

FATIGUE OF WROUGHT AND CAST Ti-6Al-4V TITANIUM ALLOY (In bending and under axial loading)

1. NOTATION

f_p	0.2 per cent proof stress	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 area		
N	endurance		
S_a	alternating stress, based on net area	N/m ²	lbf/in ²
S_{a0}	alternating stress at zero mean stress, based on net area	N/m ²	lbf/in ²
S_m	mean stress, based on net 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

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

2. INTRODUCTION

This Item presents data on the fatigue strength of the six per cent aluminium, four per cent vanadium, titanium alloy at normal temperature. The data are presented in terms of $K_t S_a / f_t$ plotted against N and, where pertinent, the ranges of mean stress values are indicated in terms of S'_m / f_t . Data are provided for forged bar, rod and sheet, extruded strip and castings. The data are sub-divided according as to whether the alloy was annealed or solution 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 was forged above or below its $(\alpha + \beta) / \beta$ transus temperature. In all cases details of the specimens from which the data were derived are provided in the tables and Section 10 provides a figure and table location chart.

3. GENERAL NOTES

The microstructure of Ti-6Al-4V has a marked effect on its fatigue strength. The microstructure is governed by the phase state of the alloy at the time of forging or extruding. Forging above the $(\alpha + \beta) / \beta$ transus temperature of about 995°C leads to a coarse Widmanstätten microstructure. Forging below the transus temperature, in the $(\alpha + \beta)$ phase, is most usual since the microstructure obtained is capable of refinement by working and subsequent heat treatment. Extrusions are usually produced above the transus temperature and therefore have a coarse microstructure. Cast Ti-6Al-4V has a large grain size and hence a relatively poor fatigue strength.

The typical microstructure of the $(\alpha + \beta)$ forged alloy and its associated good fatigue strength are obtained by even and thorough working and heat treatment. However, the degree of working is to some extent dependent upon the size and shape of the piece of alloy and, in consequence, a good microstructure is usually obtained in small diameter rod and in sheet but is not so easily obtained in large bars and forgings. Therefore, the fatigue characteristics obtained from bar stock are only strictly comparable with those of stock that has received a similar amount of work and similar heat treatment. **Thus, the size of the original rod or bar stock or the sheet thickness and the sizes of both the fatigue test specimen and the component must be considered before the probable fatigue characteristics of the component can be deduced.** To assist in the making of this estimate details of the specimens, the size of the original rod or bar or the thickness of the sheet from which they were cut are provided in tables.

Curves are provided for both plain and notched specimens in bending and under axial loading. To facilitate comparison between plain and notched specimen results, the data are presented in terms of $K_t S_a/f_t$ and S'_m/f_t . For notched components for which 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 specimen curve and the notched specimen results at the given endurance. However, the larger the specimen, the smaller the difference.

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

4. FATIGUE STRENGTH OF THE $(\alpha + \beta)$ FORGED ALLOY

4.1 Annealed Alloy

The ductility of the alloy increases with increasing annealing temperature and reaches a maximum after annealing at about 900°C. However, oxidation of the surface becomes more serious at the higher temperatures and it is currently common practice to anneal at about 700°C.

4.1.1 Annealed rod, bar and sheet in bending

Figure 1 presents the results of 218 tests, in both plane and rotating bending, on notched and unnotched specimens annealed between 700°C and 850°C. A mean line is drawn through the unnotched data only. Fifty nine of the specimens were heated above the transus temperature and were subsequently worked (in the $(\alpha + \beta)$ condition) to obtain reductions of cross-sectional area of between 3:1 and 90:1 and were then annealed at 700°C. From consideration of Figure 1 and Table 10.1 it may be seen that the specimens worked to the comparatively small reduction of 3:1 tend to be below the mean line. This suggests that a reduction of more than 3:1, probably about 7:1, is required to obtain the microstructure necessary for good fatigue strength. Twenty four of the specimens were stress relieved (at 625°C for four hours then air cooled) after annealing but this treatment produced no significant differences in the fatigue characteristics.

Figure 2 presents the results of 61 tests on unnotched specimens in which the specimens were either annealed at high temperatures or not heat treated. The mean curve for unnotched data on Figure 1 is added to Figure 2 for comparison. The 14 specimens annealed at 1050°C, well above the transus temperature and consequently in the β condition, exhibit poor fatigue strength. The 26 specimens annealed at between 910°C and 950°C also show poor fatigue strength.

4.1.2 Annealed rod, bar and sheet under axial loading

Figures 3 and 4 show the results of 95 axial loading tests on unnotched and notched annealed rod respectively. Figures 5 and 6 show the results of 111 fatigue tests on unnotched and notched specimens cut from large forged and annealed bar. The wide disparities between the curves of Figures 3 and 5 and between the curves of Figures 4 and 6 are mainly due to the problems inherent in the production of large bars and forgings, as discussed in Section 3. Although results up to 5×10^7 cycles are available for the unnotched annealed bar (see Figure 5) no fatigue limit is indicated.

Figures 7 and 8 show the results of 207 fatigue tests on unnotched and notched sheet respectively. The curves of Figure 7 are added to Figure 8 for comparison. The unnotched data of Figure 7 exhibit large scatter particularly in the medium level mean stress range. The curves provided are mean curves based upon all of the data shown.

4.2 Solution Treated and Age Hardened Alloy

The tensile strength of the alloy is improved significantly by solution treatment, usually at about 950°C, followed by quenching in water and ageing, usually at about 500°C for 3 to 6 hours.

4.2.1 Solution treated and age hardened rod, sheet and bar in bending

Figure 9 shows the results of 138 fatigue tests on both notched and unnotched specimens in plane and rotating bending. A mean line is drawn through the unnotched data only.

4.2.2 Solution treated and age hardened bar and rod under axial loading

Figures 10 and 11 show the results of 69 fatigue tests on unnotched and notched specimens, respectively, manufactured from rod. Curves are provided through these data. In addition, Figures 10 and 11 show the results of 23 fatigue tests on notched and unnotched bar. No curves are drawn through these few data points, nevertheless it is evident that they fall significantly below those of the rod data. This is probably due to the problems inherent in the production of large bars and forgings as discussed in Section 3.

4.2.3 Solution treated and age hardened sheet under axial loading

Figures 12 and 13 show respectively the results of 237 fatigue tests on unnotched and notched specimens manufactured from sheet. Both figures include a small number of results from specimens that have been over-aged (see Table 10.6). These appear higher than those of the normally aged alloy and have been ignored when drawing the curves. 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 comparable.

5. FATIGUE STRENGTH OF β FORGED ALLOY

Forging the alloy at high temperature 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.

5.1 Annealed Alloy Bar Under Bending

Figure 14 shows the results of 29 fatigue test results on unnotched bar for three different annealing treatments. Unlike the $(\alpha + \beta)$ forged alloy (see Figures 1 and 2) the variation in fatigue strength as a result of annealing at between 730°C and 950°C is not significant.

5.2 Annealed Alloy Bar Under Axial Loading

Figures 15 and 16 show the results of 117 unnotched and notched fatigue tests respectively on specimens cut from β forgings that were subsequently annealed at 700°C. Three forging temperatures were used, 1025°C, 1065°C and 1150°C, and the results relating to each forging temperature are identified on the figures. As can be seen there is a wide scatter of the results for each forging temperature and as a result there is insufficient evidence to attribute any particular benefits to any one of the forging temperatures.

5.3 Solution Treated and Age Hardened Bar Under Bending

Figure 17 shows the results of 59 fatigue tests on unnotched bar. The tests cover six different combinations of solution treatment and ageing temperatures. This limited amount of data indicates that solution treatment close to the transus temperature is more beneficial with respect to fatigue strength at very high endurances.

6. EXTRUDED AND ANNEALED STRIP

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

Figure 18 shows the results of 49 fatigue tests on notched extruded strip. The data are taken from two sources (see Table 10.8) and the curves provided are a best fit to all the data. The available data on unnotched strip show wide variations from source to source and are therefore not presented. The scatter may be due to residual stresses and to the different annealing processes for which data are available. It is therefore recommended that, in the event of unnotched data being required, fatigue tests be carried out on the specific extrusion material to be used.

In the case of 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.

7. CAST AND ANNEALED ALLOY

Figure 19 shows the results of 152 fatigue tests on unnotched machined surfaces of castings. With the exception of the data for the material manufactured by metallic investment (Supplier I), see Table 10.9, the data correlate. The data for each S_m/f_t range fall into relatively small bands of 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 metallic investment (Supplier I) which fall well below the body of the data. Insufficient details of the metallic investment casting procedures of Suppliers I and II are available to discern the differences between them. However, it is clear that the casting process can have a marked effect on fatigue strength of machined surfaces and testing of samples manufactured by the particular casting process to be employed is recommended.

Figure 20 shows the results of 109 fatigue tests on notched ($K_t = 2.7$ or 3.0) machined surfaces of castings. No attempt has been made to identify the various sources of the data since correlation between all the sources listed on Table 10.9 is good. Thus, for small notches, K_t in the range quoted on Table 10.9, the effect of the notch appears to overwhelm variations due to the various casting processes. As on Figure 19, 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 19 are also shown dashed on the figure.

Figure 21 shows the results of 65 fatigue tests on as-cast surfaces produced by four different casting methods. This shows that castings produced by metallic investment (Supplier I) have a much higher fatigue strength than the other three casting processes, all of which appear to have similar fatigue strengths. Because of this, two curves are provided on the figure; each curve relates to $0.251 \leq S'_m/f_t \leq 0.450$, the dashed curve being a mean curve for the metallic investment (Supplier I) data and the solid curve a mean curve for all the other data. It is clear that the surface finish and condition of the casting significantly affect the fatigue strength. It is therefore recommended that testing of samples manufactured by the particular process to be employed should be carried out.

Figure 22 shows the results of 57 fatigue tests on shot peened samples of the four as-cast surfaces presented in Figure 21. Details of the shot peening process are given on the figure. A small number of specimens were subjected to half the duration of shot peening as the others. There appeared to be no measurable change in fatigue strength as a consequence. No curves are provided through the data. However, the curves for $0.251 \leq S'_m/f_t \leq 0.450$ from Figures 19 and 21 are added for comparison. These suggest that peening can improve the fatigue strength of an as-cast surface that is poor in fatigue and conversely that it can reduce the fatigue strength of an as-cast surface that has good fatigue strength. Generally, shot peened as-cast surfaces are comparable in fatigue strength to machined cast surfaces. However, the metallic investment cast data (Supplier I) is the exception since its machined surface is poor but its as-cast fatigue strength is high; further its as-cast fatigue strength is reduced by peening. Thus, it is recommended that testing be carried out to determine the effect of peening on the particular cast surface to be employed.

8. COMPARISON OF FATIGUE STRENGTHS OF THE VARIOUS FORMS OF THE ALLOY

Figure 23 compares the available zero mean stress lines for unnotched specimens. The figure illustrates the indicated, and relatively high, fatigue limit for both forms of heat treatment of the ($\alpha + \beta$) forged rod. This is in accordance with the comments in the second paragraph of Section 3. It should be noted that 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 also 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 23 illustrate the relatively poor fatigue strength of both forms of the material at high endurances. The reason for the poor performance of the large bar is as noted in the second paragraph of Section 3. 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 exhibit a fatigue limit is that for the solution treated and age hardened sheet. The indicated fatigue limit is $0.30f_t = 351 \text{ MN/m}^2$ ($51\,000 \text{ lbf/in}^2$).

The effect of annealing temperature is illustrated by Figure 2. As noted in Section 4.1.1 annealing at high temperatures reduces the fatigue strength. The effect of solution treatment and ageing temperatures is shown on Figure 9 for $(\alpha + \beta)$ forged rod and on Figure 17 for β forged bar. In both the $(\alpha + \beta)$ and (β) forged alloys, solution treatment at the higher temperatures, approaching the transus temperature, appears to yield the better fatigue strength.

Noting that the (β) and $(\alpha + \beta)$ forged and annealed alloys have f_t values that are comparable, Figure 23 shows 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 $0.38 f_t = 370 \text{ MN/m}^2$ (53 800 lbf/in²). Thus, at endurance 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 lbf/in²).

No zero mean stress data for unnotched extruded strip are available. As discussed in Section 6 the available data for unnotched extruded strip are inconclusive and testing of the specific extrusion material is recommended.

Figure 23 shows that machined surfaces of cast alloy have a relatively low fatigue strength, indicating a fatigue limit at about $0.28 f_t = 260 \text{ MN/m}^2$ (37 700 lbf/in²). The unnotched fatigue strength of castings is significantly affected by the casting process, see Section 7. It is therefore recommended that testing of samples manufactured by the particular casting process to be employed be carried out.

Comparison of the figures shows that the conclusions drawn from Figure 23 are generally true if 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} value resulting from the various forging and heat treatments. Further information on fracture toughness values may be obtained from Reference 26.

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

* The fracture toughness, K_{IC} , referred to is described in Item No. 80036 "Estimation of fatigue crack growth rates and residual strength of components using linear elastic fracture mechanics".

9. DERIVATION AND REFERENCE

9.1 Derivation

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Reference

The reference given is a recommended source of information supplementary to that in this Item.

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10. TABLES

FIGURE AND TABLE LOCATION CHART

<i>Production process</i>	<i>Form</i>	<i>Heat treatment</i>	<i>Loading and specimen form</i>	<i>Figure Number</i>	<i>Table Number</i>
$(\alpha + \beta)$ Forged	Rod	Annealed	Axial: Unnotched	3	10.3
				4	10.3
			Bending: Unnotched	1 and 2	10.1 and 10.2
				1	10.1
		Solution treated and age hardened	Axial: Unnotched	10	10.5
				11	10.5
			Bending: Notched	9	10.5
				9	10.5
	Bar	Annealed	Axial: Unnotched	5	10.3
				6	10.3
			Bending: Unnotched	1 and 2	10.1 and 10.2
		Solution treated and age hardened	Axial: Unnotched	10	10.5
				11	10.5
			Bending: Unnotched	9	10.5
	Sheet	Annealed	Axial: Unnotched	7	10.4
				8	10.4
			Bending	1	10.1
		Solution treated and age hardened	Axial: Unnotched	12	10.6
				13	10.6
			Bending: Notched	9	10.6
		Solution treated and over-aged	Axial: Unnotched	12	10.6
				13	10.6
			Notched		
β Forged	Bar	Annealed	Axial: Unnotched	15	10.7
				16	10.7
			Bending: Unnotched	14	10.7
		Solution treated and age hardened	Bending: Unnotched	17	10.7
Extruded	Strip	Annealed	Axial: Notched	18	10.8
Cast	Machined surfaces	Annealed	Axial: Unnotched	19	10.9
				20	10.9
	As cast		Axial: Unnotched	21	10.9
	As cast then shot peened			22	10.9

TABLE 10.1 Fatigue in Bending of ($\alpha + \beta$) Forged Rod, Sheet and Bar Annealed at Between 700°C and 850°C and Air Cooled, Zero Mean Stress (Figure 1)

Symbol	Type of test	K_t	Initial form of material	Working and heat treatment (if additional to annealing)	Tensile strength		Proof stress		Specimen critical dimension(s)		Notch root radius		Number of results	Derivation Number
					MN/m ²	10 ³ lbf/in ²	MN/m ²	10 ³ lbf/in ²	mm	in	mm	in		
●	Rotating bending	1	235 mm × 57 mm (9¼ in × 2¼ in) forged and annealed bar.	14 off, stress relieved at 625°C for 4 h and AC.	910	132	—	—	4.07	0.160	—	—	24	21 and 23
■		1	114 mm (4½ in) diameter forged bar.	—									15	21
△		1	235 mm × 57 mm (9¼ in × 2¼ in) forged and annealed bar.	Annealed above transus temperature. Worked to achieve a 3:1 reduction (below the transus temperature) and annealed at 700°C.	945	137	—	—					14	
▲		1	As above or 114 mm (4½ in) diameter forged bar.	As above but with a reduction of between 8:1 and 10:1.	931 to 945	135 to 137	—	—					18	
▼		1	As above.	As above but with with a reduction of between 32:1 and 90:1.	972 to 1010	141 to 146	—	—					27	
○		1	12 mm (0.47 in) diameter forged rods, annealed.	—	902	131	783	114	6.0	0.236			20	8
+		3.5							6.0*	0.236*	0.12	0.005	18	
◇		1	32 mm (1.25 in) diameter forged rod reduced to 16 mm (0.625 in) diameter rod by hot rolling at 900°C.	—	1010	147	876	127	6.86	0.270	—	—	8	14
*		3.5							6.86*	0.270*	0.25	0.010	9	
▽ †		1	406 mm (16 in) diameter by 51 mm (2.0 in) thick disc.	Cooled from annealing temperature at 55°C per h down to 550°C then AC.	951	138	—	—	5.84	0.230	—	—	10	15
×	Plane bending	2.2	13 mm (0.51 in) diameter forged hot rolled and annealed rod.	Vacuum furnace annealed.	958	139	876	127	6.0*	0.236*	0.50	0.020	15	4
□		1							6.0	0.236	—	—	16	
∧		1.2	Forged and rolled sheet 4 mm (0.157 in) thick.	—	1130	164	783	114	4 × 15 [‡]	0.157 × 0.590 [‡]	25.0	0.985	24	8

AC = air cooled.
h = hours.

- * Minimum diameter at notch root.
† Data are not plotted on Figure 1.
‡ Minimum width at notch root.

TABLE 10.2 Fatigue in Rotating Bending of ($\alpha + \beta$) Forged, Unnotched Rod and Bar Having Various Annealing Treatments, Zero Mean Stress (Figure 2)

Symbol	Initial form of material	Heat treatment	Tensile strength		Proof stress		Specimen diameter		Number of results	Derivation Number
			MN/m ²	10 ³ lbf/in ²	MN/m ²	10 ³ lbf/in ²	mm	in		
×	114 mm (4½ in) diameter forged bar.	Cut from inside of forging. No heat treatment.	938	136	841	122	4.07	0.160	6	21
+		Cut from surface of forging. No heat treatment.							6	
●	235 mm × 57 mm (9¼ in × 2¼ in) forged and annealed, at 700°C for 2 h, bar.	Annealed at 1050°C, 1 h, AC and SR at 625°C for 4½ h, AC.	979	142	910	132			7	
○		Annealed at 1050°C, 1 h, FC to 700°C, held for 2 h, AC and SR at 625°C for 4½ h, AC.	924	134	876	127			7	
□		Annealed at 910°C, 1 h, AC and annealed at 700°C, 1 h, AC.	883	128	827	120			6	
△	30.5 mm (1.2 in) diameter hot rolled rod.	SR.	1050	152	993	144	5.84	0.230	9	15
◇	406 mm (16 in) diameter by 51 mm (2 in) thick disc.	Annealed at 950°C, 1 h, AC and annealed at 680°C, 2 h, AC.	958	139	—	—			10	
▷		Annealed at 930°C, cooled to 560°C at 55°C/h, AC.	924	134	—	—			10	

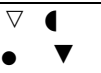
SR = stress relieved.

AC = air cooled.

FC = furnace cooled.

h = hours.

TABLE 10.3 ($\alpha + \beta$) Forged, Axially Loaded, Notched and Unnotched Annealed Rod and Bar

Figure Number	$\frac{S'_m}{f_t}$	K_t	Symbol	Number of results	Initial form of material	Heat treatment	Tensile strength		Proof stress		Specimen critical dimension(s)		Notch root radius		Derivation Number
							MN/m ²	10 ³ lbf/in ²	MN/m ²	10 ³ lbf/in ²	mm	in	mm	in	
ROD															
3	0	1		6	16 mm (5/8 in) diameter rod.	Annealed.	1030	150	986	143	4.07	0.160	–	–	20 and 23
				7		Annealed and SR at 625°C for 4½ h.	1050	152	1000	145					
				14	30.5 mm (1.2 in) diameter hot rolled rod.	SR at 625° for 4½ h.	1060	154	993	144	5.74	0.226	–	–	
				12							4.07	0.160			
	see figure		19	32 mm (1.25 in) diameter rod.	Annealed at 700°C for 2 h, AC.	938	136	883	128	5.08	0.20	–	–	1	
4	see figure	3.3	untagged symbols							15	6.40*	0.252*	0.25	0.010	
3	see figure	1		10	25.4 mm (1.0 in) diameter rod.	Annealed at 700°C for 1 h, AC.	1010	147	945	137	–	–	–	–	18
4	see figure	3.0	tagged symbols	12											
BAR															
5	0	1		44	235 mm × 57 mm (9¼ in × 2¼ in) forged and annealed bar to DTD 5173.	Specimen blanks SR at 625°C for 4½ h.	903	131	848	123	5.74	0.226	–	–	22
	0	1		11	297 mm × 162 mm × 89 mm (11.72 in × 6.4 in × 3.5 in) two step forging.	Specimen blanks annealed at 704°C for 2 h, AC.	958	139	876	127	6.35	0.250	–	–	11
	$S'_m/f_t \neq 0$ see figure	1	see figure	22											
6	see figure	3	see figure	34							7.62*	0.30*	0.05	0.016	

AC = air cooled.
 SR = stress relieved.
 h = hours.

* Minimum diameter at notch root.

TABLE 10.4 ($\alpha + \beta$) Forged, Axially Loaded, Notched and Unnotched Annealed Sheet

Figure Number	$\frac{S'_m}{f_t}$	K_t	Symbol type	Number of results	Sheet thickness	Heat treatment	Tensile strength		Proof stress		Specimen width		Notch root radius		Derivation Number
							MN/m ²	10 ³ lbf/in ²	MN/m ²	10 ³ lbf/in ²	mm	in	mm	in	
7	0.168	1	Untagged symbols	37	1.02 mm (0.040 in)	Annealed for 1 h at 800°C, FC to 500°C, AC.	1030	149	979	142	19	0.75	—	—	17
	see figure		Single tagged symbols	25	2.79 mm (0.11 in)	Not specified.	1060	154	1000	145	9.52	0.375			10
			Double tagged symbols	10	4.0 mm (0.157 in)	Annealed.	1030	149	961	139	—	—			19
			Symbols with two diagonal tags	55	0.5 mm (0.020 in) 0.9 mm (0.035 in) 1.6 mm (0.063 in)	Annealed at 700°C for 0.33 h, AC.	1000	145	908	132	20	0.787			24
8		4	Untagged symbols	33	1.02 mm (0.040 in)	Annealed for 1 h at 800°C, FC to 500°C, AC.	1030	149	979	142	38.1	1.50	1.47	0.058	17
		3	Single tagged symbols	24	2.79 mm (0.11 in)	Not specified.	1060	154	1000	145	6.35	0.25	0.53	0.021	10
		3.6	Double tagged symbols	12	4.0 mm (0.157 in)	Annealed.	1030	149	961	139	—	—	—	—	19
		2.57	Symbols with two diagonal tags	11	0.9 mm (0.035 in)	Annealed at 700°C for 0.33 h, AC.	1000	145	908	132	20	0.787	1.7	0.067	24

AC = air cooled.
 SR = stress relieved.
 FC = furnace cooled.
 h = hours.