

FATIGUE STRENGTH OF COLD-ROLLED TITANIUM ALLOY SCREW THREADS UNDER AXIAL LOAD

1. NOTATION

f_p	proof stress of fully heat treated material	N/m ²	lbf/in ²
f_t	tensile strength of fully heat treated material	N/m ²	lbf/in ²
f_{tt}	tensile strength of loaded thread based on core area	N/m ²	lbf/in ²
N	endurance (at room temperature)		
N_r	geometric mean endurance at room temperature		
N_t	endurance at elevated temperature		
R	S_{min}/S_{max}		
S_a	alternating stress based on core area of thread	N/m ²	lbf/in ²
S_m	mean stress in loading cycle based on core area of thread	N/m ²	lbf/in ²
S_{max}	maximum stress in loading cycle based on core area of thread	N/m ²	lbf/in ²
S_{min}	minimum stress in loading cycle based on core area of thread	N/m ²	lbf/in ²

1.1 Conversion Factors

Both SI and British units are shown in the notation. The data are presented primarily in SI units with scales in British units added. The following conversion factors apply.

Multiply MN/m² by 145 to convert to lbf/in².

Multiply lbf/in² by 0.006895 to convert to MN/m².

2. DATA ANALYSED

This Item presents the analysis of approximately 500 constant amplitude fatigue tests on cold-rolled threads in titanium alloys. Data for the six alloy groups listed in Table 2.1 are presented.

TABLE 2.1

Section	Alloy group	Material current specification and origin
3	Ti-6Al-4V	2TA 28 (British Standard, Aerospace Series)
4	Ti-4Al-4Mn	DTD 5053, DTD 5303 (UK Ministry of Defence)
5	Ti-5Al-3Mn	ST-A130 (Sumitomo Light Metals Co., Japan)
6	Ti-6Al-6V-2Sn	MIL-T-81556 (USA)
7	Ti-7Al-12Zr	Hi Ti 815 (Standard Pressed Steel, USA)
8	Ti-8Al-1Mo-1V	AMS 4973 (USA)

The most popular alloy is Ti-6Al-4V even though it is shown to have a lower fatigue strength than the other alloys listed in Table 2.1 (see Section 9). Although the fatigue strength is an important strength criterion the choice of material for a bolt or other threaded member is not always governed by the fatigue strength of the thread.

The major portion of the data relates to tests conducted at room temperature. Some data are provided both on the effect of elevated temperature on fatigue strength and on the room temperature fatigue strength after soaking at elevated temperatures. All the tests were carried out on solid bolts with standard thread forms which were cold-rolled after the completion of the full heat treatment processes. Data are included on the effects of zinc plating the Ti-4Al-4Mn threads. Except for a few failures in the thread run-out, noted on Figure 2, all the failures analysed in this Item occurred in the thread just inside the nut, close to the loaded face. Further details of the tests and materials are given in Section 11.

The fatigue strength of titanium alloy threads is very dependent upon the method of manufacture. Cold rolling the threads after the completion of all heat treatment produces residual compressive stresses at the thread root. Such compressive stresses considerably improve the fatigue strength. Further heat treatment, subsequent to thread rolling, will relax the beneficial residual compressive stresses and thus reduce the fatigue strength. Because of this there is a practical limit to the elevated temperatures to which the threads can be exposed and still retain their room temperature fatigue strength. See Sections 3, 4, 6, 7 and 8.

The various thread forms dealt with in this Item have slightly different geometric stress concentrations. However, variations in fatigue strength resulting from these differences in stress concentration are small in comparison with variations resulting from the range of thread fits and consequential contact areas that can exist within standard tolerances, which can significantly affect the load distribution along the thread.

3. Ti-6Al-4V (Figures 1 to 5)

Prior to thread rolling the usual heat treatment for this alloy consists of heating to 900°C and holding for more than ½ an hour then water quenching followed by heating to 500°C and holding for more than 2 hours then air cooling. This results in a tensile strength in the region of 1150 MN/m². The heat treatment is carried out with the alloy in the ($\alpha + \beta$) condition and results in a microstructure that is capable of being refined by the working of the thread rolling process. Some data are provided here on the effect on fatigue strength of heat treatment above the ($\alpha + \beta$)/ β transus temperature of 995°C.

Figures 1 and 2 provide room temperature data on unplated Ti-6Al-4V threads. Two different presentations are necessary to show all the available information. Figure 1 presents S_{max}/f_t plotted against N for $R = 0.1$ for 2 sizes of UNF (unified) thread and also $R = 0.25$ for an M8 ISO metric thread (8 mm nominal diameter). Mean lines are drawn through both sets of data. Figure 2 presents S_a/f_t plotted against N for various values of S_m/f_t for M8 ISO metric threads. Seventeen of the results relate to failures in the thread run-out and these are identified on the figure. No details of the form of the thread run-out are available. The mean lines on Figure 2 were obtained using both the thread failures and the thread run-out failures. The data and dashed line for $0.871 \leq S_m/f_t \leq 0.922$ relate to the condition $S_{max} = f_p$, when the complete core area will have yielded. These data show a longer endurance than that obtained with lower mean stress levels when S_a/f_t is above about 0.042. This may be because the high mean stress causes yielding of the core and this improves the load distribution along the loaded threads. In this case the improvement appears to be such that the fatigue strength of the threads is improved beyond that of the run-out. Note that thread run-out failures may also occur if the run-out receives less cold working than does the fully developed thread.

Figure 3 shows the relationship between S_a/f_t , S_m/f_t , R and N as deduced from Figures 1 and 2. This figure relies completely on the M8 ISO metric thread data.

Figure 4 provides data on the effect of heat treating the alloy at temperatures in excess of its $(\alpha + \beta)/\beta$ transus temperature prior to thread rolling. All the data show endurances above those of the comparable line on Figure 1 which is superimposed upon the figure. Over the limited range of the data the trends indicated that the effects of the three heat treatments are similar and no one treatment emerges as being superior to the others.

Figure 5 presents the results of tests on threads soaked at elevated temperature for 100 hours and then fatigue tested at room temperature with $R = 0.1$. The values of N_r used were those obtained from the same batch of tests (not the mean values obtainable from Figure 1). The data are for two values of S_{max} ; no significant difference is apparent so a single mean line has been drawn through all the data. The data also indicate that prior soaking at temperatures below about 170°C (340°F) has no effect on the room temperature fatigue strength. Some of the reasons for the reduction of N_r/N_r below unity with increasing temperature are described in the last paragraph of Section 4.

4. Ti-4Al-4Mn (Figures 6 to 9)

Figure 6 presents the room temperature data for unplated Ti-4Al-4Mn for 2BA (British Association), $\frac{1}{4}$ inch UNF and $\frac{5}{16}$ inch BSF (British Standard Fine) threads all tested at $R = 0.1$. Mean curves are provided for each thread form. The scatter at the low stress/high endurance end of the figure is large, particularly for the $\frac{1}{4}$ inch UNF threads. Figures 7, 8 and 9 present data similar to those of Figure 6 but for plated threads. Most of the data relate to zinc plating and only four results are available for the alkaline anodised conversion coating. Mean curves are provided through the data for zinc plated threads for the 2BA and $\frac{5}{16}$ inch BSF thread forms on Figures 7 and 9. A mean curve is not provided on Figure 8 owing to the excessive scatter. The mean curves from Figure 6 are reproduced on Figures 7, 8 and 9 to facilitate comparison between the plated and unplated results. Comparison of the curves indicates that zinc plating reduces the fatigue endurance by a factor of between 5 and 10. As with unplated threads there is no fatigue limit. Zinc plating is employed to prevent galvanic corrosion which may occur between titanium and various aluminium alloys and also to reduce the likelihood of seizure between nut and bolt. The four results for $\frac{1}{4}$ inch UNF threads with alkaline anodised conversion coatings are within the bounds of the data for unplated threads and therefore no advantages or disadvantages from the treatment are indicated. This treatment is designed to provide protection against galvanic action. As it uses no acid cleaners hydrogen embrittlement does not occur.

Figure 10 presents the results of tests conducted at 300°C (572°F) with $R = 0.1$. When compared with the room temperature data for Figure 6 these show a considerable reduction in fatigue strength at high values of S_{max} but show no significant reduction at lower values of S_{max} . The limited data, only 22 results, may not be sufficient to show the range of scatter that may occur in the low stress level region.

Figure 11 presents the results of two types of test which show the effect either of fatigue testing at temperature or of pre-test soaking at temperature and then fatigue testing at room temperature. In each case $S_{max} = 572 \text{ MN/m}^2$ and $R = 0.1$. The values of N_f used were those from the same batches of tests (not the mean values obtainable from Figure 6). The scatter for one of these values is large. At the temperature of 300°C four results are available and these give an indication of the scatter that may be expected in N_f/N_r . The mean lines drawn on Figure 11 suggest that temperature effects occur above about 70°C (160°F). The fatigue tests conducted at elevated temperature lasted for less than one hour and produced a larger reduction in N_f/N_r than 100 hours of pre-test soaking at elevated temperature and then fatigue testing at room temperature. One of the main reasons for the deleterious effect of elevated temperature soaking on room temperature fatigue strength may be a partial relaxation of the residual stresses generated by the cold rolling process used during manufacture. Oxidation of the surface may also be a contributory factor. The larger reduction in N_f/N_r resulting from fatigue at elevated temperature may be due to the combined effect of the relaxation of the residual stress coupled with a reduction in the yield stress and consequently a reduction in the fatigue strength. Other factors such as cyclic creep may also reduce the fatigue strength at temperature.

5. Ti-5Al-3Mn (Figure 12)

Figure 12 presents the results of 16 tests conducted at $R = 0.1$ at room temperature or at 300°C (572°F). The data for tests at room temperature indicate a fatigue limit at an S_{max} of about 390 MN/m². The five tests conducted at 300°C give no indication of a fatigue limit. The effect of temperature appears to be negligible at higher stress levels but a considerable reduction in fatigue strength is evident in the range $300 \leq S_{max} \leq 400 \text{ MN/m}^2$.

6. Ti-6Al-6V-2Sn (Figure 13)

Figure 13 presents the results of tests on $\frac{3}{8}$ inch and $1\frac{1}{2}$ inch UNF threads tested at $R = 0.1$. Mean straight lines are provided through each set of data. These show a significant size effect such that the endurance attained by the larger thread is only a tenth of that attained by the smaller thread. This reduction in endurance with increase in absolute size may be attributed largely to two factors. First, in the larger threads the area subjected to the highest stress is also larger so that the probability of early initiation of a fatigue crack is increased. Secondly, a given crack will propagate more rapidly in a larger thread than in a smaller thread of the same form. This is because in a thread the axial stress acting at the thread root decays rapidly with increasing depth from the root surface and the stress gradient for this decay is directly proportional to size. Thus the stress to be transmitted past the crack tip in a large thread is greater than that for a similar depth crack in a smaller thread.

The three results available for (β) or ($\alpha + \beta$) phase processing of the alloy suggest that these processes may offer some benefits in the high stress region.

7. Ti-7Al-12Zr (Figures 14 and 15)

Figures 14 and 15 present the results of tests on $\frac{3}{8}$ inch UNF threads. On Figure 14 a mean line is drawn through those data which relate to a relatively narrow range of S_m/f_t . Figure 15 shows the effect on endurance of soaking the thread for 100 hours at elevated temperature and then fatigue testing at room temperature for $R = 0.1$ and 0.242 . The data are presented in terms of the ratio N_t/N_r . The available room temperature data used as a basis for calculating N_t in this ratio are also indicated on the figure to facilitate comparison of the scatter. A mean line is drawn through the data for $R = 0.1$ and this suggests that N_t/N_r is reduced below unity by pre-soaking at temperatures above about 150°C (300°F). The linear relationship implied by the mean and boundary lines shown on Figure 15 only applies over the range of data available.

Three results are provided on Figure 15 for fatigue tests conducted at 400°C (752°F). They show a large reduction in endurance such that $0.047 \leq N_t/N_r \leq 0.057$. Thus, as with the Ti-4Al-4Mn data (see Section 4), fatigue testing at elevated temperature produces lower values of N_t/N_r than does soaking at elevated temperature and then fatigue testing at room temperature.

8. Ti-8Al-1Mo-1V (Figures 16 and 17)

The only data available for this alloy are for $\frac{3}{8}$ inch UNF threads tested with S_{max} at 552 or 586 MN/m^2 and $R = 0.1$. Because of this the data are shown on Figure 17 as mean points together with the limits of the data.

Figure 16 shows the effect on endurance, expressed as the ratio N_t/N_r , of soaking the thread for 100 hours at elevated temperature and then fatigue testing at room temperature. The range of the available room temperature data used as a basis for calculating N_r is also shown on the figure to facilitate comparison of the scatter. The data indicate that N_t/N_r is reduced below unity by presoaking at temperatures above about 100°C (212°F) (see Section 4 for discussion of reasons for reduction). The linear relationship implied by the mean and boundary lines on Figure 16 only applies over the range of data available.

9. SUMMARY FIGURES (17 and 18)

Figures 17 and 18 compare the mean curves for $R = 0.1$ obtained for all the alloys. Figure 17 shows a curve for Ti-6Al-4V that is obtained from the $R = 0.1$ curve of Figure 1 and values read from Figure 3 at $R = 0.1$. This shows that Ti-6Al-4V has a much lower fatigue strength than the other alloys on the figure and that it only becomes comparable with the Ti-4Al-4Mn, Ti-6Al-6V-2Sn and Ti-8Al-1Mo-1V alloys in the region of $S_{max} > 600 \text{ MN/m}^2$, $N < 10^5$. The short curve for Ti-7Al-12Zr alloy (derived from the data on Figure 14 having $f_t = 1067 \text{ MN/m}^2$ and $R = 0.1$) follows the curve for Ti-6Al-4V over the short range $500 \leq S_{max} \leq 550 \text{ MN/m}^2$. The data on Ti-8Al-1Mo-1V are too sparse to give any indication of its fatigue strength except over the narrow range $550 \leq S_{max} \leq 600 \text{ MN/m}^2$. The Ti-5Al-3Mn has the lowest fatigue strength for endurance below about 2×10^5 cycles and above this endurance it has a lower fatigue strength than all the alloys except Ti-6Al-4V. On Figure 18 the values of S_{max} used are given against each curve. These values are all within the relatively narrow range of $483 \leq S_{max} \leq 586$ so that the curves are reasonably comparable.

10. DERIVATION

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

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BENSON, V. Beta heat treatment of Ti-6Al-4V fasteners. American Society for Metals and American Society of Tool and Manufacturing, Weston Metal and Tool Conference and Exposition, Los Angeles, March 1969.



11. TABLES

TABLE 11.1 DETAILS OF THREADS

Fig No.	Thread details	f_u^* MN/m ²	f_t^* MN/m ²	f_p^* MN/m ²	Material heat treatment prior to thread rolling [†]	Surface treatment after rolling	Test frequency Hz	Detail composition of specimens*												Derivation Number
								A1	C	Fe	H ₂	Mn	Mo	N ₂	O ₂	Si	V	Zr		
Ti-6Al-4V																				
1 and 5	3/8 inch 24 UNF	1356	1159	1113	1h at 950°C, WQ, 4h at 593°C, AC	None	NA	6.3	0.04	0.16	0.0075			0.01	0.18		4.1		7	
1	¼ inch 28 UNF	1448	1192	1075	1h at 900°C, WQ, 4h at 510°C, AC	None	133	6.5	0.04	0.17	0.00005			0.009	0.169		4.3		12	
1, 2 and 3	M8 ISO metric (8 mm)	NA	1079 1148	1030 1068	NA	None	NA	NA											6	
4	¼ inch 28 UNF	1053	1189	1103	1h at 1010°C, WQ, 1h at 900°C, WQ, Ag at 510°C for 4h, AC	None	133	NA											12	
		1441	1196	1141	1h at 1010°C, WQ, Ag at 510°C for 4h, AC	None														
		1510	1172	1102	1h at 1066°C, WQ, Ag at 510°C for 4h, AC	None														
Ti-4Al-4Mn																				
6 and 7	2BA	NA	1030	NA	NA	Some threads zinc plated in fluoboric acid to thickness of 0.005 mm. Resulting H content 163 ml/kg	50	NA											1, 3, 4	
6 and 8	¼ inch UNF	NA	1030	NA			50 [‡]												1, 3, 4	
6			1096				NA												2	
6 and 9	5/16 inch BSF	NA	1030	NA			50 [‡]												1, 3, 4	
6	5/16 inch UNF		1096				NA												2	
6, 10 and 11	¼ inch UNF	1379	1030	910	ICI 314A, An at 790°C for 2h, WQ, Ag for ¼ h at 566°C, AC	None	50	NA											1	
8	¼ inch 28 UNF	NA	NA	NA	NA	Four threads given alkaline anodise conversion coats	NA	NA											8	
11	—	1158	NA	NA	NA	None	NA	NA											2	
Ti-5Al-3Mn																				
12	5/16 inch 24 UNF	NA	963	888	NA	None	109 to 114	4.94 5.38		0.005 0.18		3.06 3.16		0.005 0.006		0.001 0.02			10	
Ti-6Al-6V-2Sn																				
13	3/8 inch 24 UNF	1512	NA	NA	Heat treated below ($\alpha + \beta$)/ β transus	None	NA	NA											9	
		1430	NA	NA	Heat treated above ($\alpha + \beta$)/ β transus															
	1½ inch 12 UNF	1219	1130	NA	NA	None	NA	NA										11		
	3/8 inch 24 UNF	1410	1183	1119																
Ti-7Al-12Zr																				
14 and 15	3/8 inch 24 UNF	1132 1143	1086	1015	Ag at 730°C	None	NA	6.88 7.1	0.02 0.021	0.01 0.114	0.00005 0.00008			0.01 0.033	0 0.05			11.65 12.1	5	
	3/8 inch 24 UNF	1216	1067	1035	1h at 760°C, WQ	None	NA	7.1	0.01	0.02	0.00012			0.01	0.08			12.1	7	
Ti-8Al-1Mo-1V																				
16 and 17	3/8 inch 24 UNF	1265	1008	NA	1h at 900°C, AC, 24h at 590°C, AC	None	NA	7.9	0.023	0.1	0.006		1.0	0.009	0.008		0.9		7	

* All values relate to tests on the specimens.
† An = Anneal
Ag = Age
WQ = Water quench
AC = Air cool
h = Hours
NA = Not available
‡ Derivation 1 only



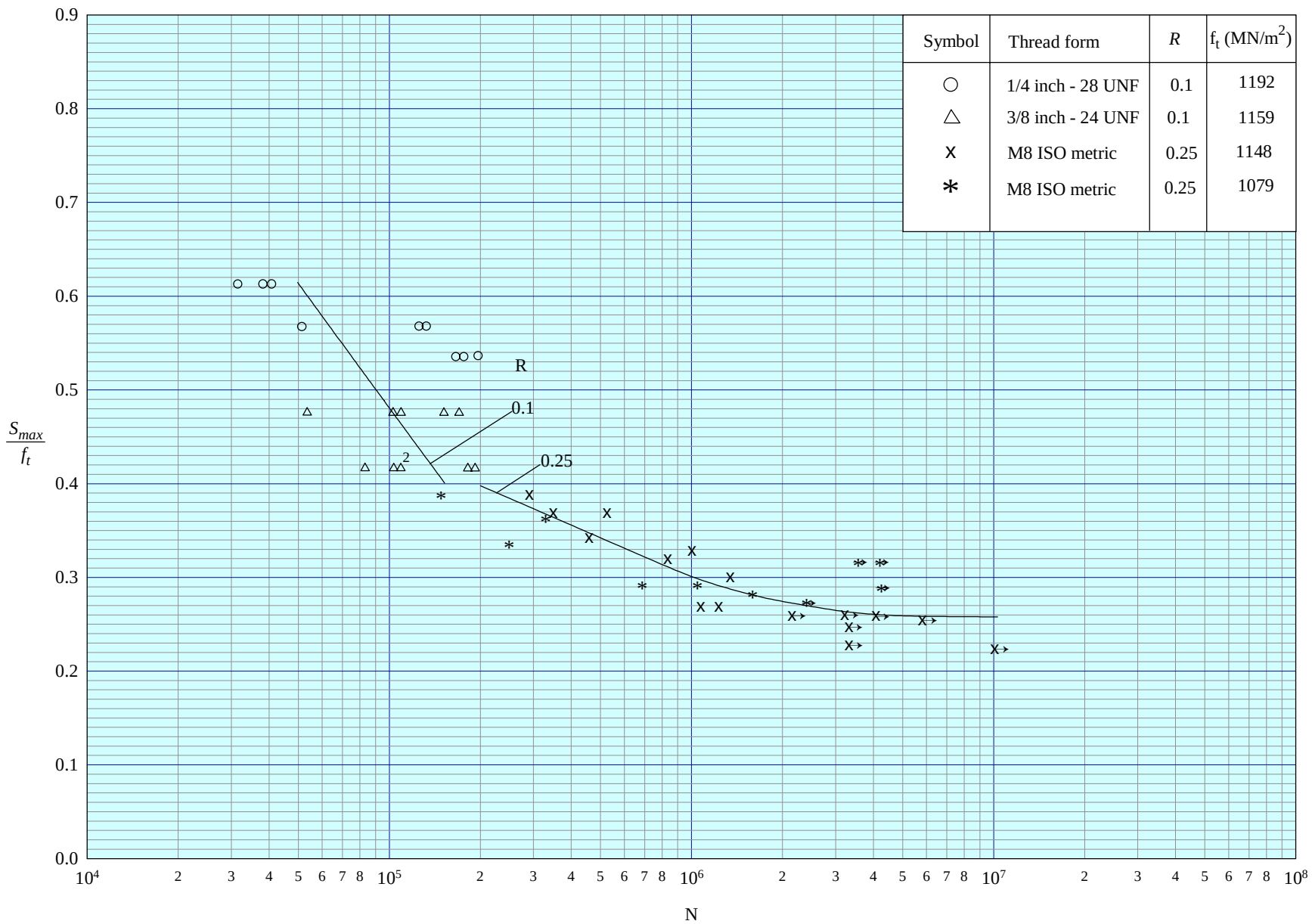


FIGURE 1 Ti-6Al-4V. R = 0.1 AND 0.25, UNPLATED THREADS TESTED AT ROOM TEMPERATURE