Property-Microstructure Relationships in Metastable-Beta Titanium Alloy Weldments

Ti-15V-3Cr-3Al-3Sn, Ti-8V-7Cr-3Al-4Sn-1Zr, and Ti-8V-4Cr-2Mo-2Fe-3Al alloy welds gain significantly in strength with postweld heat treatment, and Ti-15V-3Cr-3Al-3Sn and Ti-8V-7Cr-3Al-4Sn-1Zr offer the best combination of strength and ductility although Ti-8V-4Cr-2Mo-2Fe-3Al exhibits the highest strength level.

By D. W. Becker and W. A. Baeslack III

Abstract. Weldment property-microstructure relationships were investigated for the formable-sheet titanium alloys Ti-15V-3Cr-3Al-3Sn, Ti-8V-7Cr-3Al-4Sn-1Zr, and Ti-8V-4Cr-2Mo-2Fe-3Al. Studies were performed on autogeneously produced gas tungsten arc weldments in both the as-welded and postweld aged conditions. For comparable aging treatments, the Ti-84223 alloy exhibited the highest strength, followed by Ti-87341 and Ti-15-333. Microstructures generally corresponded well with the underaged to overaged trend noted in the mechanical property data, showing a general coarsening of the alpha precipitation as aging progressed. The higher heat treatment temperatures resulted in extensive, nearly continuous grain boundary alpha formation, and together with the mechanical properties and fractography, revealed the complexity of any microstructure-property correlation for this condition. These complexities were further revealed by a comparison of the results obtained in the present investigation with those of a previous investigation on weldments in similar alloys.

Introduction

Metastable-beta titanium alloys exhibit properties highly desirable in a formable-sheet material. Despite a modulus somewhat lower than that found in alpha-beta titanium alloys, good fabricability in the solution heat-treated beta condition and an excellent aging response to high strength levels render these alloys ideal candidates for a variety of aerospace structural applications.1-3

The fusion and near heat-affected zones of fusion welds in metastable-beta titanium alloys are characterized by a low-strength, retained beta struc-

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Heat no.</th>
<th>V</th>
<th>Cr</th>
<th>Al</th>
<th>Fe</th>
<th>Mo</th>
<th>Sn</th>
<th>Zr</th>
<th>O</th>
<th>H</th>
<th>N</th>
<th>C</th>
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</thead>
<tbody>
<tr>
<td>Ti-15V-3Cr-3Al-3Sn</td>
<td>V5031</td>
<td>15.8</td>
<td>3.2</td>
<td>3.0</td>
<td>-</td>
<td>-</td>
<td>2.9</td>
<td>-</td>
<td>0.090</td>
<td>0.0126</td>
<td>0.018</td>
<td>0.02</td>
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<tr>
<td>Ti-8V-7Cr-3Al-4Sn-1Zr</td>
<td>V5029</td>
<td>8.4</td>
<td>6.0</td>
<td>3.1</td>
<td>-</td>
<td>-</td>
<td>4.1</td>
<td>1.0</td>
<td>0.104</td>
<td>0.0094</td>
<td>0.015</td>
<td>0.01</td>
</tr>
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<td>V5030</td>
<td>8.3</td>
<td>4.4</td>
<td>3.0</td>
<td>2.4</td>
<td>1.8</td>
<td>-</td>
<td>-</td>
<td>0.090</td>
<td>0.0131</td>
<td>0.010</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 2—Annealed Base Metal Mechanical Properties

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Annealing Temperature,°F (°C)</th>
<th>Test direction</th>
<th>Yield strength, ksi (MPa)</th>
<th>Ultimate tensile strength, ksi (MPa)</th>
<th>Elongation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-15-3-3-3</td>
<td>1450 (788)</td>
<td>L</td>
<td>106 (730)</td>
<td>110 (760)</td>
<td>24</td>
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<tr>
<td>Ti-8-7-3-4-1</td>
<td>1400 (760)</td>
<td>L</td>
<td>119 (820)</td>
<td>121 (835)</td>
<td>23</td>
</tr>
<tr>
<td>Ti-8-4-2-2-3</td>
<td>1500 (816)</td>
<td>L</td>
<td>119 (820)</td>
<td>124 (855)</td>
<td>19</td>
</tr>
</tbody>
</table>

1° Annealing time was 10 minutes.
Previous weldability studies on the metastable-beta titanium alloy Ti-8Mo-8V-2Fe-3Al found that postweld aging can significantly strengthen these large-grained regions and thereby provide high weld joint efficiency. Unfortunately, high weldment strengths are normally accompanied by very low ductilities. More recent postweld aging studies on Ti-8823 by Greenfield and Pierce have shown, however, that proper postweld aging can result in the production of weldments exhibiting moderately high strengths and acceptable ductilities.

The present investigation studied the welding characteristics of three formable-sheet metastable-beta titanium alloys. Effects of postweld heat treatment on weldment microstructure, mechanical properties, and fracture behavior were determined and evaluated in the context of previously determined microstructure-property correlations for metastable-beta titanium alloy weldments.

Experimental Procedure

Formable sheet titanium alloys studied in this investigation included Ti-15V-3Cr-3Al-3Sn, Ti-8V-7Cr-3Al-4Sn-1Zr, and Ti-8V-4Cr-2Mo-2Fe-3Al (Table 1). Base metal processing involved hot rolling at 1750°F (954°C) to 0.250 in. (6.3 mm) and cold rolling to a final 0.100 in. (2.5 mm) thickness. A final air annealing treatment provided a uniformly recrystallized beta microstructure. Annealing temperatures and times, as-annealed mechanical properties, and aged mechanical properties are provided in Table 2 and Fig. 1, respectively. These base metal data
Table 3—GTA Welding Parameters

<table>
<thead>
<tr>
<th>Weldment type:</th>
<th>Full-penetration, bead on plate, full restraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current:</td>
<td>155 A</td>
</tr>
<tr>
<td>Voltage:</td>
<td>10 V, DCSP</td>
</tr>
<tr>
<td>Travel speed:</td>
<td>6.0 ipm (2.5 mm/s)</td>
</tr>
<tr>
<td>Electrode type:</td>
<td>Diameter thorialed tungsten (AWS EWTh-2)</td>
</tr>
<tr>
<td>Torch gas:</td>
<td>Argon, 15 cfh (7 liters/min)</td>
</tr>
<tr>
<td>Trailing shield gas:</td>
<td>Argon, 30 cfh (14 liters/min)</td>
</tr>
<tr>
<td>Backing gas:</td>
<td>Argon, 15 cfh (7 liters/min)</td>
</tr>
</tbody>
</table>

were extracted from AFML-TR-76-45 and have been provided for comparative purposes.

Weldability studies were performed on autogenous, full-penetration gas tungsten arc weldments (Table 3). Subsequent to welding, coupons were vacuum heat treated at temperatures of 1050°F (566°C), 1150°F (621°C), and 1250°F (677°C) for 4, 8, and 16 hours (h). Figure 2 illustrates the longitudinal weld tensile specimen employed to study fusion and heat-affected zone strength and ductility. Such specimens were advantageous for fracture studies since all regions of the weldment were strained equally, a condition which does not normally exist in transverse weld test specimens. Duplicate tensile tests for each alloy heat treatment were conducted on a conventional Instron testing machine at a strain rate $1.1 \times 10^{-3} \text{ sec}^{-1}$.

Crack initiation studies were performed on longitudinally welded bend specimens of Ti-15V-3Cr-3Al-3Sn (weld parallel to tensile stress) electro-polished in a solution previously described by Williams and Blackburn. Specimens were progressively bend tested around dies of decreasing radius until surface cracks initiated. Testing with this weld orientation strained all regions of the weldment equally, as pointed out for the longitudinal weld tensile. A test of this type identifies the region of minimum ductility but cannot be construed to identify the region where failure would occur for a tensile stress transverse to the weld.

Weldment microstructure characterization was performed on polished and etched (HF + HNO$_3$) specimens using optical microscopy. Scanning electron microscopy was employed for fractographic evaluation and in the crack initiation studies.

Results

Microstructural Characteristics

Weldments produced in the three solution heat-treated alloys were char-
acterized by large, columnar grains in the fusion zone and smaller, nearly equiaxed grains in the heat-affected zone, with the heat-affected zone grain size continually decreasing with distance from the fusion boundary. As might be expected, the rapid cooling rates associated with welding and the high proportion of beta-stabilizing elements in these alloys (e.g., V, Cr, Fe, Mo) combined to promote the retention of beta in weldment regions which experienced super-transus temperatures during the weld thermal cycle. The rapidity of the weld thermal cycle was also evidenced by an absence of observable aging of metastable-beta grains in the far heat-affected zone.

Postweld heat-treatment promoted both heterogenous and homogenous alpha precipitation in all regions of the weldment. Low aging temperatures promoted fine, locally homogenous alpha precipitation and inhibited grain boundary alpha formation—Fig. 3. Increased aging temperature, and to a lesser extent, increased time at temperature, allowed coarser, locally homogenous intragranular alpha and heterogenous intergranular alpha precipitation—Fig. 4. Although comparatively heat-treated weldments in the three alloys did experience slight microstructural variations, the trend

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Yield strength, ksi (MPa)</th>
<th>Ultimate tensile strength, ksi (MPa)</th>
<th>Elongation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-15-3-3-3</td>
<td>105 (725)</td>
<td>109 (750)</td>
<td>20.5</td>
</tr>
<tr>
<td>Ti-8-7-3-4-1</td>
<td>119 (820)</td>
<td>123 (850)</td>
<td>21</td>
</tr>
<tr>
<td>Ti-8-4-2-2-3</td>
<td>121 (835)</td>
<td>125 (860)</td>
<td>16.5</td>
</tr>
</tbody>
</table>

Table 4—As-Welded Mechanical Properties

![Graphs showing yield and ultimate tensile strengths and % elongation vs. aging time](image)
towards increased intergranular alpha coarseness and increased propensity for grain boundary alpha formation with increased aging temperature was consistent.

Macroscopic variations in the nature and extent of alpha precipitation were evident in all weldments studied. Such macro-inhomogeneities in the weldment fusion zone (the mottled appearance of Fig. 4A) apparently resulted from alloying element compositional gradients residual from microsegregation during weldment solidification. Base metal aging inhomogeneities, such as illustrated in Fig. 3B, probably resulted from residual compositional banding in the sheet and from variations in the extent of recrystallization during solution heat treatment.

Mechanical Properties

Unaged-welded specimens exhibited relatively low yield and ultimate tensile strengths and high ductilities comparable to those of solution heat-treated base metal specimens (Table 4). As Fig. 5 shows, aging of the weldments significantly increased yield and ultimate strength and correspondingly decreased ductility. For comparable heat treatments, the Ti-84223 alloy exhibited the higher strength levels, followed by Ti-87341 and finally Ti-15-333.

Results obtained for the three alloys suggested that both aging temperature and time played important roles in determining weldment properties. Increases in aging temperature for a specific aging time clearly resulted in decreased yield strength and, with few exceptions, increased ductility. The effect of time on aging behavior and resulting mechanical properties appeared more complex than that of temperature and could not be as easily generalized for the three alloys. As Fig. 5 illustrates, however, aging curves often did follow the underaged, optimally aged, overaged trend commonly associated with aging phenomena.

A comparison of aged weldment properties with solution heat-treated and aged base metal properties found the weldments to be stronger and less ductile than the base metal. Cursory hardness tests on welded and aged coupons further supported these observations, with fusion zone regions normally exhibiting slightly greater hardness than the adjacent base metals. It is of importance to mention that hardness decreases in the far heat-affected zone because of aging during welding, were not found to exist.
Fracture Behavior

Aging time and temperature played significant roles in determining weldment fracture behavior. Fracture of the ductile, as-welded specimens occurred predominantly transgranularly (Fig. 6) by a void nucleation, growth, and coalescence mechanism. Low temperature-aged specimens fractured by either predominantly transgranular (Ti-15-333 and Ti-87341) or mixed transgranular/intergranular mode (Ti-84223). Observations of regions on the transgranular fracture surface which exhibited a faceted appearance (Fig. 7), and the low macroscopic ductility of these low-temperature aged specimens suggested possible cleavage fracture. Investigation of these faceted regions at high magnification, however, found that fracture actually involved a microscopically ductile mechanism—Fig. 8.

Aging at 1150°F (621°C) promoted transitions from predominantly transgranular or mixed transgranular/intergranular fracture to predominantly intergranular fracture. Welded specimens aged at 1250°F (677°C) behaved in two entirely different manners. Fracture of the Ti-87341 alloy was characterized by continuously increasing amounts of intergranular fracture (Fig. 9) with increasing aging time, while ductile, transgranular (Fig. 10) failure was the principle mode of fracture in the Ti-84223 and Ti-15-333 alloy weldments.

Fracture initiation in the longitudinal-bend specimens was found to occur at beta grain boundaries for the as-welded and all postweld heat treatment conditions. The postweld heat-treatment conditions which failed by a predominantly transgranular failure appeared to experience a transition from intergranular initiation to transgranular propagation. These observations complemented those of an earlier study on the alpha-beta alloy Ti-662. The nature of intergranular initiation and propagation was similar to that observed in another alpha-beta alloy, Ti-6246.

Discussion

Although it was not possible to ascertain definite, all-inclusive correlations between microstructures, mechanical properties, and fracture behavior in these three alloys, trends were noted. These trends, as well as the discrepancies and unexplained behavior, will now be pointed out. Aging of the metastable-beta welded structures was found to occur quite rapidly at all aging temperatures. Low aging temperature promoted locally homogeneous alpha precipitation which resulted in high strengths, low ductilities, and a predominantly transgranular mode of fracture. Also, the aging response or the effect of time was evident in the microstructures and properties of the low-temperature aged samples. This was most apparent for the alloy in Fig. 6B where the microstructures, as well as properties, showed a typical underaged to over-aged trend.

Increased aging temperatures allowed coarse intragranular alpha precipitation and heterogeneous grain boundary alpha formation, which resulted in decreased strength and increased ductility, as well as a trend from transgranular to intergranular fracture. Aging at a high temperature (1250°F, 677°C) created a coarse microstructure characterized by a nearly continuous grain boundary alpha network. Despite similarities in the microstructures of the three alloys heat treated at this temperature, the fracture surface morphology differed significantly. This will be discussed in subsequent paragraphs.

As stated earlier it was possible to observe microstructural differences within one alloy and thereby follow the aging response of the alloy and correlate this microstructure to the observed tensile strengths. However, it was not possible to determine through optical microscopy the reasons for the observed strength level differences between alloys in Fig. 5, i.e., 175 ksi (1215 MPa) vs. 145 ksi (1000 MPa) yield strength. The two alloys with a high yield strength had quite high beta eutectoid stabilizer content which suggests the possibility of moderate...
amounts of eutectoid decomposition products. These transformation products would likely be very fine and unable to be resolved by optical metallographic techniques.

In the previously mentioned paper on Ti-8823, Greenfield and Pierce indicated that the relationships which were previously found to exist in alpha-beta titanium alloys between microstructure, mechanical properties, and fracture behavior also apply to metastable-beta titanium alloys. They found that the fracture strength and ductility were strongly affected by microstructural characteristics, particularly with respect to the characteristics of the grain boundary alpha.

Low aging temperatures and times they found the Ti-8823 alloy to exhibit low elongation and high strength; whereas at high aging temperatures (1300°F, 704°C) and long aging time they noted low elongation and low strength. At intermediate combinations of temperature and time, optimal combinations of strength and elongation were found.

The explanation proposed for the uncommon combination of low strength and low macroscopic elongation was a thick and continuous grain boundary alpha layer which permitted early grain boundary crack initiation and intergranular crack propagation.

The results of the present study are compared to this earlier study by plotting the yield strength and elongation vs. a temperature-time aging parameter for the three formable-sheet alloys—Fig. 11.

All three of the plots made against yield strength show a continual decrease in strength with an increase in the temperature-time parameter. The plots of elongation on the other hand show a similar behavior for the two alloys Ti-84223 and Ti-15-333. The behavior of these microstructurally similar alloys, despite thick, continuous grain-boundary alpha, does not agree with the model proposed in the earlier Ti-8823 study with respect to the ductility or fracture mode ob-

Fig. 11—Yield strength and elongation vs. time-temperature aging parameter for welded and aged specimens: A and B—Ti-15-333; C and D—Ti-87341; E and F—Ti-84223.
served. It should be also noted that the Ti-87341 alloy behaved quite similarly to Ti-8823 in that its ductility began to drop at the high aging temperatures and times, and also fractured intergranularly for this condition.

The results of this study are not consistent with the model proposed by Greenfield and Pierce,\(^3\) thus indicating that it is not in error but perhaps too simple, thereby leaving uncontrolled important variables which under certain circumstances also have a strong influence on mechanical behavior. Indeed, additional factors such as microstructural and compositional characteristics of the alpha-beta interface and deformation characteristics of the grain interior also may contribute significantly to determining the macroscopic mechanical properties exhibited by a weld. Further, it should be pointed out that inherent dangers exist when extrapolating relationships developed in wrought products to a weldment, without first evaluating other factors which change in such an extrapolation, such as grain size, preferred orientation, and micro-segregation.

Conclusions

1. The three formable-sheet titanium alloys studied in the present investigation were found to be readily weldable with typical parameters employed in the welding of titanium alloys.

2. The as-welded fusion and near heat-affected zones consisted of metastable-beta phase which was very ductile and low in strength. Little or no aging was observed in the far heat-affected zone.

3. All three alloys responded well to postweld heat treatment with significant increases in strength. Although Ti-8V-4Cr-2Mo-2Fe-3Al exhibited the highest strength levels, the Ti-15V-3Cr-3AI-4Sn-TiZr alloys appeared to offer the best combinations of strength and ductility.

4. Microstructure-property correlations determined previously for weldments in a similar alloy were inconsistent with results obtained in the present investigation, suggesting that factors additional to those considered previously are important when one considers these relationships.

References


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WRC Bulletin 254
November 1979

(1) A Critical Evaluation of Plastic Behavior Data and a Unified Definition of Plastic Loads for Pressure Components
by J. C. Gerdeen

(2) Interpretive Report on Limit Analysis and Plastic Behavior of Piping Products
by E. C. Rodabaugh

(3) Interpretive Report on Limit Analysis of Flat Circular Plates
by W. J. O'Donnell

These three reports summarize a four-year effort by the PVRC Task Group on "Characterization of the Plastic Behavior of Structures" to meet the need for unified and standardized methods for limit analysis on plastic collapse determinations.

Publication of this report was sponsored by the Pressure Vessel Research Committee of the Welding Research Council.

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