JMEPEG (2005) 14:691-696
DOI: 10.1361/105994905X75466

Candidate Materials for High-Strength Fastener Applications in Both the Aerospace and Automotive Industries

J.G. Ferrero

(Submitted August 24, 2005)

There are many commercially available titanium alloys that have exhibited the capability of achieving high strength. Many of these alloys have not been seriously considered for fastener applications due to their cost or availability as coil or bar product. However, because new designs, increased material requirements, and larger aircraft are being built, the need to reduce weight and improve performance continues to be a major issue. The possibility of reducing weight by replacing currently used steel or Ni-based fasteners in various sizes is a great incentive. Over the past few years, many of these titanium alloys have been processed to bar and coil products to evaluate their capabilities as potential fastener materials. This article will review and summarize the mechanical properties, tensile, shear, notch tensile, and available fatigue, as well as the microstructure of these candidate alloys.

Keywords fasteners, high strength, titanium

1. Introduction

Titanium has been used as a fastener material since the mid-1960s. The majority of aerospace and automotive fasteners used today are produced from the Ti-6Al-4V alloy. Fasteners are rated based on their intended applications in tension, shear, or fatigue. Certain applications may require a combination of all three loading modes. The typical strength requirements for Ti-6Al-4V fasteners are as follows: tensile strength 1103 MPa, shear strength 655 MPa, and fatigue run-out of minimum 65,000 cycles at 35 to 40% of the ultimate tensile strength (UTS). TheTi-6Al-4V used in aerospace fastener applications has been limited to diameters less than 19 mm. This is due primarily to the inability of Ti-6Al-4V to consistently achieve through-thickness properties in these larger diameters (Ref 1, 2). There are numerous applications that could potentially use titanium fasteners over a wide range of sizes (6-40 mm) if higher tensile and shear strength could be consistently met. Many of these applications currently use Ni-based alloys such as Inconel 718, A286, and MP35N. These alloys can easily meet the required strength requirements; however, there is a significant weight penalty. The need to reduce weight in larger aircraft such as the Airbus A380 has pushed the industry to develop a titanium alloy fastener that is capable of replacing these Ni-based and steel fasteners, particularly in the larger diameter size range.

Many of the earliest evaluations of titanium alloys for high-strength applications date back to the 1970s and continued through the 1980s. Several well-known fastener manufacturers were involved in these initial studies. The metastable β alloys were among the first titanium alloys to be evaluated for these large diameter high-strength applications. Some of these early alloys included Beta-C, Beta III, and Ti-8823. The reason for the interest in the metastable β alloys was due to their capability to be heat treated to significantly higher strengths than the traditional α-β alloys. The metastable β alloys have shown the capability of achieving strengths in excess of 1379 MPa. They also exhibit much improved hardenability in large section sizes compared with the α-β alloys (Ref 3, 4). Of the early alloys evaluated, the only one that has been used commercially in both aerospace and automotive applications is Ti Beta-C.

For many years, the titanium wire and rod producers have worked with the fastener manufacturers to develop a large-diameter titanium fastener that could replace the higher-strength steel fasteners. The industry has taken a stepwise approach over the years with an initial target being a fastener with a 1241 MPa tensile strength and a 703 MPa double-shear strength, with the ultimate goal being a titanium fastener with a 1517 MPa tensile strength and an 862 MPa double-shear strength. Even if only the initial target strengths can be achieved, there is still an opportunity for significant weight savings.

The quest for high strength continues today in an even stronger way than in the past. Today, there are many commercially available titanium alloys, both metastable β and β-rich α/β, that are capable of achieving tensile strengths of 1241 MPa and greater (Ref 5). The majority of these alloys, however, have not historically been produced in bar or coil form. In fact, many of these alloys were initially developed for forging and sheet/plate applications. The raw material cost has always been an issue with these higher-strength materials. As a result of the increased alloy content, the cost of these alloys is typically much higher than that for the standard Ti-6Al-4V. However, in most applications the potential benefit of reduced weight and/or increased performance can far outweigh the price difference.

Producing fasteners from these materials has proven to be a challenge. There have been issues with both heading and thread rolling of these high-strength alloys. The initial step in the production of a fastener is to head the material, and this op-

---

This paper was presented at the Beta Titanium Alloys of the 00's Symposium sponsored by the Titanium Committee of TMS, held during the 2005 TMS Annual Meeting & Exhibition, February 13-16, 2005 in San Francisco, CA.

J.G. Ferrero, Perryman Company, 213 Vandale Drive, Houston, PA 15342. Contact e-mail: jferrero@cartech.com.

Table 1 Average ingot chemical composition

Alloy	Al	V	Cr	Mo	Fe	Zr	Sn	C	N	O
Ti-662(a)	5.7	5.8	…	…	0.55	…	2.0	0.02	0.012	0.18
Ti-62222(b)	5.57	…	1.97	2.08	0.08	1.90	2.0	0.01	0.002	0.10
SP-700	4.58	3.08	…	2.01	2.01	…	…	0.02	0.007	0.12
Ti-10-2-3	3.10	9.46	…	…	1.83	…	…	0.02	0.011	0.10
Ti-555	5.37	4.99	3.01	5.03	0.360	…	…	0.007	0.006	0.131
VT16-1	3.38	4.97	2.67	5.25	0.427	…	…	0.005	0.01	0.121
Ti-3253	3.11	1.72	…	4.73	3.29	…	…	0.01	0.01	0.122
Ti Beta-C	3.67	8.21	6.14	4.28	0.07	3.78	…	0.02	0.012	0.08
Timetal LCB	1.47	…	…	6.69	4.24	…	…	0.01	0.002	0.15

Note: Values are in wt.%. (a) Cu, 0.64; (b) Si, 0.14

Table 2 Alloy physical properties

Alloy	Density, g/cm^3	β transus, °C	Modulus, GPa	Mo Eq(a)	Size, mm	Alloy type
Ti-662	4.54	949	114	−0.22	7.0	α/β
Ti-62222	4.65	966	117	−0.11	8.5	α/β
SP-700	4.54	899	112	5.31	7.0	α/β
Ti-10-2-3	4.65	807	110	9.21	9.7	Near β
Ti-555	4.68	854	112	9.31	11	Near β
VT16-1	4.68	788	108	11.31	7.0	Near β
Ti-3253	4.62	835	107	17.74	7.0	Metastable β
Ti-Beta-C	4.82	760	102	16.33	8.8	Metastable β
Timetal LCB	4.79	804	114	18.35	15	Metastable β

(a) Ref 3

eration is typically performed at an elevated temperature. The heading operation is then followed by a thermal treatment to achieve the desired strength, and finally the thread-rolling operation is carried out. The selection of the appropriate heading temperature is critical to avoid heavy deformation and/or cracking of the head. Heavy deformation and flow lines in the head area can result in premature head failures in the finished component.

The majority of the problems have historically been related to the thread-rolling operation. Thread rolling is performed on the fully aged material, and producing an acceptable thread form and microstructure has proven to be a significant challenge. Crest laps or seams must be avoided. Heavy shear bands due to metal flow in the thread roots must also be avoided. The presence of these types of defects in the thread root can lead to premature fatigue or tensile-type failures.

Over the past few years, there has been a strong push by the aircraft and high-end automobile manufacturers to obtain a reliable high-strength titanium fastener. The purpose of this study was to evaluate several titanium alloys that were likely candidates for achieving this goal. This article will review the mechanical property results obtained and will compare those results with a set of goal properties for nine titanium alloys. The challenge of successfully producing a high-strength titanium fastener will be left in the capable hands of the fastener manufacturers to develop heading and thread-rolling techniques to produce acceptable parts.

2. Procedure

The material for this study was produced from 101 mm diameter defect-free billet. All processing (i.e., rolling and wire finishing) was performed at the Perryman Company. The billets were heated in an in-line induction heating system and were processed to an intermediate size, 29 mm, on a two high-reversing mill. The intermediate rod was then reheated in a second set of in-line induction coils and rolled through a Kocks mill to hot-rolled coil product. The final rolling temperature for each alloy was chosen such that the material would be finished below the β transus. The secondary processing to the finished size involved annealing, drawing, and turning to remove any defects. The intermediate and final heat-treating operations for each alloy were based on historical data and information available in the open literature (Ref 6, 7). The alloys were processed to various finished sizes ranging from 7 to 15 mm in diameter. The chemical composition of the nine alloys evaluated can be found in Table 1. Table 2 contains the physical properties of each of the alloys along with the finished size and an alloy classification system based on the calculated molybdenum equivalent.

This study was designed to evaluate the mechanical properties that are essential to the successful production of aerospace and or automotive high-strength fasteners. To make a reasonable comparison of these alloys, they were all heat treated to a comparable strength level. Currently used titanium fasteners are rated at the 1103 MPa tensile strength and 655 MPa double-shear strength. Titanium alloys that are being considered as possible replacements for the currently used steel or Ni-based alloys will require a finished fastener tensile strength of 1241 MPa and a double-shear strength of 703 MPa. In order for the finished fastener to achieve this strength, the incoming material must be heat treated to a higher level. The aim strength level was set at 1379 MPa tensile strength, 10% elongation, and a double-shear strength of 745 MPa. For comparison purposes, we evaluated the following mechanical proper-

Table 3 Heat-treating conditions

Alloy	Solution treatment	Age treatment
Ti-662	899 °C 1 h WQ	537 °C 8 h AC
Ti-62222	899 °C 1 h WQ	510 °C 8 h AC
SP-700	850 °C 1 h WQ	510 °C 8 h AC
Ti-10-2-3	760 °C 1 h WQ	482 °C 8 h AC
Ti-555	815 °C 1 h WQ	537 °C 8 h AC
VT16-1	760 °C 1 h WQ	468 °C 8 h AC
Ti-3253	760 °C 1 h WQ	482 °C 8 h AC
Ti Beta-C	…	Drawn + 510 °C 6 h
Timetal LCB	760 °C 1 h WQ	510 °C 8 h AC

ties: tensile; double shear; notched tensile; and fatigue. All testing was performed in accordance with the appropriate ASTM or military standard test methods.

3. Results/Discussion

3.1 Heat Treatment and Microstructure

The selection of the solution treatment and aging cycle for each of the alloys was based on some preliminary screening tests and our historical knowledge of the behavior of these alloys. The heat treatments were selected for each alloy based on achieving the aim of a strength range of 1379 MPa tensile strength, as stated above. Table 3 shows the heat-treating cycles used for each of the alloys.

The longitudinal microstructures for each of the alloys in the heat-treated condition are shown in Fig. 1. The alloys were separated into three classifications based on their molybdenum equivalent value. The three classes were β-rich α/β, near-β, and metastable β alloys. Beta-rich α/β alloys (Fig. 1a-c) show structures consisting of primary α in an aged β matrix. The grain size is very fine, less than 10 μm. The near-β alloys (Fig. 1d-f) show structures consisting of a fine dispersion of α precipitated in the β matrix with some primary α. The metastable β alloys (Fig. 1g-i) show two different types of structures. Figure 1(g) and (i) show a fine dispersion of α in a β matrix and some grain boundary α. Figure 1(h) shows a structure of fine α precipitates in a worked β matrix with no primary α. The grain size of the near-β and β alloys is also in the size range of 10 μm or less except for the Beta-C, which has a grain size ranging from 25 to 100 μm.

3.2 Mechanical Properties

3.2.1 Tensile Properties. As mentioned above, the property level goal for this study was a tensile strength of 1379 MPa, an elongation of 10%, and double-shear strength of 745 MPa. Table 4 contains the tensile results as well as the notched tensile data for all nine alloys. The values in this table are the average results of duplicate tests. All of the material evaluated either achieved or came very close to meeting the targeted property levels. Several of the alloys missed the elongation target of 10%. However, those that did miss the elongation requirement were also significantly above the targeted tensile strength range. Therefore, there is a good possibility that the ductility target could be achieved simply by modifying the heat-treatment cycle.

3.2.2 Notched Tensile. Room temperature notched tensile tests were performed on all of the alloys in this study to determine whether any of the materials are notch sensitive. Notch sensitivity is very important when considering high-strength fasteners. The thread-rolling operation introduces natural notches into the material. The notches at the thread roots on most fasteners have a notch sensitivity factor, K_t, ranging from 2 to 4. For the purposes of this study, we selected a $K_t = 3.0$. It was thought that this would give us a general feel for the notch characteristics of the various alloys. It should be noted that the behavior with a machine-cut notch may be different than that produced by a rolled notch such as that created during the thread-rolling operation.

The notched tensile test is a common way of measuring the notch sensitivity by evaluating the notch-to-smooth tensile strength ratio. As a rule of thumb, a material is considered to be notch-sensitive if it has a notch-to-smooth strength ratio less than unity. There is little doubt that a material with a notch-to-smooth ratio of less than 1 is notch-sensitive. However, there is reasonable doubt that a material with a ratio of 1 or above truly represents a notch-insensitive material. In fact, the range of notch-to-smooth strength ratio values between 1 and 1.5 is the most difficult to assess as being either notch-sensitive or notch-insensitive (Ref 8).

The notch-to-smooth tensile ratio for all of the alloys was greater than 1.0, which by our rule of thumb would indicate that these materials are not notch-sensitive (Table 4). However, because the values fall within the range of 1 to 1.5, some caution should be exercised with respect to the assessment of the overall notch sensitivity characteristics of the materials.

3.2.3 Double Shear. Double-shear testing is unique to the fastener industry. The test involves placing a sample bar or fastener into a set of semicircular grooves, which makes up the bottom portion of the die. The blade or guillotine is then placed on top of the material, and a preload is applied. The test load is then uniformly applied, and the test is discontinued after the ultimate load has been reached or the sample shears.

All materials being considered for fastener applications must meet a specified minimum double-shear strength. As mentioned above, our target shear strength for this evaluation was 745 MPa. Table 5 contains the double-shear values for all nine alloys. All of the alloys easily exceeded the target shear-strength level. Double-shear strength is directly related to tensile strength, and in general the shear strength of a material will be approximately 60% of the ultimate strength.

A closer review of the data shows that a rather interesting trend exists. It appears that the shear-strength values can be grouped by alloy class based on the molybdenum equivalent. The β-rich α-β alloys showed a shear-strength range of 806 to 834 MPa. The near-β alloys showed a shear-strength range of 772 to 786 MPa, and the metastable β alloys showed a shear-strength range of 841 to 896 MPa. Linear trend lines drawn through the three separate groups of data showed three varying slopes. This behavior is shown graphically in Fig. 2.

The nature of this behavior is unknown, but one could speculate that it is related to the grain structure/crystal structure or possibly to the texture of the various alloys classes. Further investigation to verify/quantify this behavior will be performed at a later date.

3.2.4 Fatigue Results. Fatigue strength is extremely important for both aerospace and automotive fasteners. A review of the literature showed that there were limited data on axial load fatigue for many of the alloys in this study (Ref 9). Fatigue properties are strongly influenced by tensile strength and microstructure. Therefore, controlling the microstructure through

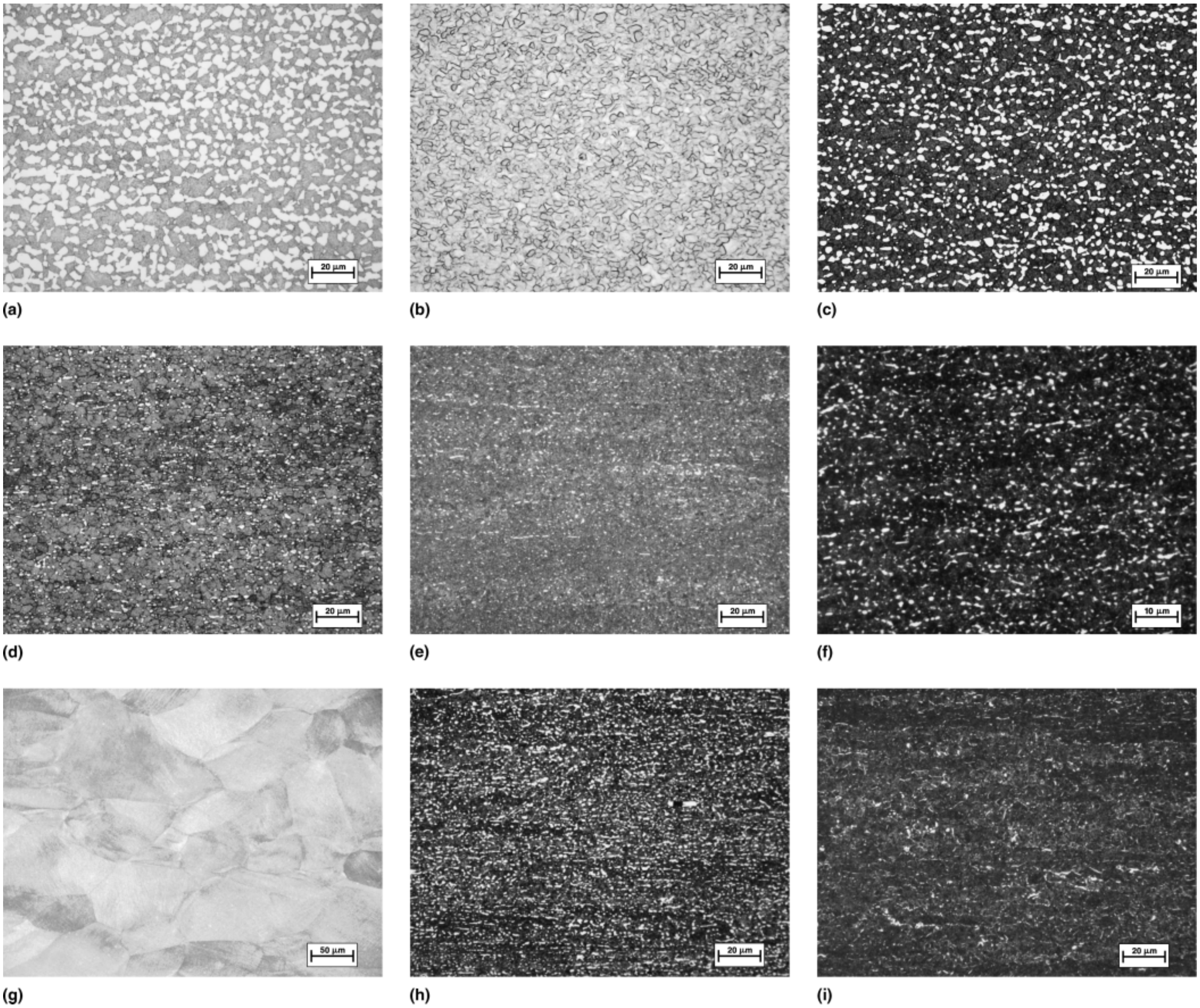

Fig. 1 Longitudinal cross sections in the solution-treated and -aged condition. (a) Ti-662, (b) Ti-62222, (c) SP-700, (d) Ti-10-2-3, (e) Ti-555, (f) VT16-1, (g) Ti-3253, (h) Ti Beta-C, (i) Timetal LCB

Table 4 Standard room temperature tensile and notched tensile data

Alloy	UTS, MPa	YS, MPa	Elongation, %	%RA	Notched UTS, MPa	N/S ratio
Ti-662	1434	1375	11.5	37	1958	1.37
Ti-62222	1475	1327	10	28.5	1806	1.22
SP-700	1455	1310	8	23.5	1730	1.19
Ti-10-2-3	1362	1268	14.5	47	1755	1.29
Ti-555	1503	1465	9	20	1731	1.15
VT16-1	1400	1317	16.5	60	1789	1.28
Ti-3253	1441	1337	14	43.5	1989	1.38
Ti Beta-C	1489	1372	7	13.4	1620	1.09
Timetal LCB	1510	1472	8.5	23	1717	1.14

Note: %RA, percentage reduction in area; N/S, notched strength to smooth strength ratio

Table 5 Double shear data

Alloy	Average double shear, MPa	UTS, %	UTS, MPa
Ti-662	807	56	1434
Ti-62222	834	56	1475
Sp-700	834	57	1455
Ti-10-2-3	779	57	1362
Ti-555	786	52	1503
VT16-1	772	55	1400
Ti-3253	841	58	1441
Ti Beta-C	896	60	1489
Timetal LCB	855	57	1510

the use of proper processing and heat treatment can greatly influence the fatigue behavior (Ref 10).

Room temperature smooth tension-tension fatigue tests were performed at 60 Hz with $R = 0.1$. These tests were performed on samples machined from coil in accordance with ASTM standard E-466. The average tensile strength for all of the alloys was 1448 MPa. Duplicate samples were run at a stress level of 724 MPa, and the tests were terminated after 1 million cycles. This equated to stress levels in the range of 48% to 53% of the ultimate strength. Termination of the tests at 1

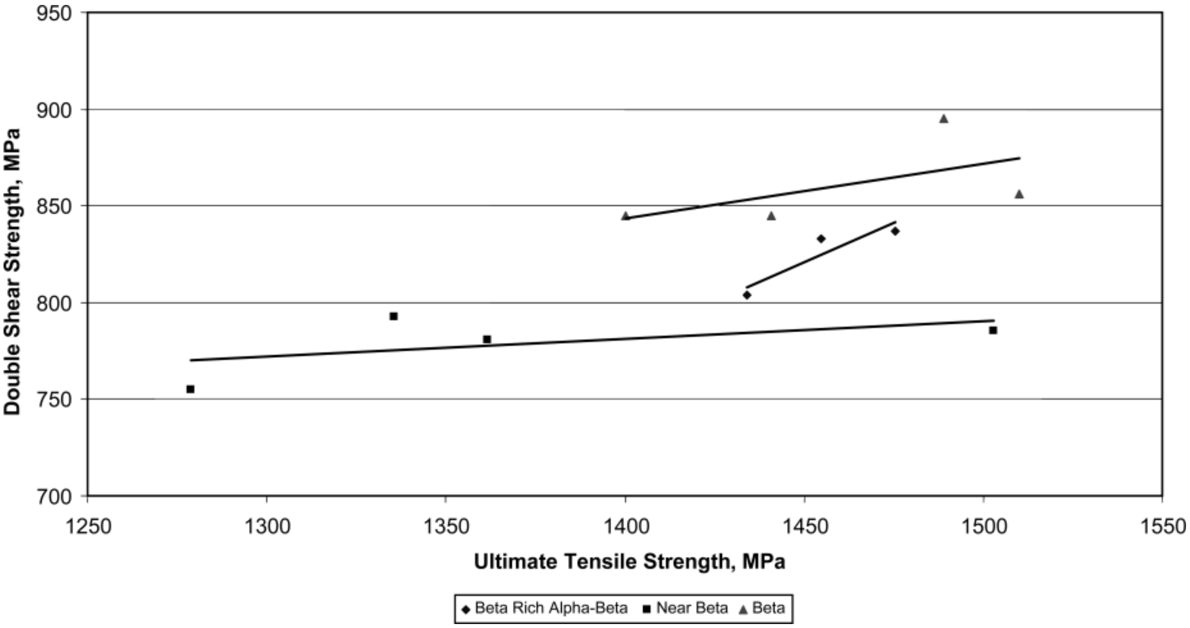

Fig. 2 Double shear strength versus tensile strength by alloy class

Table 6 Fatigue results

Alloy	UTS, MPa	UTS, %	Load, MPa	Test 1 cycles	Test 2 cycles
Ti-662	1434	50.5	724	1,000,000	1,000,000
Ti-62222	1475	49	724	1,000,000	1,000,000
SP-700	1455	49.8	724	1,000,000	1,000,000
Ti-10-2-3	1362	53	724	1,000,000	680,000 (failed)
Ti-555	1503	48	724	1,000,000	1,000,000
VT16-1	1400	52	724	1,000,000	1,000,000
Ti-3253	1441	50.2	724	1,000,000	1,000,000
Ti Beta-C	1489	48.6	724	1,000,000	1,000,000
Timetal LCB	1510	48	724	1,000,000	1,000,000

million cycles was selected in an effort to find the middle ground between aerospace and automotive requirements.

Automotive applications typically look for fatigue run-out at 10 million cycles, whereas the run-out for aerospace applications is much less, in the neighborhood of 70,000 cycles at the desired stress level. For titanium aerospace fasteners, the high fatigue load is set at 40% of the UTS (this level increases to 45% for steel fasteners). The fatigue tests are axial tension-tension tests, and the average life must be 65,000 cycles with a minimum individual life of 45,000 cycles; tests can be terminated at 130,000 cycles (Ref 11). It should be noted that these tests, whether for aerospace or automotive applications, are run on finished fasteners.

Fatigue run-out at 1 million cycles was achieved on all nine of the alloys tested. Table 6 contains the fatigue data for all of the alloys. Several of the alloys in this study have been tested to a more rigorous set of requirements and have shown run-out at even higher stress levels (Ref 12). While it is recognized that the fatigue performance on a smooth bar sample cannot fully represent the fatigue behavior on a finished threaded fastener, it is thought that, based on the limited fatigue data from this study, all of the alloys would appear to be capable of achieving the desired fatigue performance and warrant further evaluation.

4. Summary/Conclusions

- All nine alloys evaluated in this study have shown the capability of reaching the targeted tensile strength range, 1379 MPa, that is necessary for producing a 1241 MPa tension-type fastener.
- The ductility target of 10% elongation was achieved on five of the nine alloys evaluated. However, it should be noted that on those alloys that failed to meet the target elongation the strength was significantly higher than the targeted strength level of 1379 MPa. Therefore, through modification of the heat-treatment cycle it would be possible to reduce the strength and to increase the ductility to meet the targeted ranges.
- The notched-to-smooth tensile ratio for all nine alloys investigated was greater than 1.0, which is an indication that these materials are not notch-sensitive. Further evaluation of the actual threaded components should be studied to verify this conclusion.
- The double-shear results from all nine materials easily surpassed the aim strength level of 745 MPa.
- Fatigue run-out of 1 million cycles on smooth tension-tension axial tests was easily achieved on all nine alloys at 50% of the UTS. Fatigue behavior is very sensitive to surface condition and microstructure, and further testing on finished fastener components would be warranted to verify these results.
- Based strictly on the preliminary data on raw material that were generated in this study, any one of these alloys would appear to be suitable candidate material for a high-strength fastener.

References

1. Matthew J. Donachie, Jr., *Titanium: A Technical Guide,* 2nd ed., ASM International, 2000, p 62-67
2. C.I. Weiss and S.L. Semiatin, Thermomechanical Processing of Beta

Titanium Alloys: An Overview, *Mater. Sci. Eng. A,* Vol 243, 1998, p 46-65

3. Paul J. Bania, Beta Titanium Alloys and Their Role in the Titanium Industry, *Beta Titanium Alloys in the 1990's,* D. Eylon, R.R. Boyer, and D.A. Koss, Ed., The Minerals, Metals & Materials Society, 1993, p 3-14
4. G. Terlinde and G. Fischer, Beta Titanium Alloys, *Titanium 95 Proceedings of the Eighth World Conference on Titanium Volume III,* P.A. Blenkinsop, W.J. Evans, and H.M. Flower, Ed., The Institute of Materials, London, 1996, p 2177-2194
5. G. Welsch, R. Boyer, and E.W. Collings, *Materials Property Handbook Titanium Alloys,* ASM International, 1994
6. S. Ankem and S.R. Seagle, Heat treatment of Metastable Beta Titanium Alloys, *Beta Titanium Alloys in the 1980's,* R.R. Boyer and H.W. Rosenberg, Ed., The Metallurgical Society of AIME, 1984, p 107-126
7. J.R. Wood and P.A. Russo, Heat Treatment of Titanium Alloys, *Ind. Heat.,* April, 1997, p 51-57
8. F.C. Holden, "Notch Sensitivity of Titanium and Titanium Alloys," Titanium Metallurgical Laboratory, Battelle Memorial Institute, Report No. 69, April, 1957
9. S.K. Jha and K.S. Ravichandran, High Cycle Fatigue Resistance in Beta-Titanium Alloys, *Journal of Materials,* Vol 52 (No. 3), 2000, p 30-35
10. R. Chait and T.S. DeSisto, The Influence of Grain Size on the High Cycle Fatigue Crack Initiation of a Metastable Beta Ti Alloy, *Metall. Trans. A,* Vol 8, 1977, p 1017-1020
11. "Part Specification for Externally Threaded Fasteners," Specification BPS-F-69, Boeing, 2005
12. J. Ferrero, A. Hutt, and S. Sweet, Properties Comparison for Various Beta and Alpha-Beta Alloys, *Ti-2003 Science and Technology Proceedings of the 10th World Conference on Titanium,* Vol I, G. Lutjering and J. Albrecht, Ed., Wiley-VCH, Germany, 2004, p 385-392