JMEPEG (2005) 14:799-811
DOI: 10.1361/105994905X75646

Quick Reference Guide for β Titanium Alloys in the 00s

S.L. Nyakana, J.C. Fanning, and R.R. Boyer

(Submitted August 24, 2005)

Beta titanium alloys provide useful combinations of physical and mechanical properties, as well as a wide range of processing options and generally good corrosion properties. Throughout the past several decades, many β alloys have been researched, yet only a handful of these currently enjoy commercial production. While the primary applications continue to be in the aerospace market, β alloys have demonstrated usefulness in other arenas. This article provides a quick reference guide for a large variety of common and not-so-common β titanium alloys. The information provided includes chemical composition, production status, mill product forms, applications, heat treatment, fabrication, corrosion resistance, physical properties, and mechanical properties.

Keywords fabrication, heat treatment, mechanical properties, microstructure, physical properties, 21S

1. Introduction

Table 1 provides a list of near-β and metastable-β titanium alloys along with the development information and production status for each alloy. Table 2 provides physical property data for selected β alloys. Mechanical property data are provided for β alloys with current commercial production (Tables 3 through 9).

Although examples may be cited for the use of each alloy in virtually every product form, in this article alloys will be grouped for discussion based on the most commonly used product forms:

- Forging alloys: 6-2-4-6, Ti-17, 10-2-3, 555
- Strip alloys: 15-3, 21S
- Coil/spring alloys: Beta C, LCB

1.1 General Comments on Data and Abbreviations

Typical mechanical property values are for TIMET production material unless otherwise referenced. The abbreviations used in the tables are as follows: solution-treated (ST); annealed (A); solution-treated and aged (STA); solution-treated and overaged (STOA); air-cooled (AC); water-quenched (WQ); fan AC (FAC).

2. General Characteristics of β Alloys

2.1 Microstructure, Heat Treatment, and Forming

This article presents data for β-rich α-β alloys, near-β alloys, and metastable-β alloys. The degree of α and β stabilization in an alloy is quantified using the aluminum and molybdenum equivalents, respectively. Table 1 and Fig. 1 present the calculated Al and Mo equivalents for several β-type titanium alloys, which are categorized according to the β alloy type. The response to heat treatment varies with chemistry; thus, heat treatment temperatures should be tailored to the β transus (transformation temperature) of the subject material, which is the temperature above which the material is 100% β.

Beta-rich α-β alloys contain both α and β phases at room temperature, but with enough β stabilizer content that the β phase is present in greater proportion than that for standard α-β alloys such as Ti-6Al-4V (6-4).

Near-β alloys have significantly higher β stabilizer content than standard α-β alloys but are not sufficiently stabilized to readily retain an all-β structure upon the air-cooling of thin sections (Ref 19). The solution treatment of near-β alloys (e.g., 10-2-3 and 555) is typically performed below the β transus to provide the appropriate volume fraction and composition of the β phase, which can be hardened by precipitation of the α phase during subsequent aging.

Metastable-β alloys have an even greater content of β stabilizers, which facilitates the retention of an all-β structure upon the air-cooling of thin sections (Ref 19). Metastable-β alloys (e.g., 21S, 15-3-3-3, and Beta C) are typically ST above the β transus.

Beta alloys are typically formed or otherwise fabricated in the ST condition. Following the solution treatment and forming operations, β-type alloys are strengthened by aging below the β transus to precipitate finely dispersed α particles. This produces what is known as the STA condition, which is characterized by increased strength with a concomitant decrease in ductility. Some alloys are used in the STOA condition to provide a more favorable property balance (i.e., ductility, fatigue, toughness, and thermal stability) at the expense of some strength compared with the STA condition.

One of the truly unique features of β-type titanium alloys is that the modulus can be adjusted over a fairly wide range by altering the processing and/or heat treatment. Annealed material (ST condition) has a modulus of approximately 83 GPa (12 Msi) or lower. Aging results in moduli in the range of 103-110 GPa (15-16 Msi). The A material has a low strength; however, substantial cold work (e.g., cold rolling) produces significant increases in strength while still maintaining the low

---

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.

S.L. Nyakana and **J.C. Fanning,** TIMET Henderson Technical Lab, P.O. Box 2128, Henderson, NV 89009; and **R.R. Boyer,** The Boeing Co., P.O. Box 3707, Seattle, WA 98124. Contact e-mail: john.fanning@timet.com.

Table 1 Beta-rich α-β, near-β, and metastable-β titanium alloys and their current production status

Common name	UNS No.	Composition, wt.%	Equivalents(a), wt.%		Development timeframe	Current commercial production?	Comments on current commercial production status and/or primary mill product forms
			Al	Mo			
6-2-4-6	R56260	6Al-2Sn-4Zr-6Mo	7.3	6.0	1960s	Yes	Billet, bar, (sheet, plate)
Corona 5	Unassigned	4.5Al-5Mo-1.5Cr	4.5	7.4	1970s	No	Noncommercial
SP700	R54700	4.5Al-3V-2Mo-2Fe	4.5	9.8	Late 1980s	Limited	Sheet, mainly in Japan
Beta CEZ	Unassigned	5Al-4Mo-4Zr-2Sn-2Cr-1Fe	6.3	10.1	Late 1980s	No	Noncommercial
Ti-17	R58650	5Al-2Sn-2Zr-4Mo-4Cr	6.0	10.4	Early 1970s	Yes	Billet, bar, forgings
Beta III	R58030	11.5Mo-6Zr-4.5Sn	2.5	11.5	Early 1960s	Very limited	Wire
10-2-3	R56410	10V-2Fe-3Al	3.0	12.5	1971	Yes	Billet, bar, forgings
VT-22	Unassigned	5Al-5V-5Mo-1Cr-1Fe	5.0	12.8	Late 1960s	Limited	Former Soviet Union only
VST5551	Unassigned	5Al-5V-5Mo-1Cr-1Fe-1Zr	5.2	12.8	Early 2000s	Limited	Billet, bar, forgings
5-5-5-3, 555, VT22-1	Unassigned	5Al-5V-5Mo-3Cr-0.5Fe	5.0	14.6	1997	Yes	Billet, bar, forgings, fastener stock
DAT 51	Unassigned	22V-4Al	4.0	14.7	1986	Limited	Bar, wire, plate
15-3-3-3	R58153	15V-3Cr-3Al-3Sn	4.0	14.8	1978	Yes	Sheet, strip
KS 15-5	Unassigned	15Mo-5Zr	0.8	15.0	Late 1970s	No	Noncommercial
KS 15-5-3	Unassigned	15Mo-5Zr-3Al	3.8	15.0	Early 1980s	No	Noncommercial
Ti-15Mo	R58150	15Mo	0.0	15.0	1960s	Limited	Superseded by Beta 21S
21S	R58210	15Mo-2.7Nb-3Al-0.2Si	3.0	15.9	1989	Yes	Strip
Beta C	R58640	3Al-8V-6Cr-4Mo-4Zr	3.7	18.9	1969	Limited	Bar, wire
8823	R58820	8Mo-8V-2Fe-3Al	3.0	19.1	Mid-1960s	No	Experimental
8-5-1	Unassigned	8V-5Fe-1Al	1.0	19.8	1960s	No	Difficult to melt (Fe segregation)
LCB	Unassigned	6.8Mo-4.5Fe-1.5Al	1.5	19.9	1992	Yes	Bar, wire
13-11-3, B120VCA	R58010	13V-11Cr-3Al	3.0	26.3	1950s	Very limited	Billet, bar, plate, sheet, wire; difficult to melt (Cr segregation)

(a) Al equivalent = Al + 0.33(Sn) + 0.17(Zr); Mo equivalent = Mo + 0.67(V) + 0.33(Nb) + 2.9(Fe) + 1.6(Cr)

Table 2 Physical properties for selected β titanium alloys

Alloy name	Beta transus(a), °C (°F)	Density, g/cm^3(b), ($lb/in.^3$)	Tensile modulus(b), GPa (Msi)	Compressive modulus(b), GPa (psi)
6-2-4-6 (Ref 1, 2)	938 (1720)	4.67 (0.169)	A 119 (17.2)	A 121 (17.5)
Ti-17 (Ref 3)	880-900 (1620-1650)	4.65 (0.168)	STA 110-114 (16-16.5) STA 103-110 (15-16)	… STA 107-114 (15.5-16.5)
10-2-3 (Ref 4, 5)	790-805 (1450-1480)	4.65 (0.168)	STOA 96-107 (14-15.5)	STOA 104-109 (15.1-15.8)
555 (Ref 6)	860 (1580)	4.67 (0.169)	STA(f) 115 (16.7) ST 78.5-85.4 (11.4-12.4)	STA(f) 118 (17.1) ST 86.1-92.3 (12.5-13.4)
15-3-3-3(h) (Ref 7)	750-770 (1385-1415)	4.71 (0.170)	STA 105-108 (15.2-15.7) ST 72-85 (10-12)	STA 105-110 (15.3-16.0)
21S(h) (Ref 8, 9)	807 (1485)	4.93 (0.178)	STA 103-110 (15-16) ST 96.5 (14)	STA 114-117 (16.5-17.0)
Beta C (Ref 10, 11)	793 (1460)	4.82 (0.174)	STA 106.2 (15.4)	STA 102 (14.8)
LCB (Ref 12, 13)	782-816 (1440-1500)	4.79 (0.173)	STA 110-117 (16-17)	…

Table 2 Physical properties for selected β titanium alloys (continued)

Alloy name	Thermal expansion, 10^{-6}/°C (10^{-6}/°F)	Thermal conductivity(b), W/m · K (Btu · ft/h · ft^2 · °F)	Specific heat(b), J/kg-K (Btu/lb · °F)	Electrical resistivity(b), μΩ cm (μΩ in.)
6-2-4-6 (Ref 1, 2)	8.6(b), 9.4(c) (4.8, 5.2)	7.09 (4.1)	…	190-205 (75-81)
Ti-17 (Ref 3)	9.7(d) (5.4)	…	…	…
10-2-3 (Ref 4, 5)	9.7(e) (5.4)	…	…	…
555 (Ref 6)	10.8(g) (6.0)	…	…	…
15-3-3-3(h) (Ref 7)	8.45(c) (4.67)	8.08 (4.7)	508 (0.121)	147.6 (58)
21S(h) (Ref 8, 9)	7.07(i), 8.01(c) (3.93, 4.45)	7.6 (4.4)	490 (0.117)	135 (53)
Beta C (Ref 10, 11)	8.8(i), 9.6(c) (4.9, 5.3)	…	…	…
LCB (Ref 12, 13)	8.1(i) (4.5)	9.3 (5.4)	519 (0.124)	134 (53)

(a) Values provided are approximate transformation temperatures; actual beta transus varies with alloy composition; (b) Room temperature data, 22-24 °C (72-75 °F), unless otherwise specified; (c) 100 °C (212 °F); (d) 25-400 °C (77-750 °C); (e) Mean coefficient of thermal expansion 20-425 °C (68-800 °F), average varies with temperature; (f) Aged to 1241 MPa (180 ksi) ultimate tensile strength; (g) 40-640 °C (104-1184 °F); (h) Aged at 538 °C (1000 °F) for 8 hours, unless otherwise noted; (i) 38 °C (100 °F)

Table 3 Typical room temperature mechanical properties of β-forging alloys

Alloy		Heat treatment condition	Section size, mm (in.)
6-2-4-6	α-β forged, STA(a)	871 °C (1600 °F), 1 h, WQ + 593 °C (1100 °F), 8 h, AC	≤76 (3)
(Ref 1)	β forged STA(a)	871 °C (1600 °F), 1 h, WQ + 593 °C (1100 °F), 8 h, AC	≤76 (3)
Ti-17	α-β billet process (Ref 14)	843 °C (1550 °F), 4 h, AC + 802 °C (1475 °F), 4 h, FAC + 621 °C (1150 °F), 8 h, AC	Forging
	β billet process (Ref 14)	788 °C (1450 °F), 4 h, FAC + 621 °C (1150 °F), 8 h, AC	Forging
	α-β billet process(b)	802 °C (1475 °F), 4 h, AC + 593-677 °C (1100-1250 °F), 8 h, AC	Forged pancakes(b) 152-330 (6-13)
	β billet process(b)	802 °C (1475 °F), 4 h, AC + 593-677 °C (1100-1250 °F), 8 h, AC	Forged pancakes(b) 152-330 (6-13)
10-2-3	STA(c)	Age 482-524 °C (900-975 °F), 8 h, AC	32-140 (1.25-5.5)
	STA(d)	752-774 °C (1385-1425 °F), 2 h, WQ + 482-538 °C (900-1000 °F), 8 h, AC	Forged pancakes(d) ≥254 (10)
	STA(e) (Ref 15)	Age 510-566 °C (950-1050 °F), 8 h, AC	≤76 (3)
	STOA(e) (Ref 15)	Overage 566-621 °C (1050-1150 °F), 8 h, AC	≤76 (3)
555	STA	804 °C (1480 °F), 1 h, AC + 610 °C (1130 °F), 8 h, AC	Billet 178 (7)
	STA	804 °C (1480 °F), 1 h, AC + 660 °C (1220 °F), 8 h, AC	Billet 178 (7)
	STA	832 °C (1530 °F), 1 h, AC + 610 °C (1130 °F), 8 h, AC	Billet 178 (7)
	STA	832 °C (1530 °F), 1 h, AC + 660 °C (1220 °F), 8 h, AC	Billet 178 (7)

(continued)

Table 3 Typical room temperature mechanical properties of β-forging alloys (continued)

	Typical mechanical properties					
Alloy	Observations	Ultimate, MPa (ksi)	Yield, MPa (ksi)	Elongation, %	Reduction area, %	K_{Ic}, MPa√m (ksi√in.)
6-2-4-6 (Ref 1)	29 tensiles	1264 (183)	1170 (170)	11	31	…
	10 tensiles	1247 (181)	1151 (167)	7	13	…
Ti-17	4 tensiles, 1 K_{Ic}	1165 (169)	1110 (161)	10	32	37.3 (33.9)
	4 tensiles, 3 K_{Ic}	1172 (170)	1089 (158)	12	24	68-78 (62-71)
	618 tensiles	1211 (175.6)	1121 (163.3)	11.8	22.9	…
	131 tensiles	1220 (176.9)	1135 (164.6)	9.1	15.5	…
10-2-3	81 tensiles, 20 K_{Ic}	1287 (186.7)	1202 (174.3)	7.7	26.7	56.5 (51.4)
	150 tensiles	1256 (182.2)	1182 (171.5)	5.7	13.1	…
	12 tensiles, 4 K_{Ic}	1141 (165.4)	1078 (156.3)	13.3	33.4	73-92 (66-84)
	12 tensiles, 4 K_{Ic}	1024 (148.5)	937 (135.8)	18.8	50.5	97-119 (88-108)
555	4 tensiles, 1 K_{Ic}	1294 (187.7)	1218 (176.7)	7	21	48.8 (44.4)
	4 tensiles, 1 K_{Ic}	1163 (168.7)	1100 (159.6)	13	32	58.4 (53.1)
	4 tensiles, 1 K_{Ic}	1332 (193.2)	1218 (176.6)	5	9	52.1 (47.4)
	4 tensiles, 1 K_{Ic}	1189 (172.4)	1104 (160.1)	9	21	65.1 (59.2)

(a) The α-β forged (disk and square-die press) 882 °C (1620 °F); β forged disk 1010 °C (1850 °F); (b) Capability testing of production billets, 152 to 330 mm (6-13 in.) diameter; (c) Production bar material tested during the late 1990s; (d) Capability testing of production billets, 78 to 240 in.^{2} cross-sectional area; (e) Tables 4 and 5 combined data (splice angle precision forging, conventional closed-die forging), thicknesses up to 76 mm (3 in.) L-T, T-L, and S-L direction toughness result

modulus. Tensile and compressive moduli for selected β alloys and heat treatment conditions are provided in Table 2.

2.2 Weldability

Weldability depends on alloy composition and required strength. Metastable-β alloys (e.g., 15-3-3-3 and 21S) exhibit good weldability using the techniques that are generally appropriate for titanium alloys. It is slightly more difficult to produce good weld properties in near-β alloys. For example, 10-2-3 should be electron beam-welded to retain good ductility and toughness. Beta-rich α-β alloys (e.g., 6-2-4-6) tend to have somewhat poor weldability. It is more difficult to produce sound welds in β-rich α-β alloys because the properties of the weld zone are often detrimentally incongruous with the base material.

Welding should be performed in the ST (A) condition prior to aging. Aging can be performed after welding to increase strength with some loss of ductility. Typically, the recommended filler metal is the same as the base metal, although sometimes a lower interstitial content filler metal is used to enhance ductility.

A few general comments about welding titanium follow. Hot titanium will readily react with air, carbon, refractories, and other metals. Therefore, to prevent embrittlement of the weld zone, the weld area must be clean at the start of welding. During welding, it is critically important that the weld area is shielded with inert gas. Titanium cannot be directly fusion-welded to ferrous or aluminum alloys because a brittle intermetallic compound is formed, which may even occur when the metals are heated on contact.

2.3 Environmental Resistance

All β alloys exhibit excellent corrosion resistance to typical aqueous environments (including sea water, salt spray, and steam). Alloys containing at least 4 wt.% molybdenum exhibit

Table 4 Minimum specified room temperature mechanical properties of β-forging alloys

Alloy(a)	Heat treatment condition		Specification (comments)	Section size, mm (in.)
6-2-4-6	STA	816-913 °C (1500-1675 °F), 1 h, AC + 593 °C (1100 °F), 4-8 h, AC	AMS 4981 (bar)	12.7-63.5 (0.501-2.500)
				63.5-76.2 (2.501-3.000)
			AMS 4981 (forgings)	≤76.2 (3.00)
			AMS 4981 (bar, forgings)	76.2-101.6 (3.001-4.000)
10-2-3(b)	STA	482-524 °C (900-975 °F), 8 h, AC	AMS 4984C	≤76 (3.0)
	STA	510-566 °C (950-1050 °F), 8 h, AC	AMS 4986B	≤102 (4.0)
	STOA	566-621 °C (1050-1150 °F), 8 h, AC	AMS 4987A	≤102 (4.0)

Table 4 Minimum specified room temperature mechanical properties of β-forging alloys (continued)

	Industry-specified mechanical properties (minimums or ranges)(a)				
Alloy(a)	Ultimate, MPa (ksi)	Yield, MPa (ksi)	Elongation, %	Reduction of area, %	K_{Ic}, MPa√m (ksi√in.)
6-2-4-6	1172 (170)	1103 (160)	L 10	L 20	…
			T 8	T 15	
	1138 (165)	1069 (155)	L 8	L 15	…
			T 6	T 12	
	1172 (170)	1103 (160)	L 10	L 20	…
			T 8	T 15	
	1103 (160)	1034 (150)	L 8	L 15	…
			T 6	T 12	
10-2-3(b)	1193 (173)	1103 (160)	4	Report value	44 (40)
	1103 (160)	1100 (145)	6	10	60 (55)
	965 (140)	896 (130)	8	20	88 (80)

(a) Ti-17 and 555 do not have industry specifications; these alloys are currently supplied to proprietary user specifications; (b) Solution treatment: 33 to 56 °C (60-100 °F) below β transus (actual transus varies with chemistry), ≥30 min, WQ (for section sizes <25 mm [1 in.] AC is acceptable)

superior resistance to both uniform and localized corrosion attack in hot reducing acid chloride environments (Ref 20). Vanadium has also been shown, to a lesser extent, to enhance the resistance of titanium alloys to hot chloride attack (Ref 20). Aluminum and silicon additions can be beneficial to oxidation resistance (Ref 21). Molybdenum is detrimental to corrosion resistance in oxidizing aqueous environments but is beneficial to oxidation resistance in an atmospheric environment (Ref 22, 23). It has been shown that Mo and Nb have a synergistic effect on enhancing the corrosion resistance of titanium alloys (i.e., 21S) (Ref 24).

Although titanium alloys have generally good corrosion resistance in oxidizing acids, the behavior of β titanium alloys should be evaluated on a case-by-case basis. Beta titanium alloys exhibit the same characteristics under mildly oxidizing conditions as α and α-β alloys. All titanium alloys are susceptible to intergranular corrosive attack in the presence of nitrogen tetroxide (N_2O_4), which can even lead to ignition (Ref 25).

Every titanium alloy that has been tested exhibits some degree of susceptibility to stress corrosion cracking in the presence of absolute methanol (Ref 25). The addition of a relatively small amount of water is enough to create immunity, although the exact volume percent of water will depend on both the environment and the alloy. Many of the high-strength titanium alloys have a tendency to crack in the presence of halogenated organic solvents; however, this susceptibility should be examined on a case-by-case basis (Ref 26).

Heat-treatment operations that are not performed in a vacuum or an inert gas environment will result in oxygen contamination on the surface of the metal. Sufficient oxygen enrichment produces an α-stabilized layer known as α case. The α case should be removed prior to subsequent forming operations; this can be accomplished by pickling.

Beta alloys are very susceptible to rapid hydrogen diffusion during heating, pickling, and chemical milling. Due to this susceptibility, solutions for pickling or chemical milling must be carefully selected so as to minimize hydrogen absorption. Generally, a 35vol.%HNO_3-5%vol.%HF bath is appropriate for β alloys.

3. Forging Alloys

3.1 Ti–6Al–2Sn–4Zr–6Mo, Common Name 6-2-4-6

The alloy 6-2-4-6 is a β-rich α-β alloy that was designed to have the good creep and fatigue properties of Ti-6Al-2Sn-4Zr-2Mo (6-2-4-2) while providing higher room temperature and elevated temperature tensile strength with deep hardenability. Alloy 6-2-4-6 can be heat-treated to a wide range of strengths and toughnesses; it is possible to obtain ultimate tensile strengths as high as 1310 MPa (190 ksi), although it is not normally used at such a high strength level. Alloy 6-2-4-6 is appropriate for extended durations of load-carrying service at temperatures up to 399 °C (750 °F) and can be used at temperatures up to 538 °C (1000 °F) for short times (Ref 1).

Typical and industry-specified minimum room temperature tensile properties are provided in Tables 3 and 4.

3.1.1 Product Forms and Applications. Alloy 6-2-4-6 is commercially available as billet and bar for forging stock. Applications include disk and fan blade components of compressors in gas turbine engines as well as downhole oil and gas equipment (Ref 1).

3.1.2 Heat Treatment and Fabrication. Solution treatment of 6-4-2-6 is performed at temperatures between 816 and 927 °C (1500 and 1700 °F) with times ranging from a few minutes for thin sections to 1 h for large-section forgings.

Table 5 Room temperature compressive, shear, and bearing strength of selected β-forging alloys

						Bearing, *e/D* = 1.5		Bearing, *e/D* = 2.0	
Alloy		Heat treatment condition	Product form	Compressive yield, MPa (ksi)	Shear ultimate, MPa (ksi)	Ultimate, MPa (ksi)	Yield, MPa (ksi)	Ultimate, MPa (ksi)	Yield, MPa (ksi)
6-2-4-6 (Ref 1)	A	857 °C (1575 °F), 15 min, FAC + 732 °C (1350 °F), 15 min, AC + 593 °C (1100 °F), 15 min, AC	Sheet	1276 (185)	…	…	…	…	…
10-2-3 (Ref 4)	STA	730 °C (1350 °F), 1 h, AC + 580 °C (1075 °F), 8 h, AC	Bar	963 (140)	670 (97)	1650 (239)	1310 (190)	2002 (290)	1560 (226)
555	STA(a)	804 °C (1480 °F), 3 h, AC + 610 °C (1130 °F), 8 h, AC	Billet	1276 (185)	731 (106)	…	…	…	…
	STA(b) (Ref 6)	…	Casting	1138 (165)	670 (100)	…	…	2248 (326)	1931 (280)

(a) Properties of 178 mm (7 in.) TIMETAL 555 billet. Corresponding tensile properties: 1294 MPa (188 ksi) ultimate strength, 1218 MPa (177 ksi) yield strength, 7% elongation, 21% reduction of area; fracture toughness 49 MPa√m (44 ksi√in.); (b) Properties of cast bulkhead component heat-treated to 1158 MPa (168 ksi) ultimate tensile strength, 1055 MPa (153 ksi) yield strength, 9% elongation, and 93.9 and 106.4 MPa√m (85.4 and 96.7 ksi√in.) fracture toughness

Table 6 Room temperature tensile properties of β strip alloys

					Typical tensile properties			Industry-specified minimums(a)		
Alloy		Heat treatment condition	Grain direction	Observations	Ultimate, MPa (ksi)	Yield, MPa (ksi)	Elongation, %	Ultimate, MPa (ksi)	Yield, MPa (ksi)	Elongation, %
15-3	ST	ST/A (CVA), no age(b)	L	1090	799 (116)	766 (111)	15	703-945	689-869	12
			T	1087	818 (119)	786 (114)	15	(102-137)	(100-126)	
	STA	Aged at 482 °C (900 °F), 16 h, air cool(c)	L	368	1346 (195)	1243 (180)	8	1241 (180)	1172 (170)	5
			T	366	1373 (199)	1268 (184)	7			
	STA	Aged at 496 °C (925 °F), 8 h, air cool (Ref 5)	L	30	1296 (188)	1200 (174)	9	…	…	…
			T	30	1310 (190)	1214 (176)	8			
	STA	Aged at 510 °C (950 °F), 8 h, air cool(d)	L	145	1215 (176)	1103 (160)	10	1000 (145)	965 (140)	7
			T	144	1244 (180)	1133 (164)	10			
	STA	Aged at 538 °C (1000 °F), 8 h, air cool(e)	L	312	1117 (162)	1007 (146)	12	1000 (145)	965 (140)	7
			T	301	1145 (166)	1027 (149)	11			
21S	ST	ST/A (CVA), no age(f)	L	357	907 (132)	875 (127)	16	827-1000	793-965	8
			T	367	929 (135)	895 (130)	15	(120-145)	(115-140)	
	STA	Aged at 593 °C (1100 °F), 8 h, air cool(g)	L	265	1234 (179)	1158 (168)	11	993 (144)	938 (136)	5
			T	140	1207 (175)	1130 (164)	11	1014 (147)	951 (138)	5
	STA	Age 691 °C (1275 °F), 8 h + 649 °C (1200 °F), 8 h(h)	L	247	1034 (150)	958 (139)	15	862 (125)	793 (115)	6
			T	247	1048 (152)	979 (142)	15	862 (125)	793 (115)	5

(a) Minimum (or minimum and maximum) tensile properties are as specified in AMS 4914B&C (15-3-3-3) and AMS 4897A (21S); (b) 0.5 to 2.8 mm (0.020-0.110 in.) production material tested between April 1992 and January 2005; (c) 0.5 to 2.8 mm (0.020-0.109 in.) production material tested between January 1997 and November 2001; (d) 0.5 to 2.3 mm (0.020-0.090 in.) production material tested between August 2002 and December 2004; (e) 0.5 to 2.3 mm (0.020-0.090 in.) production material tested between November 1998 and July 2003; (f) 0.5 to 5.6 mm (0.020-0.220 in.) production material tested between September 1998 and January 2005; (g) 0.4 to 2.3 mm (0.016-0.090 in.) production material tested between October 1998 and December 2003; (h) 0.4 to 2.3 mm (0.016-0.090 in.) production material tested between October 1998 and November 2003

Table 7 Room temperature compressive, shear, and bearing strength of β strip alloys

					Bearing, *e/D* = 1.5		Bearing, *e/D* = 2.0	
Alloy	STA condition aging cycle	Grain direction	Compressive yield, MPa (ksi)	Shear ultimate, MPa (ksi)	Ultimate, MPa (ksi)	Yield, MPa (ksi)	Ultimate, MPa (ksi)	Yield, MPa (ksi)
15-3	482 °C (900 °F), 16 h, AC (Ref 7)	L	1329 (193)	…	1962 (285)	1858 (270)	2231 (324)	2044 (297)
		T	1350 (196)	860 (125)	1971 (286)	1843 (267)	…	2027 (294)
	496 °C (925 °F), 8 h, AC (Ref 16)	L	1269 (184)	784 (114)	2069 (300)	1959 (284)	2275 (330)	2015 (292)
		T	1307 (190)	799 (116)	2073 (301)	1955 (284)	2181 (316)	2033 (295)
	538 °C (1000 °F), 8 h, AC (Ref 7)	L	1052 (153)	729 (106)	1731 (251)	1543 (224)	2180 (316)	1745 (253)
		T	1078 (156)	734 (106)	1746 (253)	1541 (224)	2214 (321)	1767 (256)
21S	593 °C (1100 °F), 8 h, AC (Ref 9)	L	1108 (161)	780 (113)	1824 (267)	1668 (242)	2278 (330)	1876 (272)
		T	1180 (171)	791 (115)	1834 (266)	1707 (248)	2268 (329)	1959 (284)
	691 °C (1275 °F), 8 h, AC + 649 °C (1200 °F), 8 h, AC (Ref 9)	L	969 (141)	698 (101)	1664 (241)	1391 (202)	2042 (296)	1630 (237)
		T	1021 (148)	691 (100)	1654 (240)	1392 (202)	2054 (298)	1696 (246)

Table 8 Room temperature tensile properties of β coil/spring alloys

			Typical tensile properties				Industry-specified tensile properties (minimums or ranges)				
Alloy	Product form, diameter, mm (in.)	Heat treatment condition	Ultimate, MPa (ksi)	Yield, MPa (ksi)	Elongation, %	Reduction area, %	Specification	Ultimate, MPa (ksi)	Yield, MPa (ksi)	Elongation, %	Reduction area, %
Beta C (Ref 10)	Wire, 5.8 (0.23)	CW + Age	1649 (213)	…	12	28	AMS 4975A(a)	1276-1413 (185-205)	…	10	≥20
	Bar stock, 38 (1.5)	ST	903 (131)	862 (125)	16	32	…	…	…	…	…
		STA	1406 (204)	1303 (189)	5	7	AMS 4958A(b)	1241 (180)	…	8	20
LCB (Ref 12)	Wire and bar, 8.5-25 (0.3-1)	ST	1096 (159)	1054 (153)	18	…	(c)	1020-1150 (148-167)	986-1103 (143-160)	13	…
	Wire, 10 (0.39)	STA	1402 (203)	1370 (199)	13.3	39.1	(c)	1296 (188)	1241 (180)	6	…

(a) The AMS 4975A specified aging cycle is 510 to 566 °C (950-1050 °F) for 6 to 10 h followed by AC; (b) The AMS 4985A aging cycle is 454 to 566 °C (850-1050 °C) for 6 to 20 h, AC. Applicable to bars and rods of 25 mm (1 in.) or less in diameter; (c) The TIMET LCB specification covers wire and bar from 8.5 to 25 mm (0.33-1 in.) diameter (Ref 17, 18).

Table 9 Room temperature fatigue life of β coil/spring alloys in the solution-treated and aged condition

Alloy	Specimen type	Stress-concentration factor, K_t	Stress ratio	Cycles	Fatigue limit, MPa (ksi)
Beta C (Ref 10)	Unnotched	1	0.1	10^5	855 (124)
	Unnotched	1	0.1	10^7	600 (87)
	Notched	3	0.1	10^5	303 (44)
	Notched	3	0.1	10^7	276 (40)
LCB (Ref 12)	Unnotched	1	0.1	10^7	800-850 (116-123)
	Notched	3	0.1	10^7	415 (60)

Aging is performed in the range of 538 to 732 °C (1000-1350 °F) for times ranging from 15 min up to 8 h (Ref 25).

The heat-treatment temperature, time, and cooling rate (and consequently the section size) significantly affect the microstructure and properties of 6-2-4-6. Faster cooling rates result in higher strength and lower ductility. The higher end of the aging range actually results in an overaged condition with lower strength and enhanced ductility. Alloy 6-2-4-6 exhibits good hardenability in section sizes up to 76 mm (3 in.) with decreasing deep hardenability for thicker sections (Ref 1).

The forgeability and crack sensitivity of 6-2-4-6 are similar to those of Ti-6Al-4V. Alpha-β forging provides the best combination of strength, ductility, and stress-life fatigue properties (Ref 1). Beta forging yields improved resistance to fatigue-crack growth and salt-water crack propagation (Ref 1).

3.2 Ti-5Al-2Sn-2Zr-4Mo-4Cr (Common Name Ti-17)

Ti-17 is a β-rich α-β-forging alloy with deep hardenability, high strength, good toughness, and excellent low-cycle fatigue behavior (an alternate alloy to 6-2-4-6 above). Ti-17 is capable of ultimate tensile strengths of 1245 to 1265 MPa (181-183 ksi). The distinguishing feature of Ti-17 is that, unlike the typical β or near-β alloys, it offers considerable creep strength to 430 °C (800 °F) (Ref 3).

Table 3 provides typical room temperature tensile properties for α-β-processed and β-processed material. Ti-17 is currently supplied to proprietary customer specifications; thus, industry-specified minimum tensile properties are not available.

3.2.1 Product Forms and Applications. Ti-17 is available in bar and billet. It was developed for use in rotating aerospace jet engine components, specifically, in disks for fan and compressor stages. Other current applications include aftermarket automotive and racing components. Ti-17 fasteners (produced with cut or rolled threads) are being used in the automotive aftermarket with a good combination of tensile, shear, and fatigue properties.

3.2.2 Heat Treatment and Fabrication. Ti-17 can be processed in either the α-plus-β or β fields. Alpha-β processing results in good fatigue at some expense to damage tolerance. Beta processing provides good ultrasonic inspectability and maximizes damage tolerance; however, the processing must be carefully controlled to avoid recrystallization, which decreases fatigue and ductility. Solution heat treatment depends on the processing history: α-β-processed Ti-17 receives a double solution treatment; β-processed material receives a single-solution anneal (Ref 14).

The first solution treatment for α-β-processed material is performed in the temperature range of 816 to 857 °C (1500-1575 °F), approximately 30 to 70 °C (86-158 °F) below the β transus, for 4 h followed by rapid air cooling; this initiates the nucleation of acicular α. Further nucleation and growth of aged α occurs during subsequent aging (Ref 14). The second solution anneal is performed at 802 °C (1475 °F). This second solution treatment coarsens the primary α remaining after the first solution treatment, thereby providing improved creep resistance and damage-tolerance properties. It also initiates further α precipitation upon cooling and results in sufficient retained β to be responsive to subsequent aging. Fan air-cooling may be used from the second solution treatment for sections up to 76.2 mm (3 in.) thick; however, water quenching provides more consistent and slightly higher strength properties (Ref 14).

Beta-processed material receives only a single 802 °C

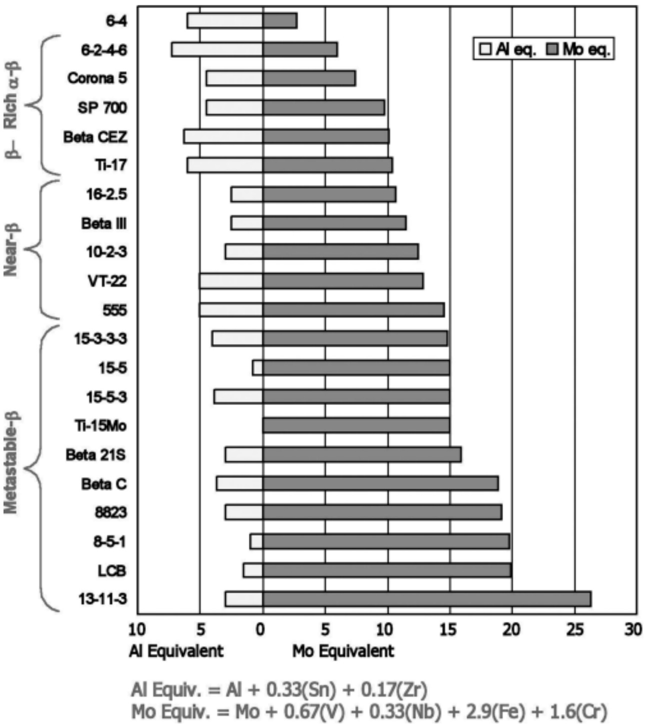

Fig. 1 Classification of selected β titanium alloys with Al and Mo equivalents provided (Note: The standard α-β alloy Ti-6Al-4V is included for comparison.)

(1475 °F) solution anneal for 4 h. Beta-processed material does not require a two-part heat treatment because acicular α is nucleated or precipitated during cooling from the forging temperature (Ref 14).

The typical aging treatment is the same for both α-β- and β-processed material: 621 to 649 °C (1150-1200 °F) for 8 h followed by air cooling (Ref 14).

3.3 Ti-10V-2Fe-3Al (Common Name 10-2-3)

Alloy 10-2-3 is a near-β forging alloy with high strength, toughness, and fatigue life combined with deep hardenability. Alloy 10-2-3 can be heat-treated to obtain ultimate tensile strengths of 965 to 1290 MPa (140-187 ksi) and corresponding fracture toughnesses of 120 to 44 MPa√m (108-40 ksi√in.). At service temperatures of 315 °C (600 °F), 10-2-3 in the STA condition retains greater than 80% of its room temperature strength and has creep-stability characteristics similar to those of α-β alloys (Ref 4).

Tables 3 and 4 provide typical and industry-specified minimum room temperature tensile properties. Compressive, shear, and bearing strengths are shown in Table 5. Figures 2 through 5 provide high cycle fatigue (HCF), fatigue crack growth, and creep data.

3.3.1 Product Forms and Applications. Alloy 10-2-3 is commonly available as billet and bar. Current applications of 10-2-3 are predominantly aircraft structural components. Large die-forging techniques are used to fabricate the truck beam components of aircraft landing gear. Other applications include fittings, fasteners, actuators, flap tracks, and rotor heads.

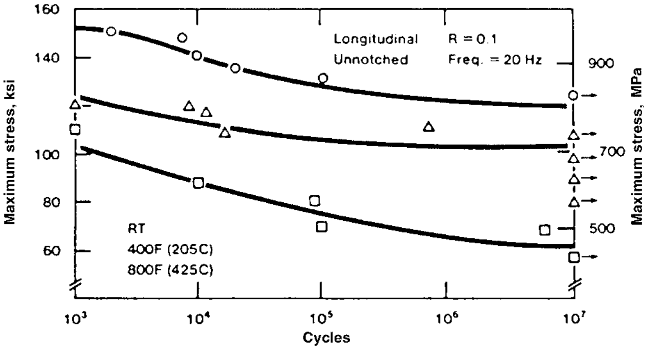

Fig. 2 Axial load fatigue behavior of unnotched 76 mm (3 in.) Ti-10V-2Fe-3Al round bar heat-treated at 760 °C for 1 h, FAC at 565 °C for 8 h, and AC (1400 °F for 1 h, FAC at 1050 °F for 8 h and AC) (Ref 4)

3.3.2 Processing. For the high-strength condition, the material must be processed within a fairly tight processing window involving β- and α-β-forging to achieve a good combination of tensile strength, ductility, and toughness (1193 MPa [173 ksi]; 4% and 44 MPa√m [40 ksi√in.] minimums, respectively). The primary forging is done above the β transus. Grain boundary α and a fine lamellar α are formed upon cooling from the β transus; both of these forms of α reduce ductility. The lamellar α is beneficial for toughness, but is detrimental to ductility. Following the β work with approximately 15% α-β work improves ductility by globularizing the lamellar α and breaking up the grain boundary α. However, work in excess of 15% will result in further globularization of the lamellar α, continuing to improve the ductility but further reducing the toughness. If fracture toughness is not a concern, greater amounts of work will continue to improve the strength-ductility combination (Ref 27). Manufacturers of dynamically critical helicopter components have developed an alternate 10-2-3 processing route using the material at a lower strength to maximize the HCF properties (Ref 17).

3.3.3 Heat Treatment. To achieve the desired combination of mechanical properties, 10-2-3 must be WQ from the solution treatment. Consequently, 10-2-3 has a practical thickness limitation of about 76 mm (3 in.) at the time of heat treatment, although reasonably good properties can be obtained in sections up to 125 mm (5 in.) thick (Ref 18). The solution heat treatment for 10-2-3 is 28-56 °C (50-100 °F) below the β transus for a minimum of 30 min, followed by a water quench, although an air cool can suffice for parts that are less than 25 mm (1 in.) thick.

Alloy 10-2-3 can be aged to achieve a range of strength-toughness combinations. Aging is performed at temperatures between 482 and 593 °C (900 and 1100 °F) for 8 h. Table 4 provides the AMS-specified aging treatments and the corresponding strength-toughness combinations. Generally, lower aging temperatures yield higher strengths and lower toughnesses. Conversely, higher aging temperatures provide lower strength and higher toughness.

3.4 Ti-5Al-5V-5Mo-3Cr-0.5Fe (Common Names 555, 5-5-5-3, VT22-1)

The near-β forging alloy TIMETAL555 was developed as an improved version of the Russian alloy VT22. Alloy 555 exhibits more favorable combinations of strength, ductility, and toughness than VT22 with a more simplified processing approach. Alloy 555 is also a better choice than 10-2-3 for some applications. Alloy 555 is capable of achieving strengths up to

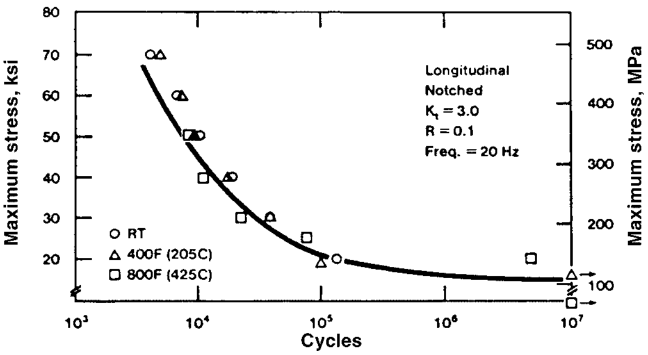

Fig. 3 Axial load fatigue behavior of notched (Kt = 3.0) 76 mm (3 in.) Ti-10V-2Fe-3Al round bar heat-treated at 760 °C for 1 h, FAC to room temperature, then 565 °C for 8 h, and AC (1400 °F for 1 h, FAC to room temperature, then 1050 °F for 8 h, and AC) (Ref 4)

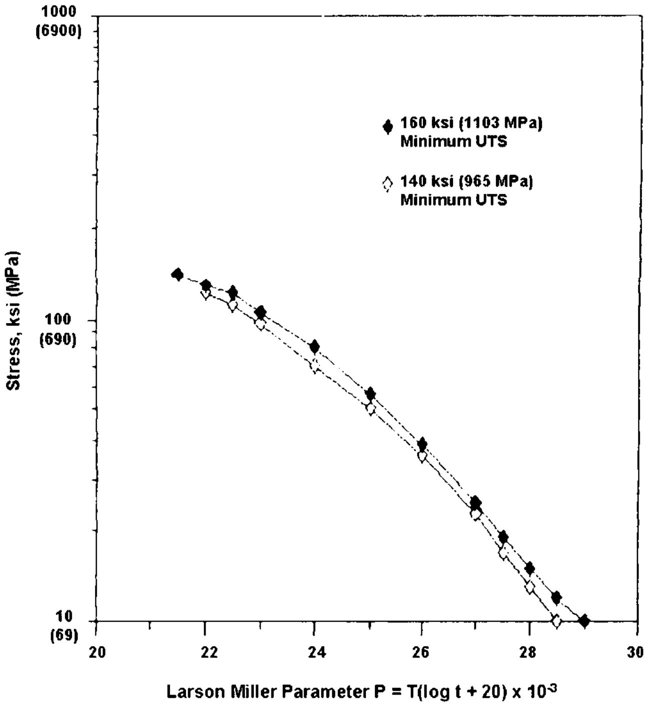

Fig. 4 Creep data at 0.2% for 10-2-3 forgings processed to two ultimate tensile strength levels: 1103 MPa (160 ksi); and 965 MPa (140 ksi) (Ref 15)

1517 MPa (220 ksi), although it is not typically used at this strength level. Similar to 10-2-3, 555 is suitable for use in applications with service temperatures up to 315 °C (600 °F).

Typical room temperature tensile properties for 555 are presented in Table 3. Industry-specified minimum tensile properties are not available for 555 because it is currently supplied to proprietary customer specifications. Compressive and shear strengths are given in Table 5.

3.4.1 Product Forms and Applications. Alloy 555 is available as billet, bar, and fastener stock. Alloy 555 is under evaluation for several major airframe components on new programs.

3.4.2 Heat Treatment and Fabrication. Alloy 555 offers practical improvements over 10-2-3 for large section components due to its deep hardenability and improved producibility. Unlike 10-2-3, which must be quenched, 555 can be AC from the solution treatment temperature and still provide higher strength with larger section sizes. Alloy 555 section sizes as thick as 150 mm (5.9 in.) exhibit only minor decreases in STA strength compared with 10-2-3 maximum section sizes of 76 mm (3 in.) (Ref 18).

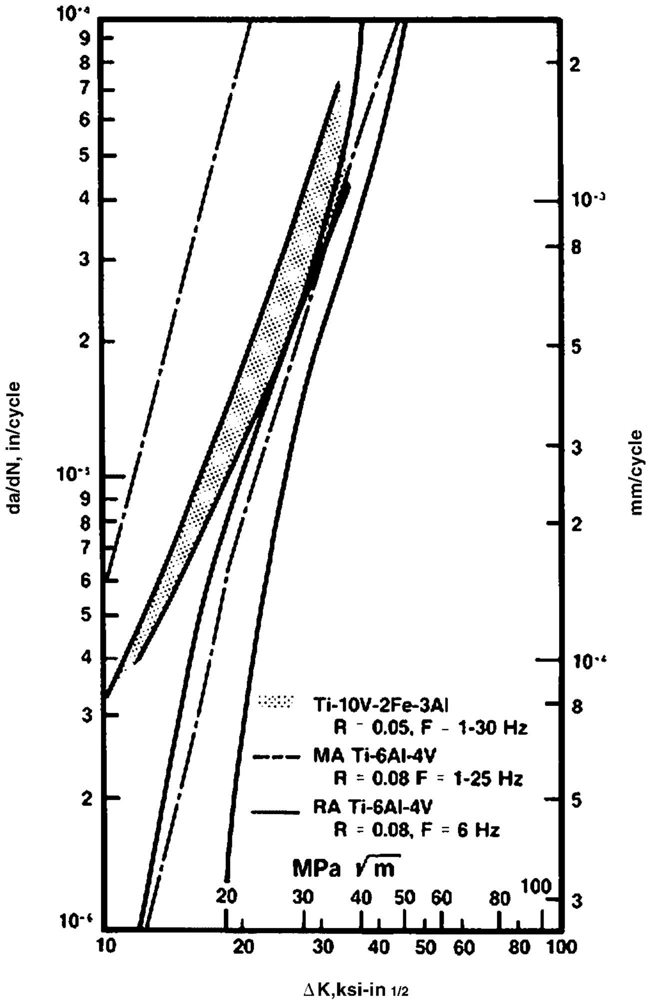

Fig. 5 Comparison of fatigue crack growth rates of 10-2-3 forgings to Ti-6Al-4V (Ref 5)

Additionally, 555 exhibits more robust thermomechanical processability than 10-2-3. Typically, new suppliers of 10-2-3 forgings must go through a learning curve before achieving the desired combinations of strength, ductility, and toughness. However, several forging suppliers have been able to supply 555 forgings, meeting the mechanical property requirements with their first attempt.

Alloy 555 is ST at 28-66 °C (50-150 °C) below the β transus for a minimum of 30 min followed by air cooling. Aging is performed at temperatures of 566-677 °C (1050-1250 °F) for 8 h.

As solution-treated 555 can have relatively high strength and low ductility, a partial aging cycle or stress relief cycle is recommended prior to machining (Ref 18). The material is completely aged after 4 to 6 h, and once this condition is reached, the material is relatively insensitive to additional aging time (Ref 18).

Although 555 was initially developed as a high-strength replacement for 10-2-3 and steel components at the 1241 MPa

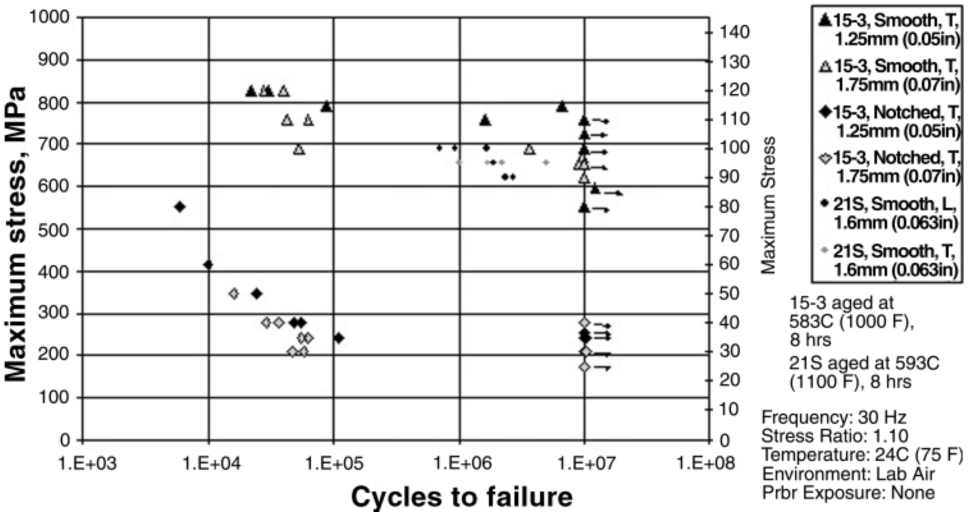

Fig. 6 Axial HCF for 15-3 and 21S Strip (15-3 data Ref 28; 21S data TIMET production material)

(180 ksi) strength level, a lower-strength heat treatment to drop the strength and improve the damage tolerance properties is under investigation for product forms such as forgings and potential extrusion and plate applications.

4. Strip Alloys

4.1 General Forming Guidelines for β Strip Alloys

If present, surface contamination (α case) must be removed prior to forming β strip alloys (mill product is typically supplied free of α case). Alpha case can be removed by chemical milling (pickling) with a solution that does not result in excessive hydrogen absorption. The recommended pickling solution is 5vol.%HF-35vol.%HNO_3.

Typical 90° minimum bend radii are 1.5-2.0 times the thickness (Ref 8). Cold reductions in excess of 80% are possible in most compressive operations. Alloys 21S and 15-3 are strain rate-sensitive and have relatively low work hardenability; thus, slow strain rates and uniform strains will improve formability. Intermediate anneals can be used between forming operations to restore workability for forming operations more complex than simple bending. However, it is essential to choose a combination of cold work and solution heat treatment that produces a high degree of recrystallization with minimal grain growth. Moreover, it will be necessary to repickle if intermediate anneals are not performed in a vacuum or inert gas environment.

Although springback is relatively severe, it can be compensated for either by overforming or by forming at higher temperatures (i.e., 204-760 °C [400-1400 °F]), which increases deformation capability and reduces springback. It is recommended that hot forming and hot sizing be performed at the aging temperature, which is then counted as part of the total aging cycle. The exposure of ST material to temperatures of 260-427 °C (500-800 °F) should be kept to less than 1 h to avoid the possibility of embrittlement. If forming temperatures exceed the β transus (~807 °C [1485 °F]), then time at temperature should be minimized to avoid excessive grain growth.

Machining should always be performed after aging because machining creates a severely cold-worked layer that will have an enhanced aging response and will result in a brittle surface. Moreover, the material is somewhat gummy in the ST condition, making it more difficult to machine.

4.2 Ti-15V-3Cr-3Al-3Sn (Common Names 15-3-3-3, 15-3)

Alloy 15-3-3-3 (also known as simply 15-3) is a strip-producible metastable-β titanium alloy with outstanding cold formability in the ST condition and high strength in the aged condition. It was designed on an Air Force contract to lower the cost of titanium sheet metal parts by minimizing processing and fabrication costs. Alloy 15-3 is heat-treatable to ultimate tensile strengths of 896-1310 MPa (130-190 ksi) and is generally suitable for use at temperatures up to 288 °C (550 °F) (Ref 7).

Table 6 provides typical and industry-specified room temperature tensile properties of 15-3 strip. Table 7 presents compressive, shear, and bearing strengths. Figure 6 through 8 provide HCF life, creep resistance, and crack-propagation data.

4.2.1 Product Forms and Applications. The most common mill product form is strip in thicknesses of 0.25-2.4 mm (0.010-0.094 in.). Castings are also produced. Alloy 15-3 is used in critical components on both military and commercial air and space vehicles. Alloy 15-3 is also used in flat spring applications, such as clock springs. Other applications include environmental control system ducts, fire extinguishers, propellant tanks, fasteners, springs, foil, honeycomb, and body armor.

4.2.2 Heat Treatment and Fabrication. Alloy 15-3 is supplied in the ST condition, which is also referred to as the A or continuous vacuum A (CVA) condition. The CVA process prevents surface contamination, removes hydrogen throughout the thickness, and enables uniform control of the cooling rate along the entire strip length (unlike batch annealing of coils). Forming or welding of 15-3 should be performed in the ST condition prior to aging. Solution treatment of 15-3 is typically performed at 10 °C (50 °F) above the β transus within the temperature range of 788-843 °C (1450-1550 °F) for 4-30 min, followed by an air cool (Ref 7).

Alloy 15-3 can be directly aged after forming; strength will vary depending on the amount of cold work in the part. Cold deformation increases both the aging rate to full strength, and the strength level of aged and unaged material (Ref 7). Cold rolling (60-75% reduction) can develop a high yield strength to modulus ratio (Ref 29).

A variety of strength levels can be achieved by aging between 480 and 620 °C (900 and 1150 °F) for 4 to 16 h. Between

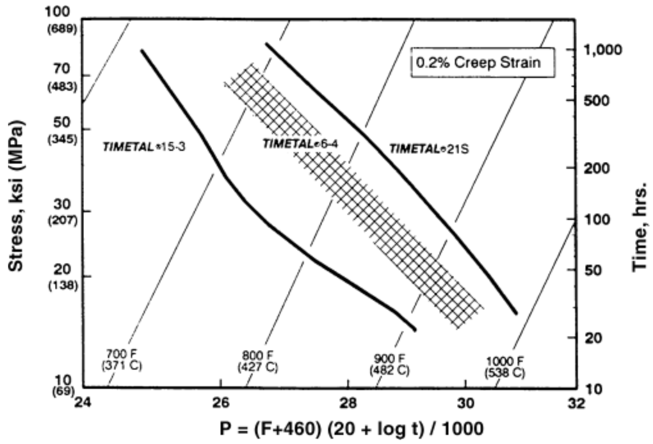

Fig. 7 Larson-Miller 0.2% creep comparison for titanium alloys 6-4, 15-3, and 21S (Ref 8)

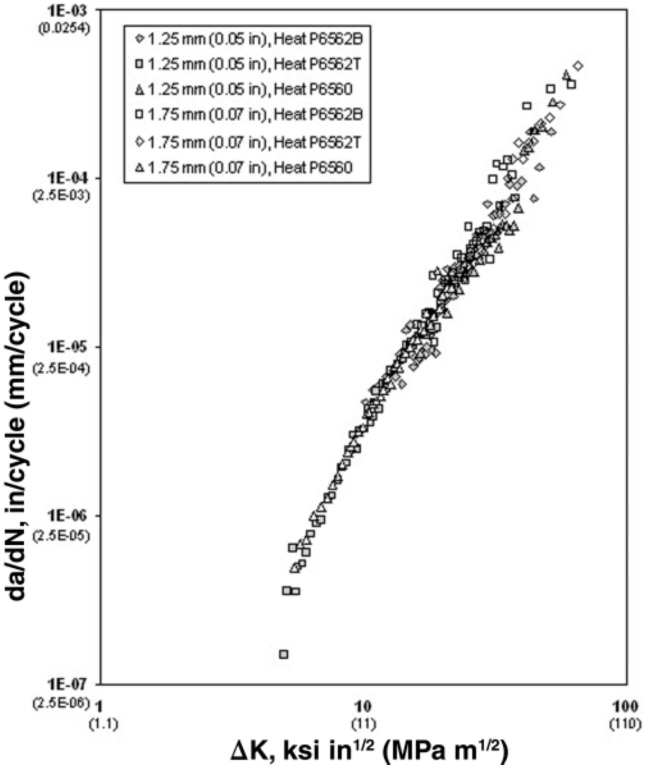

Fig. 8 Fatigue crack growth resistance of 15-3 strip, aged at 583 °C (1000 °F) for 8 h, of 1.25 and 1.75 mm (0.05 and 0.070 in.) (Ref 28)

455 and 593 °C (850 and 1100 °F), the strength of 15-3 is a linear function of aging temperature, where higher aging temperatures produce lower strength and higher ductility (Ref 7). Table 6 provides the AMS-specified aging treatments and the corresponding strength-ductility combinations.

4.3 Ti-15Mo-2.7Nb-3Al-0.2Si (Common Name 21S)

TIMETAL21S is a metastable-β titanium alloy that offers a unique combination of properties, including the high specific strength and good cold formability that are typical of metastable-β alloys. It was specifically designed for improved oxidation resistance, elevated temperature strength, creep resistance, and thermal stability. Alloy 21S can attain an ultimate tensile strength of 1470 MPa (210 ksi) with better than 2% elongation (Ref 8). It is useful for applications with service temperatures up to 593 °C (1100 °F). In comparison to other β alloys, 21S has the best corrosion resistance and the lowest coefficient of thermal expansion.

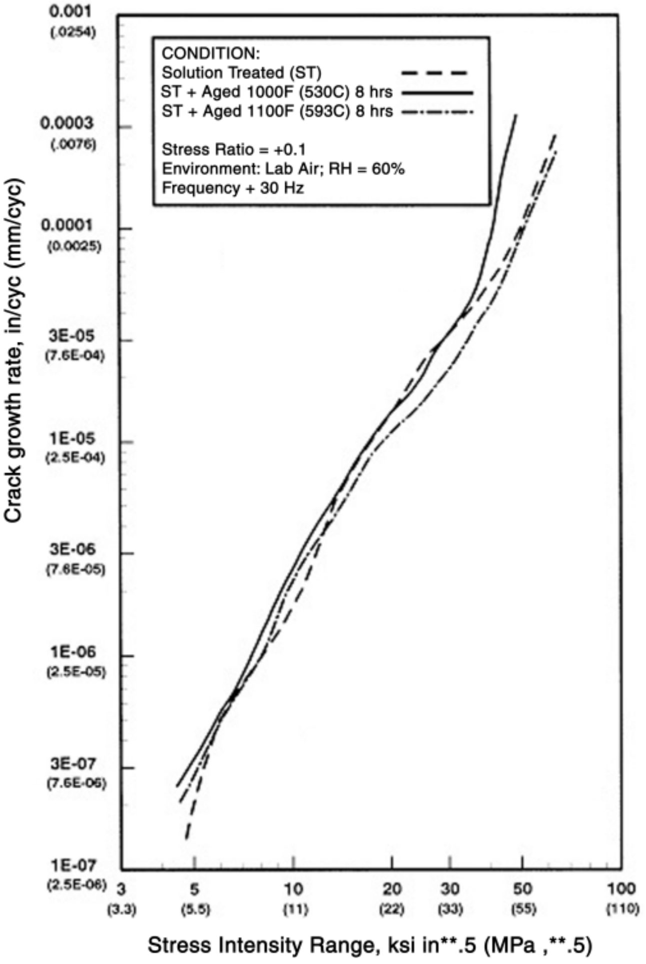

Fig. 9 Fatigue crack growth resistance of 21S in three heat-treated conditions (Ref 8)

Table 6 presents typical and industry-specified room temperature tensile properties of 21S strip. Table 7 provides compressive, shear, and bearing strengths. Figure 6, 7, and 9 provide HCF life, creep resistance, and fatigue crack growth rate data.

4.3.1 Product Forms and Applications. Alloy 21S was developed for use in metal matrix composites; however, 21S is now predominantly used in monolithic applications in the form of strip. Alloy 21S is well suited for metal matrix composites because it can be economically rolled to foil, is compatible with most fibers, and is sufficiently stable and oxidation-resistant up to 816 °C (1500 °F). Alloy 21S strip is commercially available in gages from 0.4 mm (0.016 in.) to 2.3 mm (0.090 in.).

Current 21S applications include warm and hot airframe or engine structures, particularly those within the engine exhaust areas.

4.3.2 Environmental Resistance. Alloy 21S has substantially better overall corrosion resistance than any other high-strength titanium alloys. Also, the corrosion resistance of 21S surpasses that of commercially pure titanium in all but highly oxidizing environments. Alloy 21S is currently the only titanium alloy that has demonstrated the ability to sufficiently withstand exposure to commercial aircraft hydraulic fluids (i.e., Skydrol) above approximately 149 °C (300 °F). If the hydraulic fluid accumulates on the structure above this temperature, the Skydrol decomposes to form an organophosphoric acid, which etches the material and results in hydrogen embrittlement. Its high resistance at all temperatures to Skydrol and similar hydraulic fluids has enabled the use of 21S in nacelle components on commercial aircraft, resulting in substantial weight savings. Additionally, 21S has the best oxidation resistance of any metastable-β alloy, further increasing its suitability for use in elevated-temperature applications.

Alloy 21S also exhibits an unusually high creep resistance for a β titanium alloy. The creep resistance of 21S exceeds that of Ti-6Al-4V.

4.3.3 Heat Treatment and Fabrication. Alloy 21S is supplied and formed in the ST condition (also known as the A or CVA condition, previously described in section 4.2.2). Solution treatment is typically performed at 10 °C (50 °F) above the β transus within the temperature range of 816-843 °C (1500-1550 °F) for 3 to 30 min followed by an air cool. After forming, 21S is aged to the desired strength. The typical aging treatment is 510-691 °C (950-1275 °F) for 8-16 h.

For applications where service temperatures are less than 427 °C (800 °F), 21S is usually aged at 593 °C (1100 °F) or 621 °C (1150 °F) to produce ultimate strength levels of 1120-1260 MPa (160-180 ksi). For elevated-temperature applications (i.e., service temperatures up to about 650 °C [1200 °F]), a duplex age of 691 °C (1275 °F) followed by 650 °C (1200 °F) is used to provide maximum long-term thermal stability. Unaged material should not be used above approximately 204 °C (400 °F) because the potential exists for embrittlement by the precipitation of ω phase or very fine α. Care should be used during aging to avoid heating or cooling too slowly, because this can result in very high strength with concomitant low ductility (Ref 8).

5. Coil/Spring Alloys

5.1 Ti-3Al-8V-6Cr-4Mo-4Zr (Common Names Beta C, Ti-38-6-44)

Beta C is a metastable-β titanium alloy that was developed to improve upon the alloy Ti-13V-11Cr-3Al, which had problems with melt segregation due to the high Cr content and significant fabrication issues. Beta C can offer ultimate tensile strengths in excess of 1400 MPa (203 ksi) with 5% elongation; however, Beta C requires approximately 30% cold work to attain high strengths (Ref 12). In the STA condition, Beta C is suitable for extended-time use at temperatures up to 316 °C (600 °F) and for short-time use at temperatures up to 427 °C (800 °F) (Ref 30).

Table 8 gives typical and industry-specified room temperature tensile properties for Beta C. Axial fatigue life data are given in Table 9 and Fig. 10 and 11.

5.1.1 Product Forms and Applications. Beta C is used primarily as bar and wire for spring and fastener applications, including coil springs for aircraft (Ref 12).

5.1.2 Environmental Resistance. Like other β alloys, Beta C is resistant to corrosive attack by salt water and marine environments (Ref 30). The Mo content also contributes toward resistance to reducing acids and chloride crevice corrosion (Ref 2).

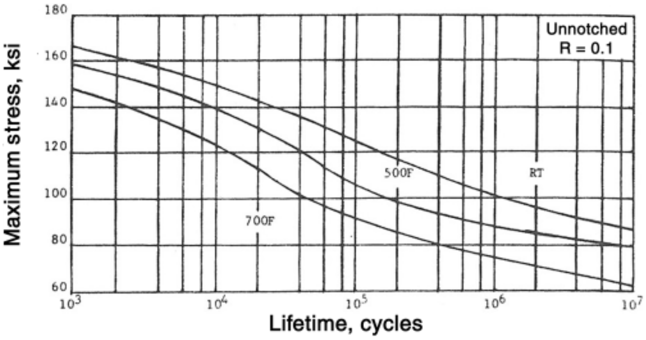

Fig. 10 Effect of temperature on axial load fatigue of 152 mm (6 in.) diameter Beta C forging in the STA condition (unnotched) (Ref 30)

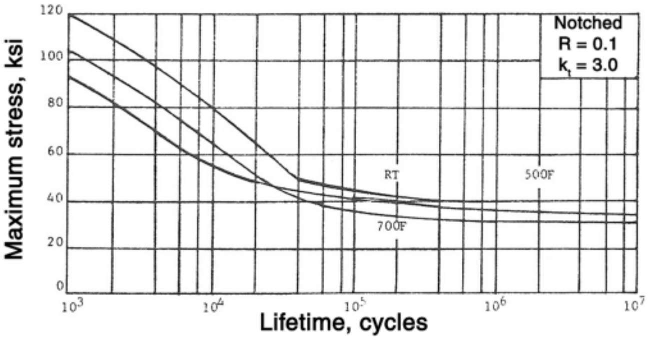

Fig. 11 Effect of temperature on axial load fatigue of 152 mm (6 in.) diameter Beta C forging in the STA condition (notched) (Ref 30)

5.1.3 Heat Treatment and Fabrication. Beta C is cold-formable in the ST (A) condition. After forming, Beta C is typically aged to increase strength. A wide range of tensile strengths can be obtained by varying the aging temperature and time. The industry-specified aging treatments are performed at 510-566 °C (950-1050 °F) for 6-10 h followed by air cooling (AMS 4975A, after cold work) and aging at 454-566 °C (850-1050 °C) for 6-20 h followed by air cooling (AMS 4985A, after solution anneal). This results in tensile strengths from 1241 MPa (180 ksi) up to about 1448 MPa (210 ksi).

5.2 Ti-6.8Mo-4.5Fe-1.5Al (Common Name LCB)

TIMETAL LCB was developed as a low-cost metastable-β titanium alloy for automotive coil spring applications. Although β titanium alloys offer the advantages of low density, low elastic modulus, and excellent corrosion resistance, the cost of titanium alloys can be a significant impediment to their use in the cost-sensitive, mass production environment of the automotive industry (Ref 12). Consequently, raw materials selection and finishing operations for LCB were formulated with the goal of reducing cost while still achieving properties that meet the requirement of the spring and automotive manufacturers (Ref 12).

LCB is heat-treatable to 1400 MPa (203 ksi) ultimate tensile strength with 13% elongation. Typical and industry-specified room temperature tensile properties for LCB are provided in

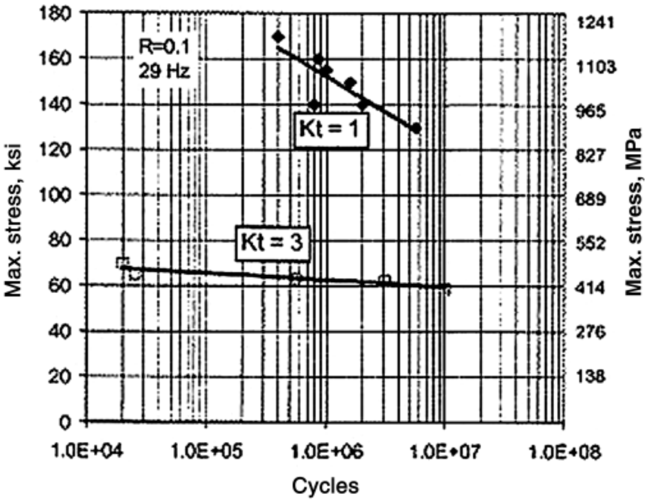

Fig. 12 Axial fatigue of *TIMETAL* LCB wire (Ref 12)

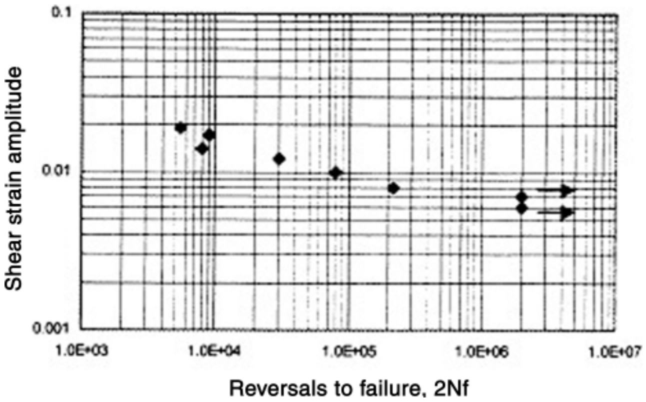

Fig. 13 Torsional fatigue of *TIMETAL* LCB wire (Ref 12)

Table 8. Fatigue life data are presented in Table 9 as well as in Fig. 12 and 13.

5.2.1 Product Forms and Applications LCB is available in round stock from 3.7-50 mm (0.15-2 in.) diameter (Ref 13). Applications of LCB include suspension springs (e.g., automotive, motorcycles, and military vehicles), engine valve springs, and torsion bars (Ref 13).

5.2.2 Heat Treatment and Fabrication. Coil spring winding of LCB (and other β titanium alloys) should be done in the ST condition at 760 °C (1400 °F) for 10-30 min for LCB, which provides sufficient cold formability (Ref 12). However, because cold work is not necessary for LCB to achieve high strength, hot winding can be performed by heating to the solution temperature for less than 30 min (Ref 12). Hot winding must be followed by acid pickling or mechanical material removal to guarantee that there is no loss in fatigue performance due to the presence of the oxygen-rich layer formed during hot winding (Ref 12). LCB springs can be wound with essentially the same equipment that is used for steel springs.

After spring winding, aging at 538-549 °C (1000-1020 °F) for 2-4 h provides high strength by the precipitation of fine α particles in the β matrix (Ref 12). As iron is the strongest noninterstitial strengthener, the high iron content of LCB facilitates a relatively short aging time compared with other β alloys (Ref 12).

After aging, shot peening is applied to introduce a compressive residual stress on the spring surface, which enhances the fatigue performance of suspension springs (Ref 12).

References

1. J.R. Kattus, Ti-6-2-4-6, *Aerospace Structural Metals Handbook,* Vol 4, Department of Defense, 1972, Code 3714
2. T. Sugimito, K. Kamei, S. Komatsu, and K. Sugimato, Aging Behavior of α Martensite Formed in a Quenched Ti-6Al-2Sn-4Zr-6Mo Alloy, *Titanium Science and Technology*, Vol 3, G. Lütjering, U. Zwicker, and W. Bunk, Ed., Deutsche Gesallschaft Für Metallkunde, 1984, p 1583
3. H.W. Rosenberg, Ti-17 Properties," *Beta Titanium Alloys in the 1980's,* R.R. Boyer and H.W. Rosenberg, Ed., The Metallurgical Society of AIME, 1984, p 433-439
4. H.W. Rosenberg, Properties and Processing of Ti-10V-2Fe-3Al, TIMET, Sept 1979
5. R.R. Boyer and H.W. Rosenberg, Ti-10V-2Fe-3Al Properties, *Beta Titanium Alloys in the 1980's,* R.R. Boyer and H.W. Rosenberg, Ed., The Metallurgical Society of AIME, 1984, p 441-454
6. S. Veeck, D. Lee, R. Briggs, and R. Boyer, The Castability of Ti-5553 Alloy, *Adv. Mater. Proc.,* Vol 162 (No. 10), 2004, p 47-49
7. J.C. Fanning, *TIMETAL*®15-3 Property Data, *Beta Titanium Alloys in the 1990's*, D. Eylon, R.R. Boyer, and D.A. Koss, Ed., The Minerals, Metals & Materials Society, 1993, p 411-437
8. J.C. Fanning, *TIMETAL*®21S Property Data, *Beta Titanium Alloys in the 1990's*, D. Eylon, R.R. Boyer and D.A. Koss, Ed., The Minerals, Metals & Materials Society, 1993, p 397-410
9. J. Jackson and R. Rice, *Preliminary Material Properties Handbook*, Vol 1 and 2, AFRL-ML-WP-TR-2001-4027, Battelle with Air Force Research Laboratory, 2000, p 5.21-5.29
10. D.E. Thomas, S. Ankem, W.D. Goodin, and S.R. Seagle, "Beta-C: An Emerging Titanium Alloys for the Industrial Marketplace," Report No. 643, RMI Company Research Department, 1984
11. C.F. Hickey, Jr., Ti-38-6-44, *Aerospace Structural Metals Handbook,* Vol 4, Department of Defense, 1975, Code 3723
12. Y. Kosaka and S.P. Fox, "Properties and Production Experiences of *TIMETAL*®LCB for Automotive Spring Applications," SAE World Congress, (Detroit, MI), March 3, 2003, SAE Technical Paper Series No. 2003-01-1181
13. Y. Kosaka, personal communication, TIMET Henderson Technical Laboratory, Henderson, NV, January 2005
14. C.F. Hickey, Jr., Ti-17, *Aerospace Structural Metals Handbook,* Vol 4, Department of Defense, 1976, Code 3724
15. G.W. Kuhlman, Alcoa Titanium Alloy Ti-10V-2Fe-3Al Forgings, *Beta Titanium Alloys in the 1990's,* D. Eylon, R.R. Boyer, and D.A. Koss, Ed., The Minerals, Metals & Materials Society, 1993, p 485-512
16. J. Pengra, "Data submitted in support of AMS 4914," Lockheed Report, Revision A, Nov 1985
17. D.P. Davies, Effect of Heat Treatment on the Mechanical Properties of Ti-10V-2Fe-3Al for Dynamically Critical Helicopter Components, *Proc. Titanium '92: Science and Technology,* Vol 2, F.H. Froes and I. Caplan, Ed., The Minerals, Metals & Materials Society, 1993, p 1851-1858
18. J.C. Fanning and R.R. Boyer, "Properties of TIMETAL 555 – A New Near-Beta Titanium Alloys for Airframe Components," presented at 10th World Conference on Titanium (Hamburg, Germany), July 3, 2003, p 1-7
19. Military Handbook: Metallic Materials and Elements for Aerospace Vehicle Structures, *MIL-HDBK-5H,* 1998, p 5-94 and 5-112
20. R.W. Schutz and J.S. Grauman, Fundamental Corrosion Characterization of High-Strength Titanium Alloys, *Industrial Applications of Titanium and Zirconium,* Vol 4, C.S. Young and J.C. Durham, Ed., American Society for Testing and Materials, 1986, p 130-143
21. Y. Kosaka, S.P. Fox, and K. Faller, Newly Developed Titanium Alloy Sheets for the Exhaust Systems of Motorcycles and Automobiles, *J. Metals,* Vol 56 (No. 11), 2004, p 32-34
22. J.S. Grauman, TIMET Henderson Technical Laboratory, personal communication, 2005
23. P.J. Bania and W.M. Parris, Beta 21S: A High Temperature Metastable-Beta Titanium Alloy, *Proceedings of the Technical Program from 1990 International Conference: Titanium 1990: Productions and Applications,* Vol 2, Titanium Development Association, 1990, p 784-793

24. J.S. Grauman, Effects of Aircraft Hydraulic Fluid on *TIMETAL*®21S, *Beta Titanium Alloys in the 1990's*, D. Eylon, R.R. Boyer, and D.A. Koss, Ed., The Minerals, Metals & Materials Society, 1993, p 127-135
25. R.W. Schutz and D.E. Thomas, Corrosion of Titanium and Titanium Alloys, *ASM Handbook*, Vol 13, ASM international, 1987, p 687
26. M.J. Blackburn, W.H. Smyrl, and J.A. Feeney, Chapter 5: Titanium Alloys, *SCC in High Strength Steels and in Titanium and Aluminum Alloys,* B.F. Brown, Ed., Naval Research Laboratory, 1972, p 275-352
27. R.R. Boyer and G.W. Kuhlman, Processing Properties Relationships of Ti-10V-2Fe-3Al, *Metal. Trans. A,* Vol 18, 1987, p 2095-2103
28. G.A. Lenning, J.A. Hall, M.E. Rosenblum, and W.B. Trepel, "Cold Formable Titanium Sheet," Report No. AFWAL-TR-82-4174, Contract No. F33615-78-C-5116, TIMET Henderson Technical Laboratory, Fairchild Republic Company, Materials Laboratory Wright Aeronautical Laboratory, 1982
29. W.M. Parris and J.A. Hall, "Cold Rolled and Aged Ti-15V-3Al-3Sn-3Cr Strip for Springs," Report for Contract No. 66604-9169-2290, TIMET Henderson Technical Laboratory, 1980
30. D.H. Wilson and C.M. Esler, Properties of Ti-3Al-8V-6Cr-4Mo-4Zr, *Beta Titanium Alloys in the 1980's,* R.R. Boyer and H.W. Rosenberg, Ed., The Metallurgical Society of AIME, 1984, p 475-476