

Fatigue of wrought and cast Ti-6Al-4V alloys

In bending and under axial loading

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FATIGUE OF WROUGHT AND CAST Ti-6Al-4V ALLOYS (IN BENDING AND UNDER AXIAL LOADING)

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FATIGUE OF WROUGHT AND CAST Ti-6Al-4V ALLOYS (IN BENDING AND UNDER AXIAL LOADING)

1. INTRODUCTION

This Data Item presents data on the fatigue strength of the six per cent aluminium, four per cent vanadium, titanium alloy tested at room temperature. Data are provided for forged bar, rod and sheet, extruded strip and castings. The data are sub-divided according as to whether the alloy has been annealed or solution heat treated and age hardened. In the case of the forged alloy it is necessary to sub-divide the data further according to whether the alloy is forged above or below its transus temperature.

This Data Item accompanies ESDU 19001^{*}. In Tables 8.1 and 8.2, lists of the data available for wrought and cast alloys are given, respectively. The data are from plain and notched specimens tested in bending and under axial loading and, with only a small number of exceptions, are presented in the form of plots of $K_t S_a / f_t$ versus N . Where pertinent, the ranges of the values of mean stress are indicated in terms of S'_m / f_t . Where they are available, specimen details and mechanical properties are presented in the Tables that accompany then Figures in Section 9.

Where available, the details of the time and temperature of the heat treatments applied to the titanium alloys tested herein are provided on the Tables that accompany the Figures in Section 9. However, it is important to note that occasionally the heat treatment terminology reported from the Derivations, particularly when general definitions such as 'annealed' and 'aged' are given, should be used with caution. A summary of the most commonplace heat treatments applied to titanium and its alloys is given in Appendix A.

On Figures 1 to 13, and Figure 32 in Section 9, the curves through the data have been derived using ESDUpac A9724, the program that accompanies ESDU 97024[†] and the curve equations are written on the Figures. The $K_t S_a / f_t$ fatigue data presented in Section 9 are also available in E1902v10.xlsx, a Microsoft™ Excel file that accompanies this Data Item. (Note that in the Excel file there are some cases when the values are not actual test results but have been digitized from figures in the Derivations.)

Note that the sizes, together with the size of the original rod or bar or sheet thickness, of both the fatigue test specimen and the component must be considered before the probable fatigue characteristics can be deduced.

In addition to presenting new data, this Data Item supersedes ESDU 77027[‡].

An example of how to deal with the information and data presented in this Item is given in Section 8.

1.1 Notation

Both SI and British units are shown but any coherent system of units may be used.

f_p	proof strength	N/m ²	lbf/in ²
f_t	tensile strength	N/m ²	lbf/in ²
K_t	elastic stress concentration factor, based on net cross-sectional area		

^{*} ESDU 19001, 'Fatigue of wrought and cast titanium alloys (In bending and under axial loading)'.

[†] ESDU 97024, 'Derivation of endurance curves from fatigue test data, including run-outs'.

[‡] ESDU 77027, 'Fatigue of wrought and cast Ti-6Al-4V titanium alloy. (In bending under axial loading)'.

N	number of cycles to failure		
R	$(S_m - S_a)/(S_m + S_a)$		
r	radius of notch	m	in
S_a	alternating stress based on net cross-sectional area	N/m ²	lbf/in ²
S_{a0}	alternating stress at zero mean stress, based on net cross-sectional area	N/m ²	lbf/in ²
S_m	mean stress, based on net cross-sectional area	N/m ²	lbf/in ²
S'_m	mean stress at stress concentration, $K_t S_m$ or $f_p - K_t S_a$ if $K_t(S_a + S_m) > f_p$	N/m ²	lbf/in ²
σ_y	yield strength	N/m ²	lbf/in ²

1.2 Definitions

annealing	a heat treatment to produce an optimum combination of ductility, machinability and dimensional and structural stability at room temperature
equiaxed	a microstructure in which the grains have approximately the same dimensions in all direction
hot rolling	a metal forming process carried out above the recrystallisation temperature to reduce thickness and make thickness more uniform
lamellar	a microstructure composed of alternating plates of dissimilar phases
martensite	a microstructure formed after rapid quenching
metastable	a phase which can exist in a stable state above its lower, more stable state of equilibrium
mill anneal	not a full anneal, but a general-purpose treatment given to all mill products, leaving a less well controlled microstructure
primary α phase	an α phase that persists during heat treatment into the $\alpha + \beta$ phase field and is not really affected by ageing
solution treatment	a heat treatment either slightly above or slightly below the β transus temperature which allows elements to enter solid solution and increase the strength of the alloy
stabilized	the addition of elements to inhibit phase changes within the alloy
stress relief treatment	a treatment to relieve the deformed material and reduce residual stress during fabrication without adversely affecting strength or ductility
transformation temperature	the temperature at which a phase transformation occurs
transus temperature	the point between two phase states on a phase diagram
α	a hexagonal close-packed (hcp) phase, stable at room temperature
β	a body-centred cubic (bcc) phase found above the β transus temperature

2. GENERAL NOTES

In most cases, the microstructure of Ti-6Al-4V alloys has a marked effect on the fatigue strength. The microstructure is governed by the phase state of the alloy at the time of forging or extruding. Forging that is carried out above the $(\alpha + \beta)/\beta$ transus temperature of about 995 °C (1823 °F) results in a coarse Widmanstätten microstructure. Typical forging below the transus temperature, in the $(\alpha + \beta)$ phase, produces a microstructure which is capable of refinement by working and further heat treatment. Extrusions are usually fabricated at temperatures above the transus temperature and therefore have a coarse-grained microstructure. Cast Ti-6Al-4V alloys also have a relatively large grain size and have relatively poor fatigue strength, depending on the casting process used.

The typical microstructure of the $(\alpha + \beta)$ forged alloy, with good fatigue strength, obtained by even and thorough working and heat treatment depends on the size and shape of the piece of alloy; good microstructures are usually obtained in smaller diameter rods and in sheet, but they are not so easily obtained in large bars or forgings. Therefore, the fatigue characteristics of bar stock are only strictly comparable with those of bars that have received a similar amount of work and heat treatment. **The size of the original rod or bar stock, or the sheet thickness, and the size, cold work and heat treatment applied to both the fatigue test specimen and the component must be considered before the fatigue characteristics of the component can be found.** The details of the specimens, the size of the original rod or bar or the thickness of the sheet from which they were cut have been provided in the Tables in Section 9. Where available, details of the heat treatment applied to the specimens are given in the accompanying Tables in Section 9 and terminology used, such as annealed and solution heat treated, should be used with caution.

Curves are provided for both plain and notched specimens in bending and under axial loading. To facilitate a comparison between the plain and the notched specimen results, the data are presented in terms of $K_t S_a/f_t$ and S'_m/f_t . For notched specimens when comparable notched data are not available, the plain specimen curves may be used to provide a conservative estimate of the permissible alternating stress by treating S_a/f_t as $K_t S_a/f_t$ and S_m/f_t as S'_m/f_t . The extent to which this alternating stress is conservative may be gauged by the difference between the plain and the notched specimen results at a given endurance. Note that for the larger specimens, the smaller this difference will be.

The tensile strength and the 0.2 per cent proof stress values quoted in the Tables in Section 9 were obtained from specimens cut from the same bar or sheet as the fatigue test specimens. The surface finish of the circular cross-section specimens is, where known, longitudinal polishing with a fine grade abrasive paper. The sheet specimens have been milled from sheet and then deburred. No treatment of the original sheet surfaces was carried out. The stress concentration factors are geometric and relate to changes in the form and not to stress concentrations that are part of the loading system, such as interference fits or joints in which fretting occurs.

3. WROUGHT Ti-6Al-4V ALLOYS

3.1 Stress Ratio and Microstructure

Figures 1, 10 and 12 present data for Ti-6Al-4V alloys tested with the stress ratio, R , between -1 and 0.8 (Derivations 31, 26 and 28). As is usually the case for other materials, Ti-6Al-4V alloys show that an increase in the mean stress results in a decrease in fatigue strength. The effects of mean stress are covered in ESDU 76014* and in FAT A.00.01† and FAT A.00.02‡.

* ESDU 76014, 'Estimation of endurance and construction of constant amplitude SN curves from related data corrected for notch and mean stress effects'.

† FAT A.00.01, 'The effect of mean stress on fatigue strength (plain test piece)'.

‡ FAT A.00.02, 'The effect of mean stress on fatigue strength (test piece with stress concentration)'.

In Figure 10, in the high cycle regime ($N > 10^7$ cycles), the annealed, hot rolled bar has a greater fatigue strength than alloys with an additional $\alpha + \beta$ forging (Derivation 26).

Figure 12 shows that a greater fatigue strength for Ti-6Al-4V alloys with a lamellar microstructure compared to alloys with a bimodal microstructure, particularly when $R = 0.5$ (Derivation 28). It should be noted that at shorter lifetimes, in the low-cycle fatigue regime, it is the bimodal microstructure which has the better fatigue properties. This is because of the higher ductility of this structure although only limited data are presented in the low-cycle fatigue regime.

3.2 Notches

Figure 2 shows that there is no discernible effect on the fatigue strength of Ti-6Al-4V alloys due to the shape or the volume of notches ($K_t = 2.5$ in both cases), although the data for the small volume Vnotches show more scatter (Derivation 31).

Figures 3 and 9 (Derivation 1), Figure 13 (Derivation 29), Figure 14 (Derivations 21, 23, 9, 14, 15 and 5), Figure 17 (Derivations 2 and 18), Figure 21 (Derivations 17, 11, 19 and 24), Figure 22 (Derivations 9 and 15), Figure 24 (Derivations 2, 18 and 6), Figure 26 (Derivations 12 and 16) and Figure 31 (Derivations 7 and 16) clearly show the expected decrease in fatigue strength when a notch is introduced.

3.3 Surface Finish

The effect of surface finish on the fatigue strength of Ti-6Al-4V alloys is presented in Figure 4. The specimens with a ground surface have the lowest fatigue strength. When the surface is mechanically polished or cold rolled there is a significant improvement in fatigue strength (Derivation 1). The specimens with a cold rolled surface have the highest fatigue strength due to cold working at the surface which creates compressive residual stresses that inhibit the initiation and propagation of cracks.

3.4 Microstructure and Heat Treatment

On Figures 5 and 6, the fatigue strength of the $\alpha + \beta$ quenched and overaged unnotched specimens and β -quenched notched specimens was greater compared to that of $\alpha + \beta$ annealed alloys (Derivation 1). The microstructure produced by $\alpha + \beta$ annealing consists of α islands in a β matrix (sometimes called α plus transformed β). $\alpha + \beta$ quenched and overaging produces a structure composed of primary α plus α' martensite whereas the microstructure for the β -quenched alloy was composed of α' martensite.

Figure 11 also shows there is a slight increase in the fatigue strength of a heat treated alloy (Derivation 27).

3.5 Fatigue Strength of $\alpha + \beta$ Forged Alloy

3.5.1 Annealed rod, bar and sheet in bending

Figure 14 presents the results of 218 fatigue tests, in both plane and rotating bending, carried out on notched and unnotched specimens of Ti-6Al-4V alloy that have been annealed between 700 and 850 °C (1292 and 1562 °F) (Derivations 21, 23, 9, 14, 15 and 5). 59 of the specimens were heated above the transus temperature and subsequently worked (in the $\alpha + \beta$ condition) to reduce the cross-section area to between 3:1 and 90:1 and then annealed at 700 °C (1292 °F). A reduction of more than 3:1, probably about 7:1, is required to obtain the microstructure necessary to obtain a good fatigue strength. 24 of the specimens were stress relieved at 625 °C (1152 °F) for 4 h and then air cooled after annealing, but this heat treatment produced no significant differences in the fatigue characteristics.

Figure 15 presents the results of 61 tests on unnotched specimens in which the specimens were either annealed at high temperatures or not heat treated (Derivations 21 and 15). The mean curve for unnotched data from Figure 14 is added on to Figure 15 for comparison. The 14 specimens annealed at 1050 °C (1922 °F), well above the transus temperature and consequently in the β condition, show poor fatigue strength. The 26 specimens annealed at between 910 and 950 °C (1670 and 1742 °F) also show poor fatigue strength.

3.5.2 Annealed rod, bar and sheet under axial loading

Figures 16 (Derivations 20, 23 and 18) and 17 (Derivations 2 and 18) show the results of 95 axial loading fatigue tests on Ti-6Al-4V alloy carried out using unnotched and notched annealed rods, respectively. Figures 18 (Derivations 22 and 12) and 19 (Derivation 12) show the results of 111 fatigue tests carried out on unnotched and notched specimens, respectively, that have been cut from large forged and annealed bars of Ti-6Al-4V alloy. The wide disparities between the curves on Figures 16 and 18, and between the curves of Figures 17 and 19, are probably due to the problems inherent in the production of large bars and forgings. Although results up to 5×10^7 cycles are available for the unnotched annealed bar (see Figure 17), no fatigue limit is indicated.

Figures 20 and 21 (Derivations 17, 11, 19 and 24) show the results of 207 fatigue tests carried out on unnotched and notched sheets of Ti-6Al-4V alloy, respectively. The unnotched data on Figure 20 show a large amount of scatter particularly around the medium level mean stress range.

3.6 Alloy Additions

Figures 7 and 8 (Derivation 32) show the effects of alloy additions in $\alpha + \beta$ annealed condition Ti-6Al-4V alloys for unnotched and notched specimens.

3.7 Fatigue Strength of Solution Treated and Aged Hardened Alloy

3.7.1 Rod, sheet and bar in bending

The tensile strength and the corresponding fatigue strength of an Ti-6Al-4V alloy is improved significantly by solution treatment, usually at around 950 °C (1742 °F), followed by quenching in water and ageing, usually at about 500 °C (932 °F) for between 3 to 6 hours.

Figure 22 shows the results of 138 fatigue tests carried out on unnotched and notched specimens in plane rotating bending (Derivations 9 and 15). A mean line is drawn through the unnotched data only.

3.7.2 Bar and rod under axial bending

Figures 23 (Derivations 8, 2 and 6) and 24 (Derivations 2, 18 and 14) present the results of 69 fatigue tests carried out on unnotched and notched specimens, respectively, that have been manufactured from rods of Ti-6Al-4V alloy. In addition, these figures also show the results of 23 fatigue tests carried out on unnotched and notched bars. It is evident that the bar data fall significantly below the rod data, and this is probably due to the problems inherent during the production of large bars or forgings.

3.7.3 Sheet under axial loading

Figures 25 (Derivations 3, 16 and 4) and 26 (Derivations 4 and 16) show the results of 237 fatigue tests carried out on unnotched and notched specimens respectively, manufactured from sheet of Ti-6Al-4V alloy. These figures also include a small number of results taken from specimens that have been over-aged which

are higher than those of the normally aged alloys. Because the tensile strength of the over-aged alloy is lower than that of the normally aged alloy, the absolute fatigue strengths resulting from these two heat treatments are not directly comparable.

3.8 Fatigue Strength of β Forged Alloy

Forging Ti-6Al-4V alloy at high temperatures in the β phase offers a more malleable billet with a resulting reduction in the number of forging operations required. The tensile properties are comparable to those of the $\alpha + \beta$ forged alloy.

3.8.1 Annealed alloy bar under bending

Figure 27 shows the results of 29 fatigue tests carried out on an unnotched bar subject to three different annealing treatments (Derivation 20). After a β forge there is no retained α phase so, unlike the ($\alpha + \beta$) forged alloy (see Figures 14 and 15), there is no significant variation in fatigue strength because of annealing between 730 and 950 °C (1346 and 1742 °F).

3.8.2 Annealed alloy bar under axial loading

Figures 28 and 29 present the results of 117 fatigue tests carried out on unnotched and notched specimens, respectively, cut from β -forgings of Ti-6Al-4V alloy which are subsequently annealed at 700 °C (1292 °F) and then forged at 1025, 1065 and 1150 °C (1877, 1949 and 2102 °F) (Derivation 12). There is a wide scatter of results at each forging temperature so there is insufficient evidence to attribute benefits to any one of the forging temperatures.

3.8.3 Solution treated and age hardened bar in bending

Figure 30 shows the results of 59 fatigue tests carried out on solution treated and age hardened unnotched bars of Ti-6Al-4V alloy under bending (Derivation 15). The tests cover six different combinations of solution treatment and ageing temperatures. Though there is only a limited amount of data, a solution treatment close to the transus temperature is more beneficial, with respect to fatigue strength, at very high endurance.

3.9 Extruded Strip and Annealed Strip

Extrusions are usually produced above the ($\alpha + \beta$)/ β transus temperature of the alloy and the resulting microstructures are coarse. Extruded strip is often stretch-straightened; thus, some cold working is carried out.

Figure 31 shows the results of 49 fatigue tests carried out on notched, extruded strip of Ti-6Al-4V alloy (Derivations 7 and 16). The available data for unnotched strips varies widely from Derivation to Derivation and are, therefore, not presented here. The scatter on Figure 31 may be due to either residual stresses or to the different annealing processes used so it is recommended that if unnotched data is needed then fatigue tests should be carried out on the specific extrusion of material used.

In the case of the notched extruded strip ($K_t = 2.76$ and 3.0), the scatter of the data is not exceptional so that the notch effects appear to overwhelm variances due to manufacturing techniques. Any effect of residual stresses is unlikely to show in notched data except in the unlikely event of the notch being located at a point of residual stress where the maximum stress (arising from $K_t(S_a + S_m)$ plus the residual stress) is below yield.

4. CAST Ti-6Al-4V ALLOYS

4.1 Loading Method

Figure 32 shows the effect of stress and strain controlled loading, and the combined curve for both stress and strain controlled tests, from tests carried out on a cast Ti-6Al-4V alloy (Derivation 30).

4.2 Casting Method and Surface Finish of Annealed Alloys

Figure 33 shows the results of 152 fatigue tests on cast specimens with unnotched machined surfaces (Derivations 10, 13 and 25). Apart from the data for the material manufactured by the metallic investment casting, the data correlate. The data for each S_m/f_t range fall into relatively small bands of $K_t S_a/f_t$; consequently, only two mean curves are provided, one for $S_m/f_t = 0$ and the other for $0.251 \leq S_m/f_t \leq 0.450$. In addition, a dashed curve is provided through the data for castings produced by the metallic investment mould which fall well below the body of the data. Insufficient details of the metallic investment casting procedures are available to discern the differences between them. However, the casting process can have a marked effect on fatigue strength of specimens with machined surfaces therefore testing of samples manufactured by the particular casting process to be used is recommended.

Figure 34 shows the results of 109 fatigue tests on notched ($K_t = 2.7$ or 3.0) cast specimens with machined surfaces (Derivations 10, 13 and 25). No attempt has been made to identify the various sources of the data since correlation between all the sources is good. Thus, for small notches, the effect of the notch appears to overwhelm variations due to the various casting processes. As on Figure 33, mean curves through the data are provided only for $S'_m/f_t = 0$ and $0.251 \leq S'_m/f_t \leq 0.450$. The unnotched curves from Figure 33 are also shown dashed on the Figure 34.

Figure 35 shows the results of 65 fatigue tests on specimens with as-cast surfaces produced by four different casting methods (Derivation 25). This shows that castings produced by metallic investment casting Mould 1 have a much higher fatigue strength than those produced by the other three casting processes, all of which appear to give similar fatigue strengths. Because of this, two curves are provided on Figure 35; each curve relates to $0.251 \leq S_m/f_t \leq 0.450$, the dashed curve being a curve for the metallic investment Mould 1 data and the solid curve a curve for all the other data. The surface finish and condition of the casting can significantly affect the fatigue strength therefore it is recommended that testing be carried out on specimens manufactured using the process under consideration for each case.

Figure 36 (Derivation 25) shows the results of 57 fatigue tests on shot peened samples with the four as-cast surfaces presented in Figure 35. Details of the shot peening process are given on the table that accompanies Figure 36. A small number of specimens were subjected to half the duration of shot peening as the others however there appears to be no measurable change in fatigue strength for these samples. No curves are provided through the data, however the curves for $0.251 \leq S_m/f_t \leq 0.450$ from Figures 33 and 35 are added for comparison. These suggest that peening can improve the fatigue strength of a specimen with an as-cast surface that is poor in fatigue and conversely that it can reduce the fatigue strength of a specimen with an ascast surface that has good fatigue strength. Generally, specimens with shot peened as-cast surfaces are comparable in fatigue strength to machined cast surfaces. However, the metallic investment cast data Mould 1 are the exception since those for the machined surface are poor but those for the as-cast surface are good; further their as-cast fatigue strength is reduced by peening. It is recommended that testing be carried out to determine the effect of peening on the particular cast surface to be used.

5. FATIGUE STRENGTH COMPARISON

Figure 37 compares the available zero mean stress lines for unnotched specimens and shows the relatively high fatigue limit for both forms of heat treatment of the $(\alpha + \beta)$ forged rod. The discrepancies between the bending and axial loading curves for the rod data are relatively small, particularly at high endurances. Also, there appears to be a fatigue limit for both the annealed alloy and for the solution treated and age hardened alloy with the limit for the former being distinctly higher than that of the latter. For example, in bending, the annealed alloy fatigue limit is about $0.6f_t$ and the value for the solution treated and age hardened alloy is about $0.485f_t$; however, the actual fatigue limits are very close, being 565 MN/m^2 ($81\,900 \text{ lbf/in}^2$) for the former and 550 MN/m^2 ($79\,800 \text{ lbf/in}^2$) for the latter. This order of difference exists between the two curves over all of their length and is typical of the differences between axially loaded annealed specimens and axially loaded solution treated and age hardened specimens.

The curves for specimens cut from large $(\alpha + \beta)$ forged bar and sheet shown on Figure 37 show the relatively poor fatigue strength of both forms of the material at high endurances. The differences between the two curves for sheet data follow the pattern discussed above for the two forms of heat treatment. The only curve of this group that appears to have a fatigue limit is that for the solution treated and age hardened sheet and the indicated fatigue limit is $0.30f_t = 3.51 \text{ MN/m}^2$ ($51\,000 \text{ lbf/in}^2$).

The effect of annealing temperature is shown on Figure 15. As noted in Section 3.5.1, annealing at high temperatures reduces the fatigue strength. The effect of solution treatment and ageing temperatures is shown on Figure 22 for $(\alpha + \beta)$ forged rod, and on Figure 30 for β forged bar. In both the $(\alpha + \beta)$ and β forged alloys, solution treatment at the higher temperatures, approaching the transus temperature, gives the better fatigue strength.

Noting that the β and $(\alpha + \beta)$ forged and annealed alloys have f_t values that are comparable, Figure 37 confirms the relatively poor fatigue strength of the β forged and annealed alloy. However, the β forged alloy bar does appear to have a fatigue limit at $0.38f_t = 3.70 \text{ MN/m}^2$ ($53\,800 \text{ lbf/in}^2$). Thus, at endurances of greater than 10^7 cycles, the data indicate that the β forged alloy bar is superior to the $(\alpha + \beta)$ forged alloy bar, which appears to exhibit no fatigue limit at 5×10^7 cycles at $S_{a0} = 0.32 f_t = 298 \text{ MN/m}^2$ ($43\,200 \text{ lbf/in}^2$).

No zero mean stress data for unnotched extruded strip are available. As discussed in 3.9, the available data for unnotched extruded strip are inconclusive and testing of the specific extrusion material is recommended.

Figure 37 shows that machined surfaces of cast alloy have a relatively low fatigue strength, indicating a fatigue limit at about $0.28f_t = 2.60 \text{ MN/m}^2$ ($37\,700 \text{ lbf/in}^2$). The unnotched fatigue strength of castings is significantly affected by the casting process, see Section 4.2. It is therefore recommended to carry out testing of the samples manufactured by each casting process considered.

Comparison of the figures shows that the conclusions drawn from Figure 37 are generally true if a mean stress is present.

When comparing the various manufacturing processes and heat treatments, attention is drawn to the wide variation in fracture toughness (K_{Ic})^{*} values (approaching 4 to 1 in extreme cases) resulting from them. The table below gives a guide to the relative (K_{Ic}) values resulting from the various forging and heat treatments. Further information on fracture toughness values may be obtained from Reference 33.

* The fracture toughness, K_{Ic} , referred to is described in ESDU 80036, 'Estimation of fatigue crack growth rates and residual strength of components using linear elastic fracture mechanics'.

Case	Forging type	Heat treatment	Relative K_{Ic} values
I	$(\alpha + \beta)$	None or solution treated and age hardened	Poor
II		Annealed	Up to twice Case I
III	β	None	Up to twice Case II
IV		Solution treated and age hardened	Better than Cases II and III
V		Annealed	Better than Case IV

6. DERIVATION AND REFERENCES

6.1 Derivation

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

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6.2 References

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7. HOW TO USE THIS DATA ITEM

Fatigue data, such as that for Ti-6Al-4V alloy in this Data Item, is usually collected from sets of specimens that have been tested in a laboratory and collated to help the engineer understand and compare the fatigue behaviour of the alloy during design or whilst the finished component is in service. A specimen is a typical sample of the alloy under investigation and, through a set of planned fatigue tests, is used to evaluate basic fatigue characteristics. The figures and tables that report fatigue data are a convenient way to check and compare the response of the alloy to various types of loading, stress ratios, environmental conditions, heat treatment and surface finishes applied during the design stage or can be used when estimating the remaining life of a component. A lot of the fatigue data for titanium alloys presented here can be generalised, however a full investigation is always recommended for a particular alloy and set of loading conditions.

Ti-6Al-4V titanium alloy is an $\alpha+\beta$ titanium alloy with a high strength to weight ratio and excellent corrosion resistance making it suitable for use in the aerospace industry. Titanium alloys can be costly and require expensive manufacturing techniques and machining methods so, where appropriate, the designer may choose a cheaper titanium alloy or maybe even decide to make the component from a different material altogether to save expenditure. Other titanium alloys in common use range from commercially pure titanium to alloys containing various amounts of α -phase or β -phase stabilising elements to tailor their mechanical and fatigue properties. Titanium alloys also contain interstitial alloying elements such as carbon, nitrogen and hydrogen to increase the tensile strength of the alloy. The manufacturing processes to form and treat the titanium alloys are usually carried out in a vacuum or in an inert gas atmosphere to limit the presence of oxygen due to the highly reactive nature of titanium.

Titanium alloys are usually supplied in either the wrought condition (see Section 3) or as a casting (see Section 4). The thickness of the specimen or the component from which the test specimen is taken, the grain direction (longitudinal or transverse) and the microstructure may all affect fatigue properties.

Heat treatments (such as those explained in Appendix A) are used to reduce residual stresses and increase the tensile strength and improve fatigue properties of titanium alloys. However not all heat treatments are applicable to every titanium alloy, therefore the correct heat treatment must be chosen for each alloy and its requirements.

The method of surface preparation applied after heat treatment can also have a significant effect on the fatigue behaviour of the Ti-6Al-4V alloy. Processes such as peening (see ESDU 92015 for information on shot peening) or polishing can improve the fatigue properties as well as improving the appearance of the component.

The samples used to collect fatigue data can be either plain specimens or specimens containing one of several types of notch. The stress concentration factor, K_t , arising from a notch is incorporated in the presentation of the fatigue data on the figures in this Data Item to account for the major effects of geometry and this, along with the inclusion of the material tensile strength, is used to normalise the fatigue data presented on the figures.

Types of loading applied when testing the specimen should be chosen to best represent the expected loads during service. If a wide range of loading is expected then constant or variable loading counting techniques can be found in ESDU 76014* and ESDU 95006†. During a fatigue test, the chosen applied stress ratio, R , is important and the effect of mean stress can be found in ESDU FAT A.00.01‡ and FAT A.00.02**.

* ESDU 76014, 'Estimation of endurance and construction of constant amplitude S-N curves from related data corrected for notch and mean stress effects'.

† ESDU 95006, 'Fatigue life estimation under variable amplitude loading using cumulative damage calculations'.

‡ ESDU FAT.00.01, 'The effect of mean stress on fatigue strength (plain test piece)'.

** ESDU FAT.00.02, 'The effect of mean stress on fatigue strength (test piece with stress concentration)'.

Titanium alloys can be used in service from cryogenic temperatures up to around 500 °C (932 °F), and may also be used in a corrosive environments particularly oxidizing and chloride-containing process streams. Temperature extremes and corrosive environments can have an impact on the fatigue response of the titanium alloys therefore these variables are often replicated in the fatigue test.

Furthermore, in service the component may be subject to fretting fatigue – a process of surface damage that results from the relative motion between two contacting surfaces, see ESDU 88027. Fretting, when combined with existing alternating stresses will reduce the fatigue performance of the titanium alloy.

Once the fatigue response from the rounds of test has been collected, it is useful to do some statistical analysis on the data using methods outlined in ESDU 91041^{*} and ESDU 92040[†]. Additionally, ESDU 97024 may be used to plot curves through the fatigue data.

^{*} ESDU 91041, 'The statistical analysis of data from Normal distributions, with particular reference to small samples'.

[†] ESDU 92040, 'An introduction to the statistical analysis of engineering data'.

8. INDEX FOR WROUGHT AND CAST ALLOYS

TABLE 8.1 Index to data for wrought Ti-6Al-4V titanium alloys (UNS RS56400)

<i>Figure number</i>	<i>Derivation</i>	<i>Supplementary data</i>	<i>Test Variable</i>	<i>Form</i>
1	31	Table 9.1	R	Forging
2	31	Table 9.2	Notch geometry	Forging
3	1	Table 9.3	Notches	Bar
4	1	Table 9.4	Surface finish	Rod
5	1	Table 9.5	Microstructure	Bar
6	1	Table 9.6	Microstructure	Bar
7	32	Table 9.7	Alloying additions	Bar
8	32	Table 9.8	Alloying additions	Bar
9	1	Table 9.8	Notches, heat treatment	Extrusion
10	26	Table 9.10	R , forging	Hot rolled
11	27	Table 9.11	Heat treatment	Rolled plate
12	28	Table 9.12	R , microstructure	Forging
13	29	Table 9.13	Notches	Sheet
14	21, 23, 9, 14, 15, 5	Table 9.14	Notches, heat treatment	Rod, bar, sheet
15	21, 15	Table 9.15	Heat treatment	Rod, bar
16	20, 23, 18	Table 9.16	Heat treatment	Rod
17	2, 18	Table 9.17	Notches, heat treatment	Rod
18	22, 12	Table 9.18	Heat treatment	Bar
19	12	Table 9.19	Fatigue strength	Bar
20	17, 11, 19, 24	Table 9.20	Heat treatment	Sheet
21	17, 11, 19, 24	Table 9.21	Notches, heat treatment	Sheet
22	9, 15	Table 9.22	Notches, heat treatment	Rod, bar sheet
23	8, 2, 6	Table 9.23	Heat treatment	Rod, bar
24	2, 18, 6	Table 9.24	Notches, heat treatment	Rod, bar
25	3, 16, 4	Table 9.25	Heat treatment	Sheet
26	4, 16	Table 9.26	Notches, heat treatment	Sheet
27	15	Table 9.27	Heat treatment	Bar
28	12	Table 9.28	Forging	Bar
29	12	Table 9.29	Forging	Bar
30	15	Table 9.30	Heat treatment	Bar
31	7, 16	Table 9.31	Notches, heat treatment	Strip

TABLE 8.2 Index to data for cast Ti-6Al-4V titanium alloys (UNS RS56400)

Figure number	Derivation	Supplementary data	Test Variable	Form
32	30	Table 9.32	Loading	Cast
33	10, 13, 25	Table 9.33	Casting technique	Cast
34	10, 13, 25	Table 9.34	Casting technique	Cast
35	25	Table 9.35	Casting technique	Cast
36	25	Table 9.36	Casting technique	Cast

9. TABLES AND FIGURES

Unless stated otherwise, the mechanical properties quoted are room temperature values from tests on specimens cut from the same material as the fatigue specimens. The numbers on the Figures next to some data points indicate the number of coincident data points.

In some cases, where two or more data points fall on, or very close to, one another, data points have been displaced slightly on the figures to aid presentation; the values given in the Excel file that accompanies this Item are the true, un-displaced, values.

The curves through the data have been derived using ESDUpac A9724. For a number of the sets of data, the large numbers of run-outs at relatively high stresses initially gave rise to unrealistic curves. The approach was therefore adopted whereby run-outs that occurred at stresses above those at which failure occurred in other tests were treated as failures. This approach has been used throughout, for all sets of data.

9.1 Wrought Alloys

TABLE 9.1 Supplementary data for Figure 1

Material	Ti-6Al-4V alloy			Derivation				31
Composition wt %	Al	V	C	Fe	O	N	H	
	5.5 min	3.5	0.08	0.30	0.20	0.05	0.0125	
	6.75 max	4.5 max						
σ_y MN/m ² (10 ³ lbf/in ²)	930 (135)							
f_p MN/m ² (10 ³ lbf/in ²)	–							
f_t MN/m ² (10 ³ lbf/in ²)	978 (142)							
Loading type	Axial			Specimen geometry		Unnotched		
Heat treatment	Pre-heat to 938 °C (1720 °F) prior to forging. Forgings solution treated at 932 °C (1710 °F), fan cooled, overaged at 704.4 °C (1300 °F) for 2 h.							
Test temperature °C (°F)	Room temperature							
R	(a) –1 (b) 0.1 (c) 0.5 (d) 0.8				Frequency		60 Hz	
Grain direction	Longitudinal				Surface finish		Ground and polished	
Test variable	R							

TABLE 9.2 Supplementary Data for Figure 2

Material	Ti-6Al-4V alloy					Derivation			31
Composition wt %	Al	V	C	Fe	O	N	H		
	5.5 min	3.5 min	0.08	0.30	0.20	0.05	0.0125		
	6.75 max	4.5 max							
σ_y MN/m ² (10 ³ lbf/in ²)	930 (135)								
f_p MN/m ² (10 ³ lbf/in ²)	–								
f_t MN/m ² (10 ³ lbf/in ²)	978 (142)								
Loading type	Axial	Specimen geometry		(a) Small volume V-notch, $K_t = 2.5$ (b) Large volume semi-circular notch, $K_t = 2.5$					
Heat treatment	Pre-heat to 938 °C (1720 °F) prior to forging. Forgings solution treated at 932 °C (1710 °F), fan cooled, overaged at 704.4 °C (1300 °F) for 2 h.								
Test temperature °C (°F)	Room temperature								
R	0.1				Frequency		60 Hz		
Grain direction	Longitudinal				Surface finish		Ground and polished		
Test variable	Notch geometry								

TABLE 9.3 Supplementary Data for Figure 3

<i>Material</i>	Ti-6Al-4V alloy				<i>Derivation</i>		1
<i>Composition</i> wt %	C	N	Al	V			
	0.025	0.012	5.91	3.78			
σ_y MN/m ² (10 ³ lbf/in ²)	1158 (168)						
f_p MN/m ² (10 ³ lbf/in ²)	–						
f_t MN/m ² (10 ³ lbf/in ²)	1276 (185)						
<i>Loading type</i>	Axial				<i>Specimen geometry</i>		(a) Unnotched (b) Notched, $K_t = 3.75$
<i>Heat treatment</i>	Solution heat treated 871 °C (1600 °F), water quenched, aged 468 °C (875 °F) for 6 h, air cooled						
<i>Test temperature</i> °C (°F)	Room temperature						
<i>R</i>	0.02				<i>Frequency</i>		–
<i>Grain direction</i>	–				<i>Surface finish</i>		Machined
<i>Test variable</i>	Notches						

TABLE 9.4 Supplementary Data for Figure 4

<i>Material</i>	Ti-6Al-4V alloy				<i>Derivation</i>		1
<i>Composition</i> wt %	C	N	Al	V	H		
	0.014	0.13	6.0	4.2	0.007		
σ_y MN/m ² (10 ³ lbf/in ²)	889 (129)						
f_p MN/m ² (10 ³ lbf/in ²)	–						
f_t MN/m ² (10 ³ lbf/in ²)	1027 (149)						
<i>Loading type</i>	Rotating beam				<i>Specimen geometry</i>	Unnotched	
<i>Heat treatment</i>	–						
<i>Test temperature</i> °C (°F)	Room temperature						
<i>R</i>	–1						
<i>Grain direction</i>	–		<i>Frequency</i>			60 Hz	
			<i>Surface finish</i>			(a) Mechanically polished (b) Ground (c) Cold rolled to 18.1 kg (40 lb)	
<i>Test variable</i>	Surface finish						

TABLE 9.5 Supplementary Data for Figure 5

Material	Ti-6Al-4V alloy						Derivation	1
Composition wt %	C	N	Fe	O	H	V	Al	
	0.02	0.009	0.10	0.10	0.0052	3.97	6.03	
σ_y MN/m ² (10 ³ lbf/in ²)	–							
f_p MN/m ² (10 ³ lbf/in ²)	–							
f_t MN/m ² (10 ³ lbf/in ²)	(a) 1032 (150) (b) 1160 (154) (c) 1130 (164)							
Loading type	Rotating beam			Specimen geometry		Unnotched		
Heat treatment	(a) $\alpha + \beta$ anneal 815 °C (1500 °F) for 1 h, furnace cool to 593 °C (1100 °F), air cool (b) $\alpha + \beta$ quench and overage (held at average 926 °C (1700 °F) for 1 h, water quenched, 593 °C (1100 °F) for 2 h, air cool) (c) β quench (held at 982 °C (1800 °F) for 1 h, water quenched)							
Test temperature °C (°F)	Room temperature							
R	–1				Frequency		133 Hz	
Grain direction	–				Surface finish		Hand polished	
Test variable	Microstructure							

TABLE 9.6 Supplementary Data for Figure 6

Material	Ti-6Al-4V alloy						Derivation	1
Composition wt %	C	N	Fe	O	H	V	Al	
	0.009	0.10	0.10	0.10	0.0052	3.97	6.03	
σ_y MN/m ² (10 ³ lbf/in ²)	–							
f_p MN/m ² (10 ³ lbf/in ²)	–							
f_t MN/m ² (10 ³ lbf/in ²)	(a) 1032 (150) (b) 1160 (168) (c) 1130 (164)							
Loading type	Rotating bending			Specimen geometry			Notched, $K_t = 3$	
Heat treatment	(a) $\alpha + \beta$ anneal 815 °C (1500 °F) for 1 h, furnace cool to 593 °C (1100 °F), air cool (b) $\alpha + \beta$ quench and overage (held at average 926 °C (1700 °F) for 1 h, water quenched, 593 °C (1100 °F) for 2 h, air cool) (c) β quench (held at 982 °C (1800 °F) for 1 h, water quenched)							
Test temperature °C (°F)	Room temperature							
R	–1				Frequency		133 Hz	
Grain direction	–				Surface finish		Hand polished	
Test variable	Microstructure							

TABLE 9.7 Supplementary Data for Figure 7

<i>Material</i>	Ti-6Al-4V alloy						<i>Derivation</i>	32
<i>Composition</i> wt %	C	N	Fe	O	H	V	Al	
	0.02	0.009	0.10	0.10	0.0052	3.97	6.03	
σ_y MN/m ² (10 ³ lbf/in ²)	–							
f_p MN/m ² (10 ³ lbf/in ²)	–							
f_t MN/m ² (10 ³ lbf/in ²)	(a) 1032 (150)				(d) 1150 (167)			
	(b) 1119 (162)				(e) 1189 (172)			
	(c) 1111 (161)							
<i>Loading type</i>	Rotating beam				<i>Specimen geometry</i>		Unnotched	
<i>Heat treatment</i>	(a) Ti-6Al-4V (base interstitial level) 815.6 °C (1500 °F) furnace cool to 593.3 °C (1100 °F), air cool							
	(b) Ti-6Al-4V + 0.07 N, annealed 843.3 °C (1550 °F) for 2 h, furnace cool to 593.3 °C (1100 °F), air cool							
	(c) Ti-6Al-4V + 0.20 O, annealed 871.1 °C (1600 °F) for 2 h, furnace cool to 593.3 °C (1100 °F), air cool							
	(d) Ti-6Al-4V + 0.20 C, annealed 843.3 °C (1550 °F) for 2 h, furnace cool to 593.3 °C (1100 °F), air cool							
	(e) Ti-6Al-4V + 0.07 N + 0.20 O + 0.20 C, annealed 926.7 °C (1700 °F) for 2 h, furnace cool to 593.3 °C (1100 °F), air cool							
<i>Test temperature</i> °C (°F)	Room temperature							
<i>R</i>	–1				<i>Frequency</i>		133 Hz	
<i>Grain direction</i>	–				<i>Surface finish</i>		Hand polished	
<i>Test variable</i>	Alloying additions							

TABLE 9.8 Supplementary Data for Figure 8

Material	Ti-6Al-4V alloy						Derivation	32
Composition	C	N	Fe	O	H	V	Al	
wt %	0.02	0.009	0.10	0.10	0.0052	3.97	6.03	
σ_y MN/m ² (10 ³ lbf/in ²)	–							
f_p MN/m ² (10 ³ lbf/in ²)	–							
f_t MN/m ² (10 ³ lbf/in ²)	(a) 1032 (149.7) (b) 1119 (162.3) (c) 1111 (161.2)				(d) 1150 (166.8) (e) 1189 (172.4)			
Loading type	Rotating beam				Specimen geometry	Notched, $K_t = 3.0$		
Heat treatment	(a) Ti-6Al-4V (base interstitial level) 815.6 °C (1500 °F) furnace cool to 593.3 °C (1100 °F), air cool (b) Ti-6Al-4V + 0.07 N, annealed 843.3 °C (1550 °F) for 2 h, furnace cool to 593.3 °C (1100 °F), air cool (c) Ti-6Al-4V + 0.20 O, annealed 871.1 °C (1600 °F) for 2 h, furnace cool to 593.3 °C (1100 °F), air cool (d) Ti-6Al-4V + 0.20 C, annealed 843.3 °C (1550 °F) for 2 h, furnace cool to 593.3 °C (1100 °F), air cool (e) Ti-6Al-4V + 0.07 N + 0.20 O + 0.20 C, annealed 926.7 °C (1700 °F) for 2 h, furnace cool to 593.3 °C (1100 °F), air cool							
Test temperature °C (°F)	Room temperature							
R	–1				Frequency	133 Hz		
Grain direction	–				Surface finish	Hand polished		
Test variable	Alloying additions							

TABLE 9.9 Supplementary Data for Figure 9

<i>Material</i>	Ti-6Al-4V alloy		<i>Derivation</i>	1
<i>Composition</i> wt %	–			
σ_y MN/m ² (10 ³ lbf/in ²)	(a) 910 (132) (b) 1010 (146)			
f_p MN/m ² (10 ³ lbf/in ²)	–			
f_t MN/m ² (10 ³ lbf/in ²)	(a) 984 (143) (b) 1160 (168)			
<i>Loading type</i>	Axial		<i>Specimen geometry</i>	(i) Unnotched (ii) Notched, $K_t = 2.0$
<i>Heat treatment</i>	(a) As received (b) Solution heat treated 885 °C (1625 °F) for 1 h, water quenched, aged 468 °C (875 °F) for 6 h, air cool			
<i>Test temperature</i> °C (°F)	Room temperature			
<i>R</i>	0.02		<i>Frequency</i>	–
<i>Grain direction</i>	–		<i>Surface finish</i>	–
<i>Test variable</i>	Notches, heat treatment			

TABLE 9.10 Supplementary Data for Figure 10

<i>Material</i>	Ti-6Al-4V alloy		<i>Derivation</i>	26
<i>Composition</i> wt %	–			
σ_y MN/m ² (10 ³ lbf/in ²)	–			
f_p MN/m ² (10 ³ lbf/in ²)	(a) 1100 (160) (b) 900 (131)			
f_t MN/m ² (10 ³ lbf/in ²)	(a) 880 (128) (b) 843 (122)			
<i>Loading type</i>	–		<i>Specimen geometry</i>	–
<i>Heat treatment</i>	(a) As received, annealed hot rolled bar (b) $\alpha + \beta$ forging: slowly cooled from above β –transus (1067 °C (1952.6 °F)) then annealed 700 °C (1292 °F) for 1 h			
<i>Test temperature</i> °C (°F)	–			
<i>R</i>	(i) 0 (ii) –1		<i>Frequency</i>	–
<i>Grain direction</i>	–		<i>Surface finish</i>	–
<i>Test variable</i>	R, forging			

TABLE 9.11 Supplementary Data for Figure 11

	Material	Ti-6Al-4V alloy						Derivation	27
Composition wt %	C	Fe	N	Al	V	H	O		
	0.018	0.16	0.014	6.3	4.3	0.005	0.16		
σ_y MN/m ² (10 ³ lbf/in ²)	–								
f_p MN/m ² (10 ³ lbf/in ²)	(a) 880 (128) (b) 843 (122)								
f_t MN/m ² (10 ³ lbf/in ²)	(a) 952 (138) (b) 961 (139)								
Loading type	Axial			Specimen geometry			Notched, $K_t = 3.5$		
Heat treatment	(a) As received, cross rolled at 954 °C (1750 °F) and mill annealed (b) Solution heat treated, 927 °C (1700 °F) for 4 h, furnace cool to 760 °C (1400 °F), air cool								
Test temperature °C (°F)	Room temperature								
R	0.1				Frequency		33 Hz		
Grain direction	–				Surface finish		Machined		
Test variable	Heat treatment								

TABLE 9.12 Supplementary Data for Figure 12

Material	Ti-6Al-4V alloy						Derivation	28
Composition wt %	Al	V	Fe	O	N	H		
	6.3	4.17	0.19	0.19	0.013	0.0041		
σ_y MN/m ² (10 ³ lbf/in ²)	(a) Bimodal 930 (135) (b) Lamellar 975 (141)							
f_p MN/m ² (10 ³ lbf/in ²)	–							
f_t MN/m ² (10 ³ lbf/in ²)	(a) Bimodal 978 (142) (b) Lamellar 1055 (153)							
Loading type	Axial			Specimen geometry		Unnotched		
Heat treatment	(a) Pre-heated 940 °C (1724 °F) 30 minutes, forged. Solution treated at 925 °C (1697 °F) 1 h, fan air cooled, stabilized at 700 °C (1292 °F) 2 h. Resulting microstructure is a bimodal distribution of interconnected equiaxed primary α grains and lamellar $\alpha + \beta$ colonies (transformed β). (b) Solution treated in vacuum of 10 ^{−5} to 10 ^{−6} mbar at 1005 °C (1841 °F) – slightly above β –transus temperature – for 10 to 30 minutes (depending on cross section), rapid quenched (~ 100 °C/min) in high purity helium gas, stabilized at 700 °C (1292 °F) 2 h in vacuo, furnace cool to room temperature. This results in a Widmanstätten, lamellar, microstructure.							
Test temperature °C (°F)	Room temperature							
R	(i) 0.1 (ii) 0.5			Frequency		25 Hz < 10 ⁶ cycles 1000 Hz > 10 ⁶ cycles		
Grain direction	Longitudinal			Surface finish		Chemical milling		
Test variable	R , microstructure							

TABLE 9.13 Supplementary Data for Figure 13

<i>Material</i>	Ti-6Al-4V alloy					<i>Derivation</i>	29
<i>Composition</i> wt %	C	Fe	N	H	Al	V	
	0.026	0.15	0.013	0.011	6.1	4.0	
σ_y MN/m ² (10 ³ lbf/in ²)	979 (142)						
f_p MN/m ² (10 ³ lbf/in ²)	–						
f_t MN/m ² (10 ³ lbf/in ²)	1030 (149)						
<i>Loading type</i>	Axial			<i>Speciman geometry</i>		(a) Unnotched (b) Notched, $K_t = 4$	
<i>Heat treatment</i>	Annealed 802 °C (1475 °F) 1h, furnace cooled to 704.4 °C (1300 °F), air cool.						
<i>Test temperature</i> °C (°F)	Room temperature						
<i>R</i>	–			<i>Frequency</i>		30 Hz	
<i>Grain direction</i>	Longitudinal			<i>Surface finish</i>		600 grit paper	
<i>Test variable</i>	Notches, mean stress = 170 MN/m ² (25 × 10 ³ lbf/in ²)						

TABLE 9.14 Supplementary Data for Figure 14

Material	Ti-6Al-4V alloy							Derivation	21, 23, 9, 14, 15, 5
Composition wt %		Al	V	Fe	O	H	C	N	
	min	6.1	3.97	0.07	0.01	0.005	0.02	0.01	
	max	6.5	4.2	0.16	0.15	0.03	0.32	0.06	
σ_y MN/m ² (10 ³ lbf/in ²)	–								
f_p MN/m ² (10 ³ lbf/in ²)	(a) – (h) 876 (127) (b) – (i) 876 (127) (c) – (j) – (d) – (k) 876 (127) (e) – (l) 876 (127) (f) 783 (114) (m) 783 (114) (g) 783 (114)								
f_t MN/m ² (10 ³ lbf/in ²)	(a) 910 (132) (h) 1010 (146) (b) 910 (132) (i) 1010 (146) (c) 945 (137) (j) 951 (138) (d) 931 to 945 (135 to 137) (k) 958 (139) (e) 972 to 1010 (141 to 146) (l) 958 (139) (f) 902 (130) (m) 1130 (164) (g) 902 (130)								
Loading type	(a) to (l) Rotating bending (m) Plain bending					Specimen geometry		(a) – (f), (h), (j), (l) Unnotched (g) (i) Notched, $K_t = 3.5$ (k) Notched, $K_t = 2.2$ (m) Notched, $K_t = 1.2$	
Heat treatment	(a) Annealed* then stress relieved 625 °C (1157 °F) for 4 h, air cool (b) β annealed at 1120 °C (2048 °F) then final anneal at 700 °C (1292 °F) for 1 hr per inch of section (c) As (b) including $\alpha + \beta$ working at 850 – 910 °C (1562 – 1670 °F) to achieve a 3:1 reduction before final anneal (d) As (b) including $\alpha + \beta$ working at 850 – 910 °C (1562 – 1670 °F) to achieve an 8:1 and 10:1 reduction before final anneal (e) As (b) including $\alpha + \beta$ working at 850 – 910 °C (1562 – 1670 °F) to achieve a 32:1 and 90:1 reduction before final anneal (f), (g) Annealed 700 °C (1292 °F) 2 h, air cool (h), (i) Annealed 843 °C (1550 °F) 1 h, air cool Cooled from annealing temperature* at 55 °C/h (131 °F/h) to 550 °C (1022 °F) then air cooled (j) Vacuum furnace annealed* (k), (l) Vacuum furnace annealed* (m) Annealed 700 °C (1292 °F) 2 h, air cool								
Test temperature °C (°F)	Room temperature								
R	–1					Frequency		100 to 192 Hz	
Grain direction	–					Surface finish		Hand polished	
Test variable	Notches, heat treatment								

* No further details given.