Thermomechanical Processing of a Welded Metastable Beta Titanium Alloy

Higher strengths and ductilities are achieved by post-weld working

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ABSTRACT. Gas tungsten-arc welding was used to produce full penetration bead-on-plate welds with no filler additions on solution treated sheets of 0.040 in. and 0.060 in. material. Rolled and unrolled weldments were aged in vacuum over a range of times and temperatures to produce yield strengths from 126-201 ksi. Postweld rolling was employed to introduce a more homogeneous intragranular alpha precipitate within the fusion and heat-affected zones. This caused the elimination of the previously noted fusion zone aging lag and a decrease in grain boundary alpha coarsening in the HAZ. Because of this the thermomechanically treated weldments exhibited greater ductilities at higher strength levels than were previously possible.

Introduction

This investigation is part of a study of the weldability of the metastable beta titanium alloy, Ti-8Mo-8V-2Fe-3Al. The high concentration of beta stabilizing elements, molybdenum, vanadium and iron, in this alloy result in the ability to retain the bcc high temperature beta phase to room temperature. In the solution treated condition (beta phase condition) the alloy possesses moderately low strength and high ductility, factors which make it very formable. When the alloy is given the full heat treatment (solutioned and aged), the precipitation of the hcp alpha phase results in material of extremely high strength (>200 ksi). These factors make the metastable beta alloys very attractive for aerospace sheet and tubing applications.

Previous studies (Refs. 1, 2) have shown this alloy to be readily weldable but in all cases the achievable ductility was quite limited. A recent investigation (Ref. 3) attempted to explain the mechanism for the poor ductility of these weldments. It was shown that at a constant strength level, i.e., 145 ksi, the percent elongation could vary from 0 to 14% depending upon the choice of aging temperature and heat treat time. The selection of heat treat temperature was critical, affecting not only the precipitation kinetics but also the size, type and distribution of alpha phase formed during the aging reaction. The alpha phase distribution had a direct effect on the fracture mechanism and the fracture stress of the weldment. Grain boundary alpha was shown to be highly deleterious in the heat-affected zone, promoting early fracture and low ductility during tensile loading.

It became apparent during the course of the above investigation that the aging response of the fusion zone was sluggish when compared to the base metal. This was believed to be a result of chemical segregation occurring in the fusion zone during the solidification process.

The current investigation was undertaken to study the effect of post-weld thermomechanical processing on the alpha phase precipitation. It was anticipated that the introduction of dislocation substructure due to the rolling operation would eliminate the aging lag in the fusion zone and increase ductility at high strength levels by promoting intragranular alpha precipitation in the heat-affected zone.

Experimental Procedure

Full penetration bead-on-plate gas tungsten-arc welds were made by TIMET, Inc., on 0.040 in. and 0.060 in. sheets of the alloy in the solution treated, 50% recrystallized condition,

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(1450 F-10 min). The welding parameters used are given in Table 1. Bead-on-plate 0.060 in. sheets were rolled approximately 20% (specimens were rolled in the welding direction) on a Farrel two high rolling mill with 8 in. x 12 in. rolls and a separating force of 150,000 psi. Tensile specimens were cut with the longitudinal test direction parallel to the weld axis and with sufficient test section width to include approximately one third weld metal and two thirds base metal, Fig. 1a and 1b. In order to compare elongation data, tensile specimens were cut with the width to thickness ratio held constant for the 0.040 in. and rolled 0.060 in. material. The selection of longitudinal weld specimens was based on the need to determine the ductility limiting region in the weldment. Since the longitudinal test measures the ability to plastically deform of the most strain sensitive zone, elongation data could be compared for the unrolled 0.040 in. and the rolled 0.060 in. material to determine the effects of rolling.

Rolled and unrolled specimens were aged in vacuum over a temperature range (900-1300 F) for times from 1-16 h. In order to correlate base, fusion zone and bead-on-plate properties, tensile testing along with microstructural investigations were carried out on rolled and unrolled base metal and fusion zone specimens. Miniature tensile samples were used for testing fusion zone material, Fig. 1c. Fractographic analysis with the scanning electron microscope and electron replica analyses were carried out after tensile testing.

Table 1 — Welding Conditions for Bead-on-Plate Welds

Current, A	60
Voltage, V.	10
Welding speed, ipm	12
Electrode	EWTh-2, ⅛ diam
Electrode cup size, in.	¾
Cup gas flow, cfh	30 Argon
Secondary gas, cfh	50 Argon
Backing gas, cfh	20 Argon
Filler metal	None

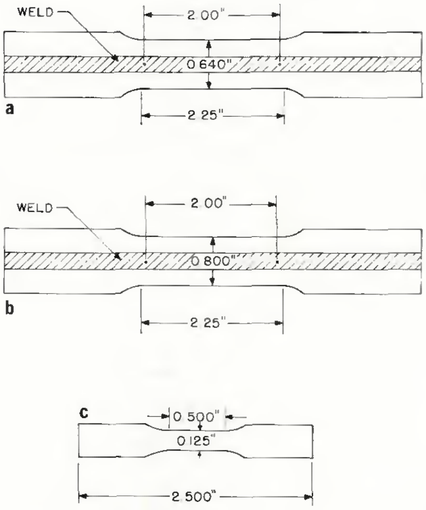

Fig. 1 — Test specimens—(a) for 0.040 in. material, (b) for 0.060 in. material rolled 20% to 0.048 in., (c) for fusion zone studies

Results and Discussion

Direct post weld aged data and 20% rolled and aged data are presented in Table 2. Examination of Table 2 shows two significant trends. First, the fusion zone ages more slowly than the base metal and second, the rolled bead-on-plate specimens show considerably higher yield and fracture strengths for all heat treatments. In order to further elucidate the data trends and study the effects of alpha precipitation more carefully, the 1100 F series will be discussed in detail. This series represents the intermediate temperature between the 900 F and the 1300 F series and shows the characteristics of all three temperatures.

Fusion Zone Effects

Initial examination of the Ti-8823 fusion zones aged at the three different temperatures showed inhomogeneous alpha precipitation. Figure 2, 1100 F-1h, is characteristic of the precipitate distribution. Microprobe analysis of the clear unaged areas showed them to be of high molybdenum concentration (Table 3). This segregation on solidification can be explained by examining the Ti-Mo phase diagram which shows an upsloping liquidus, allowing the large primary dendrites to be richest in molybdenum. Since molybdenum is an effective beta stabilizer, areas of high molybdenum concentration exhibit less alpha precipitation. Due to this inhomogeneous precipitation, large areas of the matrix remain unaged and others (around dendrite cores and at high energy grain boundaries) rapidly overage. The net result is limited strengthening which can clearly be seen in Fig. 3, a plot of yield strength versus aging time at 1100 F. The strength of the unrolled fusion zone lags far behind that of the base metal, resulting in low weld efficiency. In an attempt to increase the aging response, cold rolling was employed. Not only was some of the molybdenum segregation broken up, (Table 3), but also high energy sites for nucleation were introduced, resulting in an increased aging response as shown in Fig. 3 (Fusion Zone Rolled). In fact the fusion zone now closely paralleled the base metal response. Figure 4 shows the increased intragranular precipitation within the fusion zone, after rolling 20%.

Heat-Affected Zone Effects

An earlier study (Ref. 3) had shown that the choice of postweld heat treat temperature was critical for achieving high strength, high ductility weldments. This was attributed to the formation of a deleterious grain boundary alpha film in the heat-affected zone. Void formation at grain bound-

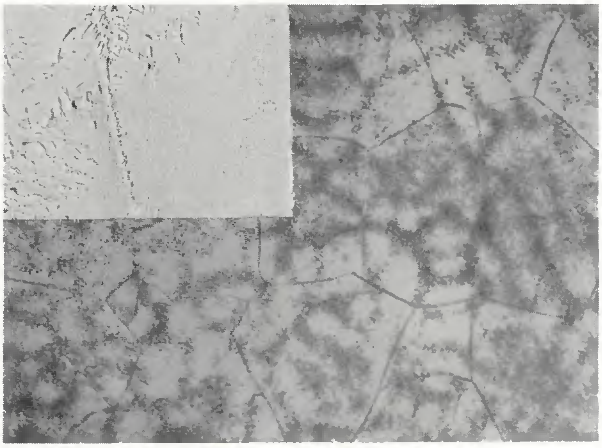

Fig. 2 — Fusion zone heat treated 1100 F-1 h exhibiting inhomogeneous alpha precipitation. X400 and X2000 replica (upper left), both reduced 21%

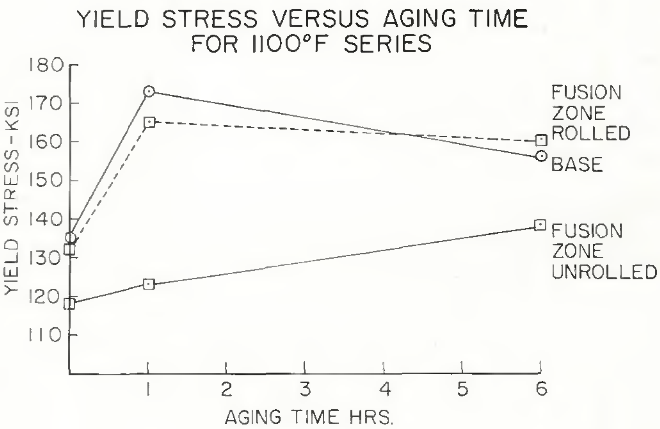

Fig. 3 — Yield strength versus aging time at 1100 F for the fusion zone and base metal

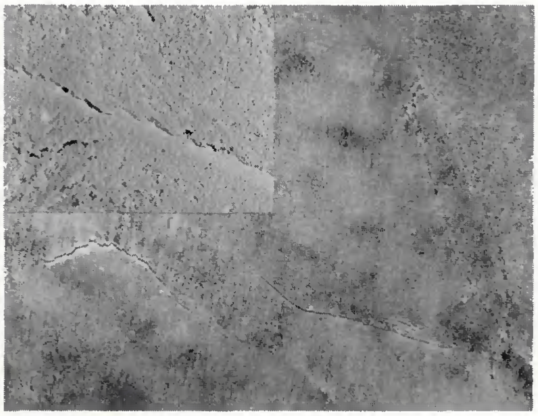

Fig. 4 — Fusion zone rolled 20% and aged 1100 F-1 h exhibiting homogeneous alpha precipitation. X400 and X2000 replica (upper left), both reduced 26%

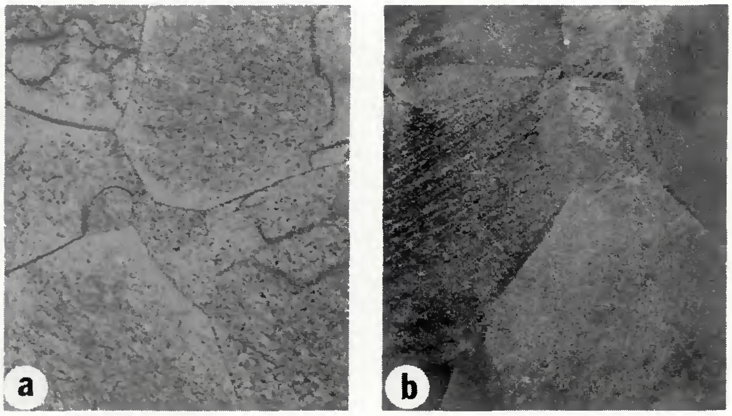

Fig. 5 — Heat-affected zone—(a) direct aged 1100 F-1 h and (b) rolled 20% +1100 F-1 h

ary alpha resulting in premature failure greatly limited the weldment ductility. Lower temperature aging treatments were suggested (increasing the tendency for intragranular precipitation) to limit the film formation. This however resulted in material of very high strength and consequently brittle behavior. Another possible approach to promote intragranular precipitation is by the introduction of precipitate nucleation sites by cold working. Figure 5 (a and b) shows the change in precipitation mode from the grain boundaries to a homogeneous distribution inside the grain. This results in a finer grain boundary alpha film and an increase in fracture strength in the critical heat-affected zone. The relationship of grain boundary alpha film thickness to fracture stress for wrought titanium microstructures is discussed in detail elsewhere (Ref. 4).

Bead-on-Plate Results

The longitudinal bead-on-plate weldment was chosen to study the effects of temperature and cold working on the fusion and heat-affected zone simultaneously. The data are presented in Table 2. The following general observations can be made:

1. Rolling 20% increased both yield strength and fracture strength (for the reasons previously discussed) when compared to unrolled material except at times and temperatures, i.e., 1100 F-16 h when overaging occurred

2. At similar strength levels, the rolled material exhibited superior ductility. This can be seen in a compari-

Table 2 — Mechanical Properties Ti 8823 Weldments

	Base Metal		Fusion Zone		Bead-on-plate		BOP
Postweld treatment [a]	Y.S., ksi	Fract. str., ksi	Y.S., ksi	Fract. str. ksi	Y.S. ksi	Fract. str. ksi	ductility % El.
AS WELDED	136	208	118	168	117	144	19.2
AS ROLLED	146	165	126	154	140	155	7.5
DA-900F-2h	168	183	156	181	166	175	0.7
R+900F-2h	208	208	186	203	201	201	0.0
DA-900F-6h	201	227	176	192	163	163	0.0
R+900F-6h	200	208	188	198	196	196	0.0
DA-900F-16h	208	232	192	201	176	182	0.2
R+900F-16h	185	208	197	217	193	193	0.0
DA-1100F-1h	173	209	123	140	142	156	6.5
R+1100F-1h	185	208	165	186	179	196	1.4
DA-1100F-6h	156	210	136	157	149	165	3.7
R+1100F-6h	183	201	160	180	173	184	1.6
DA-1100F-16h	155	208	141	161	151	159	1.7
R+1100F-16h	157	193	138	159	138	180	15.4
DA-1300F-1h	144	202	111	122	126	147	11.7
R+1300F-1h	144	181	129	156	148	178	13.1
DA-1300F-6h	145	212	112	119	130	168	18.3
R+1300F-6h	138	176	119	146	131	166	18.9

(a) DA — direct age; R — rolled 20%

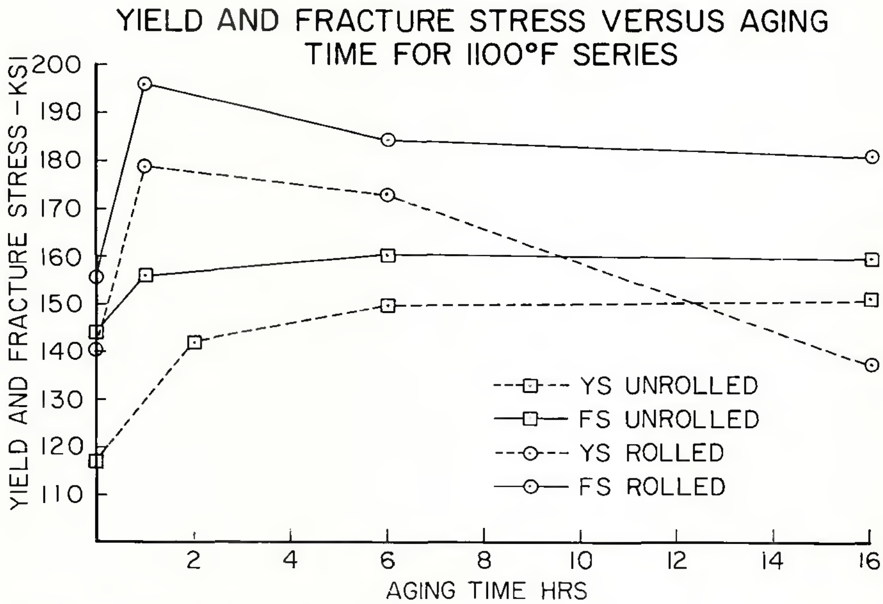

Fig. 6 — Yield and fracture stress versus aging time for 1100 F series

Table 3 — Microprobe Results — Molybdenum Concentration In Fusion Zone

Unrolled:		
Dark — aged areas	—	5.3%
Clear — unaged areas	—	10.8%
Rolled:		
Uniform concentration	—	8.2%

son of the data for direct age (DA) 1100 F-6 h (149 ksi-3.7%) versus rolled 20% (R) + 1300 F-1 h (148 ksi-13.1%).

3. Moreover, higher strength-ductility relationships could be achieved with the rolled material than was previously possible. Rolled 20% (R) + 1100 F-1 h could be strengthened to 179 ksi with some ductility (1.4%) whereas the direct aged material, direct age (DA) 1100 F-16 h exhibited similar ductility at only 151 ksi.

4. It appears rolling will not improve the 900 F ductility. This is the result of the extremely high strength levels obtained at this low temperature age.

Figure 6 shows a graphical representation of the data for the 1100 F series. It can be clearly seen that rolling increases both the bead-on-plate yield strength and fracture strength for the reasons previously discussed. The increased alpha precipitation due to the introduction of precipitation sites results in the observed early overaging effect.

Conclusions

1. Rolling has been demonstrated to increase both the yield strength and fracture strength of the metastable beta alloy Ti-8Mo-8V-2Fe-3Al weldments.

2. The observed aging retardation of the fusion zone is a result of solidification segregation and can be overcome by postweld rolling.

3. Precipitation of a homogeneous alpha phase after rolling and a decrease of alpha coarsening at the beta grain boundaries, allowed for greater ductilities at higher strength levels.

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