in Reference 37. Data were only available for the test piece type 1 of Sketch 6.1. The values of α for this test piece, as used in Equation (3.1), have been obtained from the expression given in Reference 38 (also given in Data Items Nos 81031*, 83007†, and 84001‡), namely,

$$\alpha = \left[1 - 0.5 \frac{a}{b} + 0.326 \left(\frac{a}{b} \right)^2 \right] \left(1 - \frac{a}{b} \right)^{-1/2}. \quad (3.2)$$

3.2 Effect of Stress Ratio, R

3.2.1 Effect of stress ratio on growth rate

The crack propagation data presented in this Data Item cover values of R in the range 0 to 0.9. In general, the larger the value of R the higher the crack growth rate, da/dN , for a given value of applied ΔK – although this effect appears to be very much less for titanium alloys than for aluminium alloys (see Data Item No. 81031).

Many models are available that describe the effect of R upon crack growth rate. Several such models are reviewed in Reference 53.

The influence of R on da/dN is largely explained by crack tip shielding phenomena (often referred to as crack closure), see Data Item No. 80036.

3.2.2 Effect of stress ratio on threshold

The stress ratio has a strong influence on ΔK_{TH} which, again, can largely be explained by crack tip shielding. If R is high enough to keep the crack open throughout the fatigue cycle then the level of ΔK_{TH} is unaffected by R . However, reducing the value of R so that crack tip shielding occurs will result in an increase in ΔK_{TH} .

The influence of the value of R on ΔK_{TH} is illustrated in Figure 19 for the Ti-6Al-4V alloy. Values of ΔK_{TH} taken from the figures, at $da/dN = 10^{-11}$ m/cycle, have been plotted for various values of R . The presentation allows for mean lines to be drawn through these values of ΔK_{TH} . The lower mean line passes through the values of ΔK_{TH} obtained from the mill-annealed plate data and the upper mean line passes through the solution treated and aged forged bar data, $B \leq 3.2$ mm. Note that for $R \geq 0.5$ there is very little difference between the values of ΔK_{TH} obtained from the two types of forging.

3.3 Determination of Fatigue Threshold (ΔK_{TH})

There was no clear and consistent convention used in the Derivations for determining the threshold value of the stress intensity factor range, ΔK_{TH} (that is, the value of ΔK below which fatigue cracks will not exhibit significant growth). In the majority of the Derivations fatigue crack propagation rates of less than 10^{-10} m/cycle were obtained from the tests. For this Data Item, where tests were terminated in the region of $da/dN = 10^{-10}$ m/cycle, the crack growth curves have been extrapolated by eye so that values of ΔK_{TH}

* Data Item No. 81031 "Fatigue crack propagation rates and threshold stress intensity factor ranges for aluminium alloy plate, extruded bar and forgings".

† Data Item No. 83007 "Fatigue crack propagation rates and threshold stress intensity factor ranges for aluminium alloy sheet".

‡ Data Item No. 84001 "Growth of cracks under constant amplitude fatigue loading: example calculations".

may be obtained. The values of ΔK_{TH} are considered to be valid if the crack propagation curves are vertical or very nearly vertical in the region of ΔK_{TH} . For most of the materials for which data are presented this condition is taken to be at a value of da/dN of 10^{-11} m/cycle.

In most tests the crack was grown at any one cyclic load level until the increment of growth was several times larger than the plastic zone size corresponding to K_{max} , before crack measurements were taken. This procedure minimised the effects of stress history. The plastic zone size in conditions of plane strain may be calculated using a modified form of Equation (3.13) of Data Item No. 80036, so that

$$r_p = \frac{1}{6\pi} \left(\frac{K_{max}}{f_p} \right)^2 \quad (3.3)$$

Not all the Derivations stated clearly how the testing was conducted at low crack propagation rates, but near the threshold condition load reduction (or load shedding) was the most popular method. Generally testing was terminated, and a value of ΔK_{TH} considered to have been obtained, if there was not measurable crack growth after the application of about 10^7 cycles for a given applied load.

3.4 Effect of Test Piece Thickness

For the range of test piece thicknesses covered in this Data Item (1.3 to 25.4 mm) there is no significant variation in crack propagation rate with thickness.

3.5 Effect of Orientation of Grain Flow within Test Pieces

Where possible, the direction of orientation of the grain flow within test pieces is indicated in Table 6.1 and on the figures. The two-letter code system used to identify the crack orientation is fully described in Appendix A.

In general for the materials considered and in the absence of crystallographic texture the direction of the grain flow within the test pieces does not appear to influence the crack propagation rates. Nevertheless it is known that within strongly textured materials grain flow orientation can be important, see Section 3.6.2.

3.6 Effect of Heat Treatment and Microstructure

The fatigue crack propagation rate of titanium alloy is dependent on the heat treatment and microstructure of the alloy. The effect of these factors is illustrated by comparing the crack propagation rates of the materials presented in this Data Item. For instance, if the crack propagation rates of the Ti-6Al-4V annealed plates presented on Figures 1 and 2 are compared, it can be seen that test pieces in the β -annealed condition have much lower crack propagation rates than those in the mill-annealed condition, for given values of ΔK (of the order of a tenth of the values at $\Delta K = 15 \text{ MN/m}^{3/2}$). This phenomenon is well known and many authors have shown that transforming the microstructure of $\alpha + \beta$ titanium alloys by heating in the β phase field will produce lower crack propagation rates (in air) than are obtained with alloys heated in the $\alpha + \beta$ phase field. The effect would appear to be dependent on the type of alloy, because the differences in crack propagation rates between the β -annealed and mill-annealed test pieces for the Ti-6Al-6V-2Sn alloy are much smaller than between similar heat treated test pieces for the Ti-6Al-4V alloy (see Figure 17). Note also that the Ti-6Al-4V β -forged bar data show lower crack propagation rates compared to the other forms of this alloy (see Figures 18 and 18a).

Figure 18a presents low crack propagation rate data ($da/dN \leq 10^{-7}$ m/cycle) down to the fatigue threshold for two ranges of R for the Ti-6Al-4V alloy. The crack propagation rate curves have similar trends to the da/dN curves presented on Figures 17 and 18, in that the mill-annealed plate data show higher crack

propagation rates for given values of ΔK than the solution treated and aged forged bar and the β -forged bar materials.

There are other factors that may affect the crack propagation rate of titanium alloys and some of them are discussed in the following sections.

Details of heat treatments and a description of the microstructure for each material are given, where known, in Table 6.2.

3.6.1 Reduction of original billet or forging

It has been suggested that large reductions from the original size of the billet or forging by working can improve the microstructure and thereby improve fatigue life (see Section 3 of Data Item No. 77027*); this change in microstructure may also affect crack propagation rate data. Nevertheless very few of the Derivations used for this Item gave details of the original billet size, thus preventing analysis.

3.6.2 Texture

Materials that have been subjected to deformations and heat treatment during manufacture may exhibit the phenomenon known as texturing. In titanium alloys this phenomenon can occur because the α phase particles may have a preferred orientation (texture) which in turn affects the mechanical properties, including fatigue crack propagation rates.

The α phase of titanium alloys has a hexagonal crystallographic structure which in a strongly textured material exhibits a marked anisotropy in the mechanical properties of the alloy. If the material has a random orientation of the α phase this material will behave isotropically. In plate and rolled bar the manufacturer can control the texture of the material but, for forged materials, the texture is much more difficult to control.

In only two of the Derivations were the effects of texture mentioned (Derivations 10 and 28). In Derivation 28 it has been shown that the texture of Ti-6Al-4V plate in the mill-annealed condition influences crack propagation rates in the range 10^{-8} m/cycle down to 10^{-11} m/cycle (threshold). The hatched areas at ΔK_{TH} on Figure 2a illustrate the effect for two values of R . At $R = 0.1$ there is a two-fold increase in the value of ΔK_{TH} , with the S-L/S-T test pieces having the lowest values. At $R = 0.7$ there is only a one-and-a-half-fold increase in the value of ΔK_{TH} ; the S-L test pieces have the lowest values of ΔK_{TH} and the T-S test pieces have the highest values. At this value of R , however, there are no data available for the L-T test pieces.

In Reference 53 tests on a more heavily textured Ti-6Al-4V alloy in the form of rolled bar have been reported. These tests were performed in the same crack propagation rate region and similar effects of preferred orientation were observed. At threshold, the L-T test pieces again had the highest value of ΔK_{TH} but the lowest values of ΔK_{TH} were obtained from the T-L test pieces. In the higher crack propagation rate region, however, ($da/dN > 10^{-7}$ m/cycle) Reference 41 has reported that for a rolled bar material, similar to that of Reference 53, the effect of preferred orientation changes and the lowest crack propagation rates were obtained from T-S test pieces, and the highest crack propagation rates were obtained from L-T test pieces. Reference 52 gives a summary of the effect of texture in various environments and lists other relevant literature.

3.6.3 Grain size and oxygen content

Some authors have shown that the grain size and the oxygen content of alloys can affect crack propagation rates. Derivation 11 shows that reducing the oxygen content of the Ti-6Al-6V-2Sn alloy will lower the

* Data Item No. 77027 "Fatigue of wrought and cast Ti-6Al-4V titanium alloy. (In bending and under axial loading.)".

crack propagation rate. On the other hand it has been shown that reducing the oxygen content of the Ti-4Al-4Mo-2Sn-0.5Si alloy will increase the crack propagation rate (see Derivation 27). The fracture toughness of the materials may also be affected by changes in oxygen content. The effect of grain size on crack propagation rate is also important and it has been shown in Derivations 10 and 25 that the larger the grain size, the lower the crack propagation rate. Reference 52 provides further examples of these two factors.

3.7 Effect of Dwell Time

It has been shown that holding the maximum load in the fatigue cycle for a period of time, known as dwell time, will increase the fatigue crack propagation rate. References 46, 48 and 58 show this effect in Ti-6Al-4V and Ti-4Al-4Mo-2Sn-0.5Si alloys. It should be noted, however, that both materials tested were highly textured and the effect did not exist at temperatures greater than 75°C.

3.8 Effect of Environment

Most of the test data analysed were obtained from tests conducted in air at room temperature, with uncontrolled humidity. No effects of changes in humidity, and no other environmental factors such as atmosphere, temperature, *etc.*, have been considered in this Item.

There are, however, many research reports that provide crack propagation rate data for titanium alloys tested in controlled environments such as 'dry air', that is less than 40 per cent relative humidity. Fatigue crack propagation rate data for tests conducted in dry air (Derivation 4 and References 40 and 43) have been compared with the laboratory air data given in this Item for Ti-6Al-4V mill-annealed plate. The comparison showed that the tests conducted in dry air gave lower crack propagation rates for given values of ΔK than the tests conducted in laboratory air, although the differences were not large. This trend in crack propagation is less evident when the plate is in the β -annealed condition. It may be assumed therefore that fatigue crack propagation rate tests conducted in 'wet air' (high humidity, 80-90 per cent relative humidity) will give slightly higher crack propagation rates for given values of ΔK than those obtained in laboratory air tests. Reference 51 has reported that for titanium alloys the differences in crack propagation rates from tests conducted in dry and wet air are fairly small and that trends change depending upon the microstructure of the test piece.

It has been suggested that frequency of loading is a parameter that will affect fatigue crack propagation rates in aggressive environments, such as salt water. In most of the research literature, however, the effect of this factor has been found to be moderate; see Reference 52 which gives a fuller discussion of this and other environmental factors.

3.9 Comparison of Alloys

Figure 17 summarises the crack propagation rate curves for two alloys in two heat treatment conditions, for $R = 0$ to 0.12. The Ti-6Al-4V alloy rates are given by the solid lines and the Ti-6Al-6V-2Sn alloy rates are given by the dashed-dotted lines. The curves show that for the Ti-6Al-4V alloy the differences between crack propagation rates are largest at low values of da/dN . As discussed in Section 3.6, the differences in crack propagation rates between the two heat treatment conditions presented were smaller for the Ti-6Al-6V-2Sn alloy. Alloys in the β -annealed condition have the lowest crack propagation rates for given values of ΔK .

4. CALCULATION OF CRACK GROWTH LIFE

4.1 Use of Curves

The complete curves available from the data are presented in Figures 1 to 16. The curves are suitable for use in computer programs that predict crack growth life as described in Section 4.2 of Data Item No. 80036. Alternatively, simple integration over selected portions of one of the curves will also lead to an estimate of the total crack growth and the associated number of cycles (see Data Item No. 84001). One method described in Data Item No. 84001 assumes that the crack propagation rate curves are straight lines over discrete ranges of da/dN and may be described by the equation (Reference 36)

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

Suggested values of n and C for given values of R are shown in the tables on the figures. Equation (4.1) cannot be used to describe the full range of crack growth (that is from fatigue threshold to failure). For values of $da/dN < 10^{-10}$ m/cycle the crack propagation rate curves become nearly vertical and the value of $n \rightarrow \infty$ so that Equation (4.1) is unusable. If Equation (4.1) is used in the region $da/dN < 10^{-10}$ to 10^{-9} m/cycle it should only be used over small ranges of da/dN .

4.2 Practical Solutions

Simple practical examples using Equation (4.1) are given in Data Items Nos 84001 and 84003* for crack propagation rates $> 10^{-8}$ m/cycle.

Methods of obtaining values of α for cracks in structural components of more complex geometries are outlined in Data Items Nos 80036 and 78036† and values may also be obtained directly from sources such as Reference 45.

5. DERIVATION AND REFERENCES

5.1 Derivation

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

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

† Item No. 78036 "The compounding method of estimating stress intensity factors for cracks in complex configurations using solutions from simple configurations".

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6. TABLE

TABLE 6.1

Figure No.	Derivation No.	Material	Heat treatment condition	Form	Alloy Specification	f_t MN/m ²	f_p MN/m ²	$K_Q^{(a)}$ MN/m ^{3/2}	$K_{Ic}^{(a)}$ MN/m ^{3/2}	Test frequency Hz	Test piece type	B mm	Crack ^(c) orientation
1	5, 6, 18	Ti-6Al-4V	β -annealed	Plate	TA 56	818 958	740 869		87	5	3	10 25.4	L-T T-L
2 and 2a	2, 4, 7, 8, 22, 28		Mill-annealed			943L 1052T	863L 1034T		40 76.5	1 100	1, 2 and 3	6.35 25.4	L-T T-L
3 and 3a	9, 14		Solution treated and aged forging	Forging ^(c)		1041 1148	986 1089		66	1 to 1000	1 and 3	1.3, 2 and 3.2	L-T ^(a)
4 and 4a	3, 10, 13		β -annealed forging	Bar		1000	827			40	3	6.35	
5 and 5a (e)	23, 24, 25		Solution treated and aged, (rolled bar)			936 921	835 812	84		0.1 to 100	2 and 3	12.7, 13, 16 and 20	L-T S-T T-L
6	1, 11, 17, 18	Ti-6Al-6V-2Sn	Mill-annealed	Plate		1105 1172	1043 1126		39.1 47	0.2 to 20	3 and 4	10, 12.7 and 25.4	T-L
7	1		Solution treated and aged			1257	1194		37.4	10	4	10, 12.7	
	1, 11, 17		β -annealed			1056 1068	954 968		59.6 to 82	5 and 10	3 and 4	12.7 25.4	T-L
8 and 8a	15, 23, 29	Ti-4Al-4Mo-2Sn-0.5Si	Solution treated and aged (forged and rolled bar)	Bar	TA 45 to TA 51	1163 1040	1071 934	57 to 97.7		0.1 to 100	1, 2 and 3	10.2, 12.5, 12.7 and 13	Various
9	32	Ti-5Al-2.5Sn	Normal interstitial β -annealed forging	Bar						20 to 28	2	38	T-S
			Low-interstitial β -annealed forging									32	T-L
10	31		β -annealed	Bar							3	13	
11	33	Ti-10V-2Fe-3Al	Solution treated and aged	Bar		1288 1278 1067	1149 1190 1002		46.8 37.0 86.1	40	3	5.1	
	34					1131	1034		63	50	3	6	
12	16	Ti-8Al-1Mo-1V	Mill annealed	Plate			844		62	0.1 to 30	3	12.7	T-L