Weldability Study of Advanced High Temperature Titanium Alloys

GTA weldments in Ti-5Al-5Sn-2Zr-2Mo-.25Si and Ti-5Al-5Sn-2Zr-4Mo-.25Si are very similar, respectively, to GTA weldments in Ti-6Al-2Sn-4Zr-2Mo and Ti-6Al-2Sn-4Zr-6Mo in mechanical and fracture behavior as well as microstructures

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ABSTRACT. Bead-on-plate weldments in the alpha-beta alloys—Ti-5Al-5Sn-2Zr-2Mo-0.25Si and Ti-5Al-5Sn-2Zr-4Mo-0.25Si—were evaluated for strength and ductility, and characterized by both optical and scanning electron microscopy. As-welded conditions in both alloys exhibited extremely high strengths (180-200 ksi), but low ductility (1%). Postweld heat treating served to reduce the strength (160-170 ksi), with only a slight improvement in ductility (4%).

The weldment microstructures are explained from a point of view of their Continuous Cooling Transformation (CCT) characteristics. In addition, properties and microstructures of these alloys are compared to those of two similar alloys, Ti-6Al-2Sn-4Zr-2Mo and Ti-6Al-2Sn-4Zr-6Mo.

Introduction

During the last two decades considerable attention has been given to addressing the problems associated with the welding of advanced alpha-beta titanium alloys. The near-alpha alloy Ti-6Al-2Sn-4Zr-2Mo (Ti-6242), which was specifically developed for elevated temperature creep resistance and room temperature strength, has been reported to exhibit reasonable ductility[1] in the as-welded condition. With the addition of increasing amounts of beta stabilizers, as-welded ductilities have been generally observed to deteriorate, such as in the cases of Ti-6Al-2Sn-4Zr-6Mo (Ti-6246) and Ti-6Al-6V-2Sn (Ti-662).[2,3] It has been recognized that the weldability of these alloys is highly dependent on the relationship between cooling rates and alloy chemistry.[1]

The present investigation was conducted to determine the welding characteristics of two relatively new titanium alloys. These are Ti-5Al-5Sn-2Zr-2Mo-.25Si (Ti-5522S) and Ti-5Al-5Sn-2Zr-4Mo-.25Si (Ti-55245), which were developed through the Air Force Materials Laboratory,[4] specifically for elevated temperature applications, 900° F (482° C). Silicon additions to these alloys are made to enhance their creep characteristics. Ti-5522S is a near-alpha alloy similar in composition and properties to Ti-6242S, while Ti-5524S, a more beta-stabilized alloy, is similar to Ti-6246.

Due to these similarities, this paper compares microstructures and mechanical properties for Ti-5522S and Ti-5524S GTA weldments with data reported for Ti-6242 and Ti-6246, respectively. Selected mechanical properties of these alloys are provided in Table. 1

It is apparent that the near-alpha alloys are considered primarily for creep resistance, while the more beta-stabilized alloys exhibit better short-time strength at elevated temperature. For these reasons, the potential application of these alloys would be in long life gas turbine engine components and aerospace applications where short-time, high temperature strength

is of principle interest.

Two recent studies have examined the weldability of Ti-5522S, while no data have been reported for welded Ti-5524S. Chasteen and Horowitz[7] reported ultimate tensile strengths of 160-180 ksi (1103-1241 MPa) for GTA welds, depending on the particular postweld heat treatment, while Chang[8] reported a higher ultimate tensile strength of 188 ksi (1296 MPa), with only 2% elongation.

Experimental Procedure

The alloys studied in this investigation were alpha-beta processed, duplex heat-treated at 1735° F (945° C)/15 minutes (min) and 1100° F (595° C)/2 hours (h), and ground to a thickness of 0.100 in. (2.54 mm). Vendor-supplied tensile properties are given in Table 2. The beta transus (T_β) and composition of each alloy are presented in Table 3.

Sheet material was cut into 6 × 1 in. (15 × 2.5 cm) coupons, degreased in acetone followed by chemical cleaning in an aqueous solution of HNO_3 and HF acid, and water rinsed. Coupons were given a preweld vacuum heat treatment, 1810° F (988° C)/1 h for Ti-5522S and 1770° F(965° C)/1 h for Ti-5524S followed by an argon backfill (ABF), to obtain a microstructure which reportedly optimizes both creep and fatigue properties.[9]

Autogenous full-penetration bead-on-plate welds were produced in the above coupons using an automatic GTA welding unit with the welding parameters listed in Table 4. The effect of various postweld heat-treatments (Table 5) were initially evaluated by

Table 1—Comparison of Base Metal Mechanical Properties

	Test temperature, °F (°C)	Tensile properties				Creep def. %	Post creep			
		UTS,[d] ksi	0.2% YS[d] ksi	El, %[e]	RA[e]		UTS,[d] ksi	0.2% YS[d] ksi	El, %[e]	RA[e]
Ti-5522S[a]	72 (22)	154	131	11	21	0.15	154	137	12	17
	900 (374)	114	83	16	37					
Ti-6242S[b]	72 (22)	163	147	16	30.1	.09	164	151	17.5	39
	900 (374)	123	95	15	38.8					
Ti-5524S[a]	72 (22)	175	150	—	14	0.28	181	162	10	12
	900 (374)	136	100	12	26					
Ti-6246[c]	72 (22)	192	167	10	—	.07	200	189.3	7	27
	900 (374)	143	117	10	—					

[a]Tensile and creep data for beta-processed bar + [T$_\beta$-50° F (28° C)]/1 h AC + 1100° F (594° C)/2 h AC. Exposure 1000° F (538° C)-55 ksi-96 h.
[b]Ref. 5—heat treatment [T$_\beta$-25° F (14° C)] /1h AC + 1100° F (594° C)/2 h AC. Exposure 950° F (510° C)-35 ksi-100 h.
[c]Ref. 6—tensile data for duplex annealed 1600° F (925° C)/15min AC + 1300° F (700° C)/15min AC. Creep data for 1675° F (910° C)/1h AC + 1100°F (594° C)/4h AC. Exposure 800° F (427° C)-85 ksi-50 h.
[d]Multiply by 6.89 to convert to MPa.
[e]El—elongation; RA—reduction in area.

Table 2—Room Temperature Properties of As-Received Sheet Material

	UTS,[a] ksi	YS (0.29),[b] ksi	El,[b] %
Ti-5522S	157	151	16.5
Ti-5524S	193	175	7.3

[a]UTS—ultimate tensile strength (multiply by 6.89 to convert to MPa).
[b]YS—yield strength (multiply by 6.89 to convert to MPa); El—elongation.

metallographic examination, hardness testing (Vickers-20 Kg), and longitudinal (weld parallel to tensile axis) bend testing. Subsequent to this preliminary evaluation, selected postweld heat-treatments were chosen to be further characterized by tensile testing.

Although it is felt that 1400° F(760° C) represented the maximum postweld heat-treatment for the majority of welded aerospace structural components, an additional 1600° F (870° C) heat-treatment was included for comparison. Longitudinal and fusion zone (all-weld-metal) tensile samples having 1 in. (25.4 mm) gauge sections were tested on an Instron tensile machine at a constant crosshead speed

Table 4—GTA Welding Parameters

Voltage	10 V
Amperage	145 A, 185 A
Speed	5 ipm (21.5 mm/s)
Torch gas	argon 20 cfh (9.4 L/min)
Trail gas	argon 30 cfh (14.1 L/min)
Backing gas	argon 15 cfh (7.05 L/min)
Electrode	2% thoriated, ⅛ in. (3.2 mm) diameter

of 0.005 ipm (0.0021 mm/s) with a 1 in. (25.4 mm) gauge length extensionmeter.

Results and Discussion

Mechanical Properties

Longitudinal bend data are given in Table 5, and tensile data for Ti-5522S and Ti-5524S weldments are provided in Tables 6 and 7, respectively. The progressive bend tests were conducted such that, after each die, the sample was visually examined for surface cracking; this in all specimens initiated in the fusion zone.

Both alloys exhibited poor bend ductility in the as-welded condition and after low temperature aging treatments, with slight improvements at the higher aging temperature. The as-welded tensile data for Ti-5522S showed low ductility with unusually high ultimate and yield strengths, in

Table 3—Chemical Analyses of As-Received Sheet and Beta Transus (T$_\beta$), wt-%

	Ti-5522S	Ti-5524S
Titanium	Bal.	Bal.
Aluminum	4.6	5.0
Tin	4.8	4.9
Zirconium	1.9	1.9
Molybdenum	1.8	3.9
Silicon	0.25	0.25
Iron	0.05	—
Yttria	<10 ppm	<15 ppm
Carbon	0.035	0.010
Nitrogen	0.009	0.010
Hydrogen	0.0077	0.0115
Oxygen	0.114	0.106
T$_\beta$	1825° F (996° C)	1785° F (974° C)

agreement with Chang,[8] and significantly greater than that reported for the base metal (Table 1). Postweld

Table 5—Bend Data for Postweld Heat-Treated Ti-5522S and Ti-5524S Weldments[a]

	Ti-5522S	Ti-5524S	Failure location
As-welded (AW)	23T	20T	FZ
AW + 1400° F (760° C)/8 h (ABF) + 1100° F (594° C)/2 h (A8F)	23T	23T	FZ
AW + 1400° F (760° C)/16h (ABF) + 1100° F (594° C)/2 h (ABF)	23T	23T	FZ
AW + 1600° F (870° C)/2 h (A8F) + 1100° F (594° C)/2 h (ABF)	23T	23T	FZ
AW + 1600° F (870° C)/8 h (A8F) + 1100° F (594° C)/2 h (ABF)	23T	17T	FZ
AW + 1600° F (870° C)/16 h (ABF) + 1100° F (594° C)/2 h (ABF)	7T	23T	FZ
AW + 1700° F (925° C)/2 h (ABF)	7T	7T	FZ

[a]Weld reinforcement was removed by grinding.

Table 6—Ti-5522S Weldment Mechanical Properties

Heat treatment		Ultimate tensile strength,[a] ksi	Yield strength,[a] ksi	Elongation, %	Fusion zone hardness, VHN
As-welded (AW)	L[b]	195.6	175.4	0.61	436
	FZ	193.0	182.6	0.3	
AW + 1400° F (760° C)/8 h + 1100° F (584° C)/2 h	L	173.5	165.0	.56	
	FZ	173.8	165.8	1.00	
AW + 1400° F (760° C)/16 h + 1100° F (594° C)/2 h	L	169.0	149.9	.45	384
	FZ				
AW + 1600° F (870° C)/8 h + 1100° F (594° C)/2 h	L				364
	FZ				
AW + 1600° F (870° C)/16 h + 1100° F (594° C)/2 h	L	165.4	151.6	4.29	382
	FZ				

[a]Multiply by 6.89 to convert to MPa.
[b]Longitudinal.

Table 7—Ti-5524S Weldment Mechanical Properties

Heat treatment		Ultimate tensile strength,[a] ksi	Yield strength,[a] ksi	Elongation, %	Fusion zone hardness, VHN
As-welded (AW)	L[b]	184.0	—	0.2	424
AW + 1400° F (760° C)/8 h + 1100° F (594° C)/2 h	L	168.6	156.9	1.0	404
	FZ	176.0	169.3	1.0	
AW + 1400° F (760° C)/16 h + 1100° F (594° C)/2 h	L	174.3	156.0	1.7	389
	FZ	170.9	165.6	0.9	
AW + 1600° F (870° C)/16 h + 1100° F (594° C)/2 h	L	165.4	151.1	5.0	360
	FZ	160.0	149.0	1.8	

[a]Multiply by 6.89 to convert to MPa.
[b]Longitudinal.

heat-treatments reduced the weldment tensile strength, approaching base metal strength, with only a slight improvement in ductility at the higher aging treatment.

The same general trends were observed for the Ti-5524S welds, with nearly the same strength levels except for the as-welded condition which was slightly lower. However, an important point to note is that reasonable ductility was not restored in Ti-5524S weldments until the postweld heat-treatment temperature was increased to 1700° F(925° C), 85° F(47.2° C) below beta transus; in Ti-5522S partial ductility was restored at 1600° F(870° C), 225° F(75° C) below its beta transus. This is undoubtedly related to the different aging characteristics between the two alloys. Hardness measurements made on the fusion zone with comparable heat-treatments gave almost identical values for the two alloys.

Mechanical property data for Ti-6246 GTA as-welded fusion zone data by Greenfield and Duvall[2] corresponded with the as-welded properties of Ti-5524S, showing a yield strength of 187 ksi (1289 MPa) and 0.4% elongation. For Ti-6246, Mahajan and

Baeslack[10] have reported an ultimate strength of 168 ksi (1158 MPa), yield strength of 164 ksi (1131 MPa), and 1.4% elongation for postweld heat-treated, 1400° F (760° C) GTA weldments, agreeing well with the Ti-5524S data.

GTA as-welded data reported by Mitchell[1] for Ti-6242 shows an ultimate and yield strength of 151 (1041 MPa) ksi and 125 ksi (862 MPa), respectively, with an elongation of 8%, considerably lower strength than Ti-5522S but greater ductility. This difference in properties is not entirely attributable to compositional differences but is also likely to be related to welding parameters and fixturing changes which changed the weld cooling rates. Ti-6242 postweld heat-treated weldments, 1400° F (760° C), in the same work gave a 146 ksi (1007 MPa) ultimate strength and 132 ksi (910 MPa) yield strength with 7.5% elongation.

Microstructure

Figure 1(a-d) shows the microstructures for the base metal and weldment fusion zones for the various postweld heat-treatments for Ti-5522S. Since crack initiation occurred in the fusion zone in all heat-treated conditions, the

HAZ microstructures are not discussed. The microstructure of the base metal given a preweld heat-treatment showed a large amount of primary alpha present with regions of transformed beta. The as-welded fusion zone was characterized by a large columnar grain structure composed of a martensitic matrix with laths of a darker phase, presumably alpha, emanating from the grain boundaries and interspersed in the martensite laths.

Upon postweld heat-treating at 1400° F(760° C) the fusion zone microstructure showed a very fine alpha-beta structure, and coarsened somewhat with the 1600° F(870° C) age, while still retaining the lath appearance. The amount of grain boundary alpha increased with the postweld aging temperature, but was still quite limited even after the 1600° F(870° C) postweld heat-treatment. Similar microstructures were obtained for Ti-6242 weldments by Baeslack.[11]

The microstructures for the Ti-5524S base metal and fusion zone, shown in Fig. 1(e-h), are noticeably different than for the more lean alloy (Ti-5522S). The as-welded condition exhibited a fine microstructure void of the large aspect ratio laths observed in the less

Fig. 1—Microstructures of Ti-5522S (left), Ti-5524S (right) base metal and GTA weldments, a, e—base metal; b, f—as-welded; c, g—1400° F(760° C)/16h + 1100° F(594° C)/2h; d, h—1600° F(870° C) + 1100° F(594° C)/2h. X400 (reduced 19% on reproduction)

Fig. 2—Scanning electron microscope fractographs of Ti-5522S fusion zone. Tensile samples: top—as-welded (X20, X200); middle—1400° F(760° C) /16h + 1100° F (594°

stabilized alloy. Lower temperature heat treatment produced a very fine structure similar to the same condition in Ti-5522S but again lacking the lath appearance; however, at the higher temperature a lenticular alpha structure resulted.

Again, Baeslack[11] has observed microstructures very similar to Ti-5524S for the as-welded and aged conditions in Ti-6246. The postweld heat-treated microstructures in Ti-5522S and Ti-5524S indicate different aging mecha-

nisms operating in the two alloys which were also indicated by the ductility data. As in Ti-5522S, the grain boundary alpha content in Ti-5524S appeared to increase with the higher temperature aging but was still very limited.

Fractography

Characteristics of the fracture surfaces in Ti-5522S and Ti-5524S are presented in Figs. 2 and 3, respectively.

The fusion zone of the as-welded Ti-5522S alloy failed with two distinct types of transgranular fractures which have been described elsewhere as irregular transgranular[12] and faceted transgranular failure.[13] Postweld heat-treatment caused a decrease in transgranular failure and an increase in intergranular fracture.

These trends continued with increasing postweld heat-treatment temperature and time, with temperature being most significant. Faceting was observed in all heat-treated condi-

C) /2h, (X20, X200); bottom—1600° F (870° C) /16h + 1100° F (594° C) /2h, (X20, X200). (Reduced 10% on reproduction)
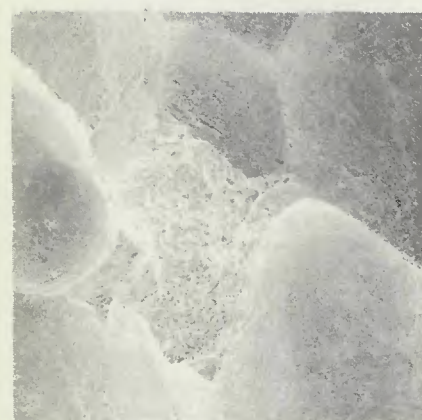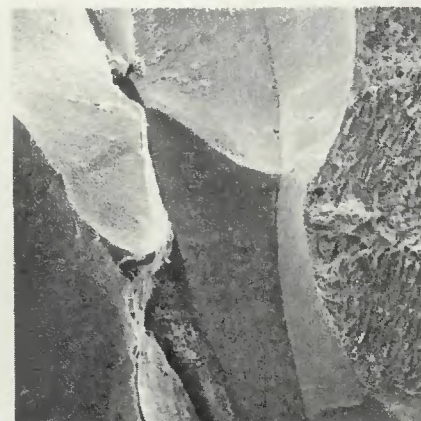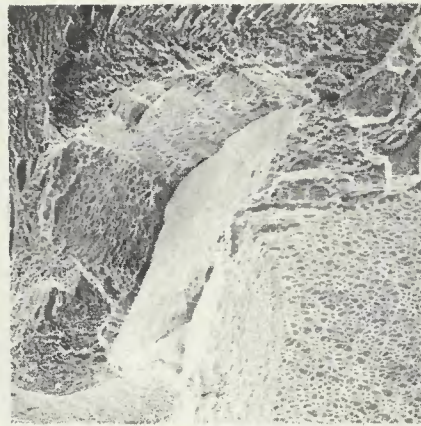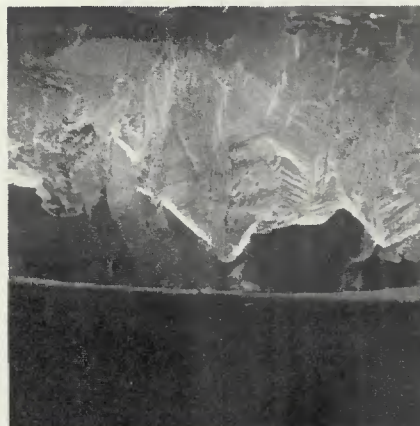
Fig. 3—Scanning electron microscope fractographs of Ti-5524S fusion zone. Tensile samples: top—as-welded, (X20, X200); middle—1400° F (760° C) /16h + 1100° F (594° C) /2h, (X20, X200); bottom—1600° F (870° C) /16h + 1100° F (594° C) /2h, (X20, X200)

tions, with the facets being largest at the 1600° F(870° C) temperature. The fracture characteristics of Ti-5524S were similar to Ti-5522S in the as-welded condition, with the noticeable exception of the occurrence of some "fluting" which has been observed in other titanium alloy weldments.[13,14] Postweld heat-treatment promoted a larger amount of intergranular fracture in the Ti-5524S weldments and a complete absence of faceting. The same fracture trends have been observed in Ti-6246, while Ti-6242 weldment frac-

tures[11] appear similar to those for Ti-5522S.

Transformation Characteristics

The results of this study are best understood when the weldment properties for Ti-5522S and Ti-5524S are considered in context with their continuous cooling curves (CCT). Even though a program to determine these curves is in progress, the authors felt that for the purposes of this study a reasonable approximation of the CCT nose times and martensite start tem-

peratures (M_s) could be made by combining the CCT curves for Ti-6242[1] and those for the titanium binary alloys.[15,16] This simply consisted of adding the effects of Zr, Sn and Mo content on the nose time and M_s for Ti-6242, assuming minimal synergistic effects. Table 8 shows these calculated values as well as those for Ti-6246 which are supplied for comparison. Note the similarity in the CCT characteristics between Ti-5522S and Ti-6242, and between Ti-5524S and Ti-6246.

With the cooling rates normally associated with thin sheet GTA weld-

ments (150–300° F/s), the nose of the CCT curve should be crossed for all the above four alloys. Therefore, upon cooling the high temperature beta phase should transform to alpha by a nucleation and growth process, with the remaining beta either being retained or transforming by shear process to martensite at the M_s. Indeed, GTA as-welded microstructures do show evidence of alpha precipitation, a homogenous precipitate in Ti-5524S, and laths of alpha appear to be interspersed within the martensite in Ti-5522S. The weldment matrix in Ti-5524S has been identified by X-ray diffraction as being orthorhombic martensitic, and for Ti-5522S all evidence suggests the presence of hexagonal martensite.[17]

The reduced aspect ratio of the martensite laths in the as-welded Ti-5524S weldments is attributed to the early precipitation of alpha during cooling which impedes the growth of the martensite. Similar as-welded microstructural features have been observed in other orthorhombic martensite alloys, Ti-6246[11] and Ti-4.5Al-5Mo-1.5Cr.[12] This mechanism was further substantiated by water quenching an as-welded Ti-5524S coupon from above the beta transus.

The resultant microstructure consisted of large aspect ratio martensite laths, similar to those in Ti-5522S. The hardness of the quenched fusion zone coupon was considerably softer (371 VHN) than for the as-weld condition (424 VHN), which further substantiates that the nose of the CCT was crossed during the cooling of the weldment. In Ti-5522S, it appears that the early precipitation of alpha has a less pronounced influence on the martensite aspect ratio; the reason for this is probably related to the temperature at which the nose of the CCT curve is crossed and possibly to the type of martensite formed.

Postweld aging of both Ti-5522S and Ti-5524S clearly show that the final microstructures and weldment mechanical properties are dependent on the as-welded conditions; these, in turn, are dependent upon weldment cooling rates. These facts, combined with the observation that in Ti-5522S ductility is restored at a lower aging temperature than in Ti-5524S, may

Table 8—Calculated Nose Times and M_s for Alpha-Beta Alloys

	Nose time, seconds	M_s, °F
Ti-6242	2.0	1290
Ti-5522S	2.0	1200
Ti-5524S	3.0	1060
Ti-6246	5.0	1000

make this alloy more amenable to improvements in weldment properties, particularly ductility, by varying the cooling rate during welding. This may be done by varying the process, welding parameters, fixturing, or preheat.

Conclusions

1. In the as-welded conditions, both Ti-5522S and Ti-5524S weldments gave high strengths, but were very brittle (1% elongation).

2. Postweld heat treatments generally reduced the weldment strengths with little increase in ductility except for the high aging temperatures, 1600–1700° F (870–925° C), and then only marginally (4.5%).

3. GTA weldments in Ti-5522S and Ti-5524S are very similar to Ti-6242 and Ti-6246 weldments, respectively, in their mechanical and fracture behavior, as well as in their microstructures.

4. The presence of alpha precipitation in the as-welded microstructures for both alloys can be adequately explained by their CCT characteristics. However, the morphology of the duplex alpha-martensite structure is probably due to a combination of the CCT characteristics and the type of martensite present.

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