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Effect of LID® Processing on the Microstructure and Mechanical Properties of Ti-6Al-4V and Ti-6A1-2Sn-4Zr-2Mo Titanium Foil-Gauge Materials

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Linda B. Blackburn

Langley Research Center
Hampton, Virginia

National Aeronautics and Space Administration

Scientific and Technical Information Branch

Summary

A Liquid Interface Diffusion (LID)[1] bonding process has been used to fabricate test panels for metallic thermal protection systems using foil-gauge Ti-6Al-4V (Ti-64) and Ti-6Al-2Sn-4Zr-2Mo (Ti-6242). This process uses application of a proprietary LID material to the joint to be bonded and heating to produce a brief eutectic melt to aid in metal contact and diffusion. Diffusion of the LID material into the parent metal, however, causes microstructural changes. This study was undertaken to determine mechanical properties and microstructures resulting from LID processing of foil-gauge specimens of Ti-64 and Ti-6242 coated with varying amounts of LID material. In addition, the effects of various elevated temperature exposures on the concentration profiles of the LID alloying elements were investigated, using specimens with a narrow strip of LID material applied to the surface.

Room and elevated temperature tensile properties were determined for both coated and uncoated specimens. Optical microscopy was used to examine alloy microstructures, and scanning electron microscopy to examine fracture surface morphologies. The chemical concentration profiles of the strip-coated specimens were determined with an electron microprobe.

Coated specimens generally exhibited higher strengths but lower room temperature ductilities than their uncoated counterparts. These properties were attributed to microstructural changes resulting from alloying of the LID materials with the titanium alloys included in the study.

Heat treatment of strip-coated specimens produced no discernible change in LID material concentration profiles when compared with profiles of the as-received specimens. Strengths were generally unaffected, and ductilities varied but exhibited a tendency to decrease following thermal exposure at 1100°F.

Introduction

Titanium alloys Ti-6Al-4V (Ti-64) and Ti-6Al-2Sn-4Zr-2Mo (Ti-6242) have been used in the fabrication of honeycomb core sandwich panels for thermal protection systems (TPS) (refs. 1 to 3). These alloys were selected for their low mass, creep and oxidation resistance, and superplastic properties. Initial TPS designs used Ti-64 in areas where peak temperatures were less than 1000°F. Use of Ti-6242 allowed peak temperatures of approximately 1100°F. In the above studies, panels were bonded using Liquid Interface Diffusion (LID), a proprietary diffusion bonding process where joint components are plated with LID elements (refs. 4 to 8). The joints are then placed in contact and heated to approximately 1715°F to melt the LID elements which form a brief eutectic with the titanium alloy. The components are held at this temperature for approximately 90 minutes, during which time the LID elements diffuse into the components to form a bond throughout the plated area. After this bonding period, the components are subjected to a slow furnace cool.

The principal bonding elements for the LID process used in this study are Cu and Ni which result in beta eutectoids when alloyed with titanium and act to stabilize the beta phase and provide some solid solution strengthening (ref. 9). Diffusion of these beta stabilizers into an equiaxed alpha-beta microstructure results in areas where the beta transus temperature is decreased beneath the LID bonding temperature. Subsequent slow cooling then causes transformation of these areas of equiaxed alpha to elongated and coarsened alpha laths typical of a Widmannstätten structure. Very slow cooling from above the beta transus temperatures may even result in formation of a lamellar eutectoid microstructure of alpha and a brittle compound such as Ti_2Cu (ref. 9), which has been associated with embrittlement.

This study was undertaken to examine the effects of various plating thicknesses of applied LID material (predominantly Cu and Ni) on the microstructure of Ti-64 and Ti-6242 foil-gauge material and to correlate microstructural differences with associated mechanical properties from tensile specimens. In addition, specimens strip coated with LID material were exposed to expected service temperatures of 800°F and 1000°F and to a higher temperature of 1100°F to determine the effect of such additional thermal exposures on the concentration profiles of the Cu and Ni alloying elements.

Experimental Procedure

Materials

The materials used for this study were nominally 0.003-in- and 0.004-in-thick sheets of titanium alloys Ti-64 and Ti-6242. Selected sheets of each material and thickness were fully coated or strip coated by the Rohr Industries, Inc., with a proprietary filler metal used in the LID bonding process. For the fully coated sheets, one side was evenly coated with filler metal (fig. 1(a)) in three varying amounts: (1) standard amount (i.e., standard amount used by Rohr for fabricating thin-gauge titanium TPS panels), (2) a decreased amount (50 percent of standard), and (3) an increased amount (200 percent of standard). For strip-coated sheets, a standard amount

[1] LID is a registered trademark of Rohr Industries, Inc.

of filler metal was applied in a nominal 1/16-in-wide strip across the midpoint of one side of the sheet, perpendicular to the axis of the primary rolling direction (fig. 1(b)). Both the fully coated and the strip-coated sheets, as well as uncoated sheets (without filler metal applied), were then exposed by Rohr Industries to the LID thermal cycle (fig. 2) with a 90-min hold at 1715°F ± 15°F.

Specimens

Upon receipt of the Ti-64 and Ti-6242 sheets exposed to a simulated LID bonding cycle, tensile specimens were machined from longitudinal blanks taken parallel to the principal rolling direction and conformed to the dimensions in figure 3. The uncoated and fully coated specimens and some strip-coated specimens received no further thermal treatments prior to testing. The remainder of the strip-coated specimens were exposed to additional thermal treatments in a vacuum furnace. Some of these were exposed to temperatures representative of anticipated service conditions (i.e., 100 hr at 800°F for Ti-64 and 100 hr at 1000°F for Ti-6242). The remaining strip-coated specimens of both Ti-64 and Ti-6242 were exposed to a slightly higher temperature of 1100°F for 24 hr. Titanium alloy doublers were spot welded to each side of the ends of each specimen to prevent localized yielding caused by the bearing loads induced by the alignment pins during testing.

Tensile Tests

Tensile tests were conducted at room temperature and at elevated temperatures of 800°F and 900°F for all specimen conditions of Ti-64 and Ti-6242, respectively. Duplicate specimens were tested for all conditions and average values are reported. Mechanical properties determined included ultimate tensile strength, yield strength, and total elongation. All tests were performed in a modified creep test machine as shown in figure 4. The top portion of the load train was rendered stationary, and the bottom portion was modified by incorporating a jack with dual motorized gears capable of applying a tensile load rate of less than 32 lb/min to the specimen through yield. The creep frame was equipped with a clamshell furnace for elevated temperature tests. Uniform temperature (i.e., less than 3°F variation) over the specimen gauge length was maintained in the furnace by an automated zone-controlled temperature and power controller. A Chromel-Alumel thermocouple was used to monitor specimen temperature. Applied load to the specimen was measured with a "mini" load cell positioned in the lower portion of the load train beneath the furnace. Room temperature strain was measured with a clip-on Material Test System (MTS) extensometer, and elevated temperature strain with a counterbalanced mechanical extensometer with a linear variable displacement transducer (LVDT).

Metallurgical Analysis

Microstructures of the tensile specimens were examined after testing with optical and scanning electron microscopy (SEM). Concentration profiles of the major alloying elements of the LID filler metal were determined in strip-coated specimens using X-ray microprobe analysis. Fracture surface analysis was also performed with SEM.

Results and Discussion

Fully Coated Specimens

Mechanical properties. Tensile test results for uncoated and fully coated specimens of Ti-64 are listed in table I and graphical comparisons of these results are shown in figure 5. The data indicate that the LID coated specimens had higher strengths than their uncoated counterparts. For a given specimen condition, the 0.003-in-thick specimens tended to achieve higher strength levels than the 0.004-in-thick specimens. At room temperature, the LID coated specimens exhibited lower ductilities (as measured by total elongation to failure) than uncoated specimens. At elevated temperature, however, scattered results were obtained. Those specimens coated with a decreased amount of LID material had ductilities generally greater than those of uncoated specimens, whereas comparable or lower ductilities were observed in specimens with standard or increased amounts of applied LID material.

Tensile test results for uncoated and fully coated specimens of Ti-6242 are listed in table II. Graphical comparisons of these results are shown in figure 6 and indicate trends in strengths and ductilities similar to those observed for the Ti-64 specimens. At elevated temperature, however, the 0.004-in. specimen with an increased amount of applied LID material exhibited an increase in both yield strength and ultimate tensile strength of at least 40 ksi above that exhibited by the 0.004-in. uncoated specimen.

Microstructure. Optical microscopy of the uncoated specimens of Ti-64 and Ti-6242 indicates that the lower strengths observed in these specimens compared with fully coated specimens are associated with microstructural features characteristic of a material exposed to a recrystallization anneal, that is, equiaxed alpha with retained beta occurring primarily at the grain boundary triple points (fig. 7). Microstructures of the fully coated specimens are characterized by a coarse Widmannstätten structure of alpha laths separated by transformed beta (figs. 8 and 9) originating at the surface where the LID material was applied and extending to varying depths of the specimen thickness. The depth of the Widmannstätten structure depends somewhat on the amount of LID material applied. Specimens with a decreased amount of LID material (figs. 8(a) and 9(a)) exhibit the transformed microstructure through less than half the specimen thickness, and those with standard and increased amounts of LID material (figs. 8(b), 8(c), 9(b), and 9(c)) exhibit it through greater than half the thickness. When the Widmannstätten structure does not extend through the entire thickness, the area adjacent to this structure is characterized by an equiaxed microstructure similar to that of uncoated specimens, except that the beta phase in the grain boundaries has coarsened and become more continuous.

The transformed microstructures (including the Widmannstätten structure and the coarsened grain boundary beta) seen in the higher strength, fully coated specimens contain higher beta contents than the equiaxed alpha microstructures observed in the uncoated specimens. This is a result of the LID material, containing the beta-eutectoid-forming elements Cu and Ni, diffusing into the alloy and stabilizing the beta phase. Enrichment of the beta phase with Cu and Ni was verified by X-ray mapping (fig. 10) using the electron microprobe.

The addition of Cu and Ni has been previously associated with the formation of brittle compounds such as Ti_2Cu and Ti_2Ni (ref. 9), which may account for the low ductilities observed in these alloys. If that is the case, the effect of these brittle compounds on ductility is most pronounced at room temperature where all fully coated specimens exhibit low ductilities, regardless of the relative concentrations of Cu or Ni available for brittle compound formation (figs. 5(a) and 6(a)).

Fractography. Fracture surfaces of the uncoated specimens exhibited a ductile fracture mode characterized by shallow, equiaxed dimples resulting from coalescence of microvoids initiated at alpha-beta interfaces (fig. 11). Fractographs of specimens coated with varying amounts of applied LID material also displayed dimpled features (fig. 12). Increasing concentrations of applied LID material increased the occurrence of transgranular fractures characterized by a cleavage-type appearance as they passed through the coarse alpha laths in the Widmannstätten structure (fig. 12(b)). This transition from predominantly equiaxed dimples to predominantly transgranular fracture then appears to be a function of the concentration of the LID alloying elements Cu and Ni.

Strip-Coated Specimens

Mechanical properties. Tensile test results for the strip-coated specimens of Ti-64 are shown in table III. These results indicate that for those tests conducted at room temperature, a majority of the 0.003-in-thick specimens, but only one of the 0.004-in-thick specimens, failed within the strip containing the LID affected area. At elevated temperature, all tensile specimens failed outside the LID affected strip. No consistent correlation was found between strength or ductility and location of the fracture.

Graphical comparisons of the tensile data from table III are shown in figure 13 and indicate that the additional thermal exposures at 800°F and 1100°F resulted in a trend of increased strength with increasing exposure temperature when compared with as-received specimens. The room temperature ductilities tended to decrease with increasing exposure temperature, whereas the elevated temperature ductilities were essentially unchanged.

Tensile test results for the strip-coated specimens of Ti-6242 are listed in table IV and indicate that the majority of the 0.003-in-thick specimens tested at room temperature failed in the LID affected strip in a manner similar to that observed for 0.003-in-thick specimens of Ti-64. All elevated temperature and all but one of the 0.004-in-thick room temperature specimens failed outside the LID affected strip. Again, no consistent correlation was observed between strength or ductility and the location of the fracture.

The tensile data of table IV are shown graphically in figure 14 and indicate that both the room and the elevated temperature strengths of the 0.003-in-thick specimens were generally larger after thermal exposure at 1000°F and 1100°F than the strengths of the as-received specimens. The room temperature specimens exposed at 1000°F, however, exhibited an exceptionally low ultimate tensile strength which could not be explained through observations of the microstructure with optical microscopy. The room and elevated temperature tensile strengths of the 0.004-in-thick specimens also increased after thermal exposures, but to a lesser extent than the 0.003-in-thick specimens.

Further examination of figure 14 indicates that strengths of the 0.003-in-thick specimens were consistently higher than those of their 0.004-in-thick counterparts. The reason for this behavior was not obvious from optical or SEM examination of the alloy microstructures, but may be related to processing history.

The effectiveness of the additional heat treatments (i.e., 100 hr at 800°F for Ti-64, 100 hr at 1000°F for Ti-6242, and 24 hr at 1100°F for remaining specimens of Ti-64 and Ti-6242), in altering the concentration profiles of Cu and Ni in the strip of applied LID material was evaluated using the electron microprobe. Results of elemental scans from the strip midpoint outward to unaffected parent metal indicated no observable change in the concentration profiles for either Cu or Ni when compared with profiles of the as-received strip-coated material.

Fractography. Features observed on the fracture surfaces of strip-coated specimens were typically related to the location of the failure. Specimens failing outside of the LID strip (fig. 15) were characterized by equiaxed dimples, similar to those observed on uncoated specimens. For failures within the strip (fig. 16) dimples were still a dominant feature, but there was an increase in the number of aligned dimple ridges associated with Widmannstätten alpha laths (fig. 17). These features, observed in specimens failing within the LID strip, are similar to those observed on fracture surfaces of fully coated specimens.

Concluding Remarks

This investigation examined the effect of three amounts of Liquid Interface Diffusion (LID) bonding material on the microstructure of two foil gauges of titanium alloys Ti-64 and Ti-6242, and the microstructure was related to tensile properties. The ability of further selected heat treatments to modify the concentration profile of the LID material was also investigated.

Application of LID material increased strength and decreased room temperature ductility. Elevated temperature ductilities in specimens with decreased amounts of LID material, however, remained high. These changes in mechanical properties were associated with a transformed microstructure of coarsened, elongated colonies of alpha laths, typical of a Widmannstätten structure. The occurrence of this type of structure is indicative of high concentrations of LID materials (Cu and Ni) which reduce the beta transus temperature below the LID bonding temperature.

The high concentration of Cu and Ni, which are beta-eutectoid-forming elements, are known to provide some solid solution strengthening of the beta phase; these elements may also be responsible for the loss in room temperature ductility as a result of brittle compound formation or microstructural changes resulting from the beta eutectoid transformation. Additional microscopy might prove useful in clarifying the relationship between these elements and the observed ductilities.

Subsequent thermal treatments of specimens coated with a strip of LID material proved ineffective in modifying the Cu and Ni concentration profiles. Apparently the temperatures and times used did not result in diffusion rates adequate to alter these concentrations.

Based on the results of this investigation, it appears that the minimum amount of LID material necessary to obtain good bonding should be used. The use of specimens with decreased amounts of applied LID material generally results in low room temperature ductilities, but the alloys typically show high and consistent strengths and good elevated temperature ductilities. Those specimens with increased amounts of LID material exhibit low ductilities at both room and elevated temperature and exhibited higher variability in tensile strengths.

NASA Langley Research Center
Hampton, VA 23665-5225
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Table I. Room and Elevated Temperature Tensile Test Results for Uncoated and Fully Coated Specimens of Ti-6Al-4V

Specimen no.	Gauge, in.	Coating	Test temp., °F	0.2-percent offset yield strength, ksi	Ultimate tensile strength, ksi	Strain to failure, percent
43-UU1	0.003	Uncoated	R.T.	118.7	140.6	11.0
UU2	.003	Uncoated	R.T.	112.9	134.8	10.7
FD1	.003	Fully (decreased)	R.T.	140.9	158.4	2.5
FD2	.003	Fully (decreased)	R.T.	140.4	157.9	3.1
FS1	.003	Fully (standard)	R.T.	145.8	162.5	1.8
FS2	.003	Fully (standard)	R.T.	143.0	161.1	2.1
FI1	.003	Fully (increased)	R.T.	123.9	136.4	1.7
FI2	.003	Fully (increased)	R.T.	148.3	161.1	1.7
UU3	.003	Uncoated	800	71.3	91.7	7.1
UU4	.003	Uncoated	800	70.0	89.9	7.5
FD3	.003	Fully (decreased)	800	80.2	95.0	12.1
FD4	.003	Fully (decreased)	800	82.9	99.8	11.9
FS3	.003	Fully (standard)	800	90.0	117.3	6.9
FS4	.003	Fully (standard)	800	87.1	104.5	7.0
FI3	.003	Fully (increased)	800	81.5	96.0	5.9
FI4	.003	Fully (increased)	800	81.5	97.2	7.2
44-UU1	0.004	Uncoated	R.T.	114.0	135.4	10.8
UU2	.004	Uncoated	R.T.	117.6	140.7	10.3
FD1	.004	Fully (decreased)	R.T.	133.3	147.3	2.2
FD2	.004	Fully (decreased)	R.T.	137.9	152.7	2.0
FS1	.004	Fully (standard)	R.T.	148.5	163.5	2.0
FS2	.004	Fully (standard)	R.T.	145.2	166.3	2.5
FI1	.004	Fully (increased)	R.T.	—	132.3	—
FI2	.004	Fully (increased)	R.T.	134.5	149.6	1.8
UU3	.004	Uncoated	800	62.4	79.3	7.5
UU4	.004	Uncoated	800	64.7	83.2	7.5
FD3	.004	Fully (decreased)	800	78.4	92.2	8.2
FD4	.004	Fully (decreased)	800	77.2	91.1	8.5
FS3	.004	Fully (standard)	800	84.9	98.9	3.4
FS4	.004	Fully (standard)	800	90.9	106.7	4.9
FI3	.004	Fully (increased)	800	—	—	—
FI4	.004	Fully (increased)	800	86.6	100.2	4.9

Table II. Room and Elevated Temperature Tensile Test Results for Uncoated and Fully Coated Specimens of Ti-6Al-2Sn-4Zr-2Mo

Specimen no.	Gauge, in.	Coating	Test temp., °F	0.2-percent offset yield strength, ksi	Ultimate tensile strength, ksi	Strain to failure, percent
23-UU1	0.003	Uncoated	R.T.	132.5	144.7	3.2
UU2	.003	Uncoated	R.T.	130.7	145.8	6.6
FD1	.003	Fully (decreased)	R.T.	152.8	162.4	1.4
FD2	.003	Fully (decreased)	R.T.	149.8	163.0	3.0
FS1	.003	Fully (standard)	R.T.	131.5	146.6	1.8
FS2	.003	Fully (standard)	R.T.	156.6	174.2	2.5
FI1	.003	Fully (increased)	R.T.	—	156.1	1.02
FI2	.003	Fully (increased)	R.T.	163.0	164.9	1.02
UU3	.003	Uncoated	900	77.4	98.2	10.7
UU4	.003	Uncoated	900	77.1	99.0	11.6
FD3	.003	Fully (decreased)	900	83.8	—	—
FD4	.003	Fully (decreased)	900	85.5	109.1	10.3
FS3	.003	Fully (standard)	900	95.2	109.9	3.0
FS4	.003	Fully (standard)	900	90.0	106.4	2.8
FI3	.003	Fully (increased)	900	92.5	114.5	5.6
FI4	.003	Fully (increased)	900	91.5	113.8	6.3
24-UU1	0.004	Uncoated	R.T.	122.5	139.7	7.5
UU2	.004	Uncoated	R.T.	130.1	145.3	7.6
FD1	.004	Fully (decreased)	R.T.	146.9	153.7	1.3
FD2	.004	Fully (decreased)	R.T.	143.9	158.6	2.6
FS1	.004	Fully (standard)	R.T.	135.6	146.6	1.2
FS2	.004	Fully (standard)	R.T.	125.0	134.3	1.3
FI1	.004	Fully (increased)	R.T.	139.3	139.8	1.1
FI2	.004	Fully (increased)	R.T.	153.2	168.8	3.3
UU3	.004	Uncoated	900	76.7	93.0	9.7
UU4	.004	Uncoated	900	72.0	87.1	9.6
FD3	.004	Fully (decreased)	900	89.3	104.6	10.5
FD4	.004	Fully (decreased)	900	90.9	94.0	7.0
FS3	.004	Fully (standard)	900	80.4	90.4	2.5
FS4	.004	Fully (standard)	900	89.7	95.1	1.8
FI4	.004	Fully (increased)	900	117.3	135.5	3.9

Table III. Room and Elevated Temperature Tensile Test Results for Strip-Coated Specimens of Ti-6Al-4V Subjected to Various Thermal Exposures

Specimen no.	Gauge, in.	Thermal exposure	Test temp., °F	0.2-percent offset yield strength, ksi	Ultimate tensile strength, ksi	Strain to failure, percent	Specimen failed in strip
43-LS1	0.003	As received	R.T.	104.9	122.5	11.2	√
LS2	.003	As received	R.T.	119.0	138.1	5.2	
LS5	.003	24 hr @ 1100°F	R.T.	129.4	140.6	3.0	√
LS6	.003	24 hr @ 1100°F	R.T.	125.0	137.7	3.1	
LS9	.003	100 hr @ 800°F	R.T.	123.2	141.4	8.0	√
LS10	.003	100 hr @ 800°F	R.T.	122.0	143.1	8.6	√
LS3	.003	As received	800	67.4	87.3	7.5	
LS4	.003	As received	800	68.3	87.5	7.9	
LS7	.003	24 hr @ 1100°F	800	72.7	89.5	9.1	
LS8	.003	24 hr @ 1100°F	800	72.8	89.2	8.8	
LS11	.003	100 hr @ 800°F	800	66.4	87.9	8.8	
LS12	.003	100 hr @ 800°F	800	67.4	89.0	8.5	
44-LS1	0.004	As received	R.T.	118.7	138.6	8.5	
LS2	.004	As received	R.T.	118.0	139.0	10.0	
LS5	.004	24 hr @ 1100°F	R.T.	126.7	140.4	3.5	√
LS6	.004	24 hr @ 1100°F	R.T.	128.2	142.6	—	
LS9	.004	100 hr @ 800°F	R.T.	120.7	140.9	4.2	
LS10	.004	100 hr @ 800°F	R.T.	123.8	144.5	4.6	
LS3	.004	As received	800	66.8	84.8	8.2	
LS4	.004	As received	800	—	—	—	
LS7	.004	24 hr @ 1100°F	800	74.2	91.1	9.0	
LS8	.004	24 hr @ 1100°F	800	70.0	86.8	9.4	
LS11	.004	100 hr @ 800°F	800	66.4	86.9	8.9	
LS12	.004	100 hr @ 800°F	800	66.0	85.3	9.0	

Table IV. Room and Elevated Temperature Tensile Test Results for Strip-Coated Specimens of Ti-6Al-2Sn-4Zr-2Mo Subjected to Various Thermal Exposures

Specimen no.	Gauge, in.	Thermal exposure	Test temp., °F	0.2-percent offset yield strength, ksi	Ultimate tensile strength, ksi	Strain to failure, percent	Specimen failed in strip
23-LS1	0.003	As received	R.T.	140.8	152.7	4.8	√
LS2	.003	As received	R.T.	132.8	145.2	6.2	√
LS5	.003	24 hr @ 1100°F	R.T.	151.3	160.4	2.0	√
LS6	.003	24 hr @ 1100°F	R.T.	147.0	147.3	1.4	√
LS9	.003	100 hr @ 800°F	R.T.	143.7	144.9	1.5	√
LS10	.003	100 hr @ 800°F	R.T.	139.4	139.4	1.1	
LS3	.003	As received	900	77.2	99.7	12.5	
LS4	.003	As received	900	74.5	99.2	12.5	
LS7	.003	24 hr @ 1100°F	900	88.2	102.7	4.7	
LS8	.003	24 hr @ 1100°F	900	88.2	107.8	7.4	
LS11	.003	100 hr @ 800°F	900	86.3	110.9	11.6	
LS12	.003	100 hr @ 800°F	900	83.3	110.3	11.7	
24-LS1	0.004	As received	R.T.	129.0	140.0	3.9	
LS2	.004	As received	R.T.	121.3	130.5	3.4	
LS5	.004	24 hr @ 1100°F	R.T.	130.6	135.7	2.0	
LS6	.004	24 hr @ 1100°F	R.T.	133.4	139.8	2.9	
LS9	.004	100 hr @ 800°F	R.T.	126.8	137.1	3.8	√
LS10	.004	100 hr @ 800°F	R.T.	127.6	137.9	3.7	
LS3	.004	As received	900	74.2	92.2	8.8	
LS4	.004	As received	900	72.6	88.0	8.6	
LS7	.004	24 hr @ 1100°F	900	81.8	88.6	4.1	
LS8	.004	24 hr @ 1100°F	900	78.6	92.4	7.8	
LS11	.004	100 hr @ 800°F	900	77.9	94.3	9.1	
LS12	.004	100 hr @ 800°F	900	83.0	93.7	7.3	

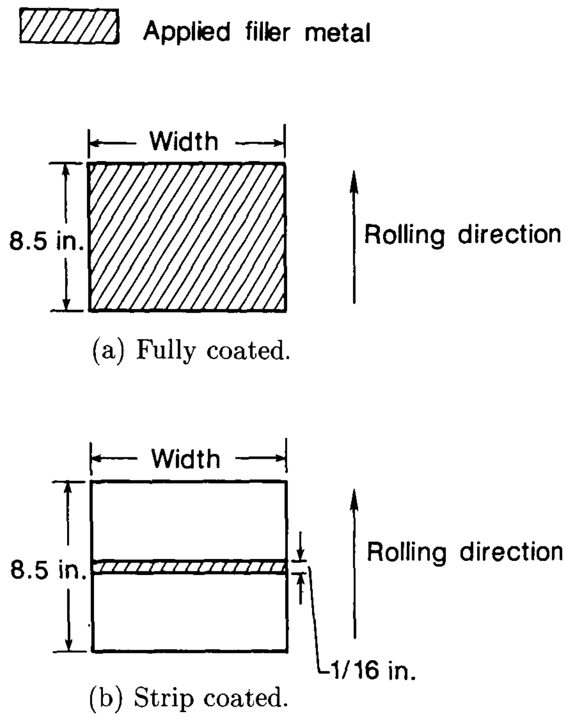

Figure 1. Configuration of coated sheets for exposure to LID processing.

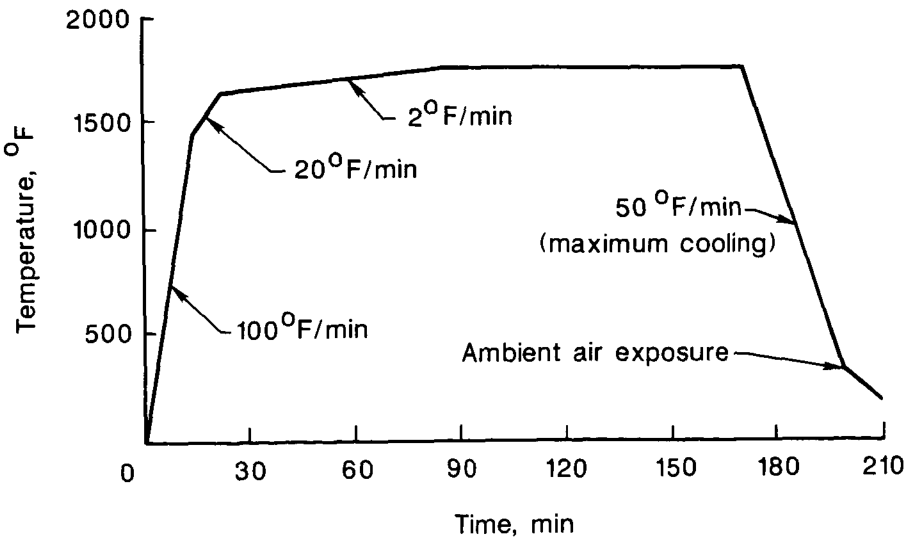

Figure 2. LID thermal bonding cycle.

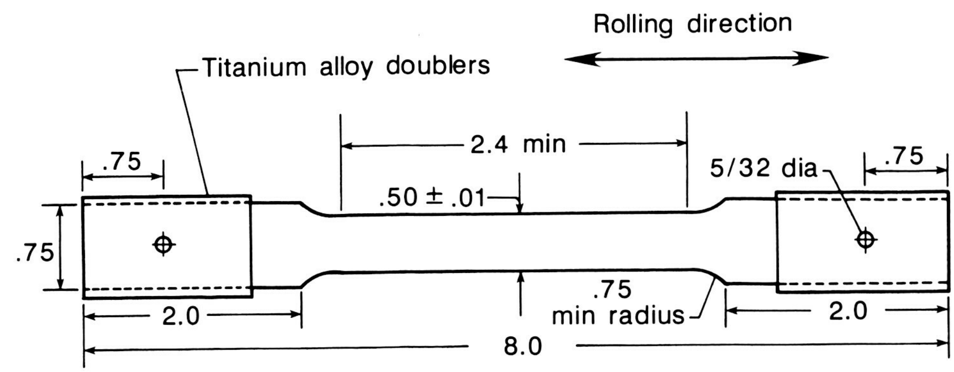

Figure 3. Tensile test specimen configuration with titanium alloy doublers attached. Dimensions are in inches.

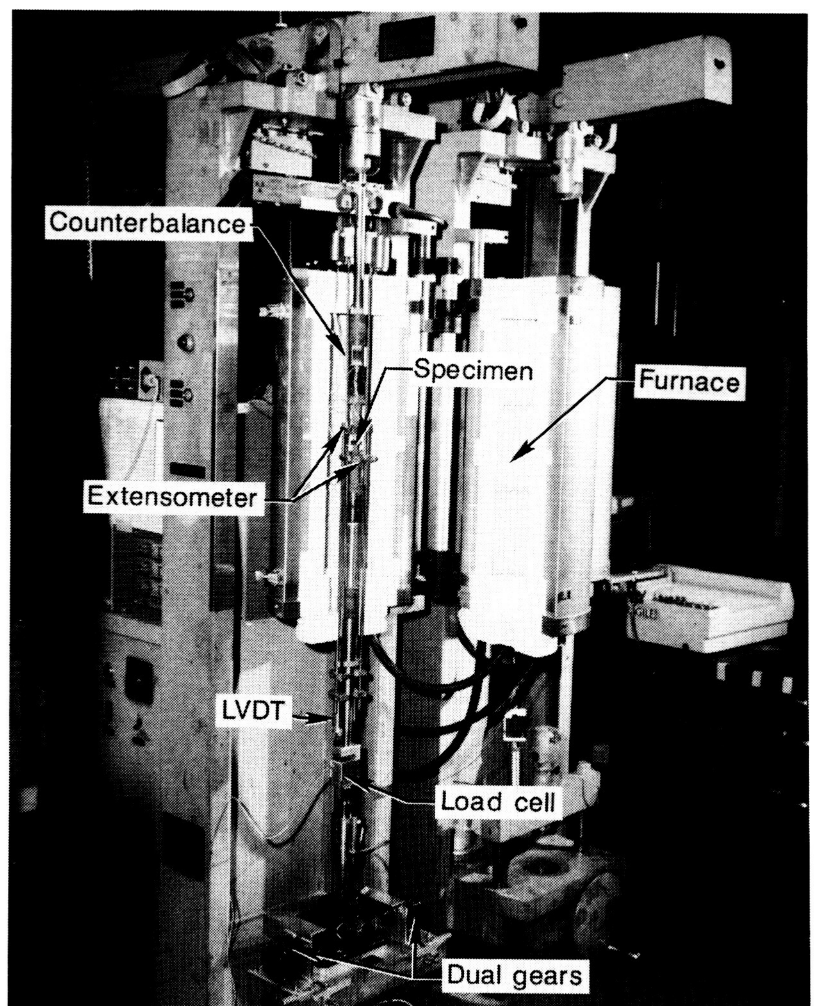

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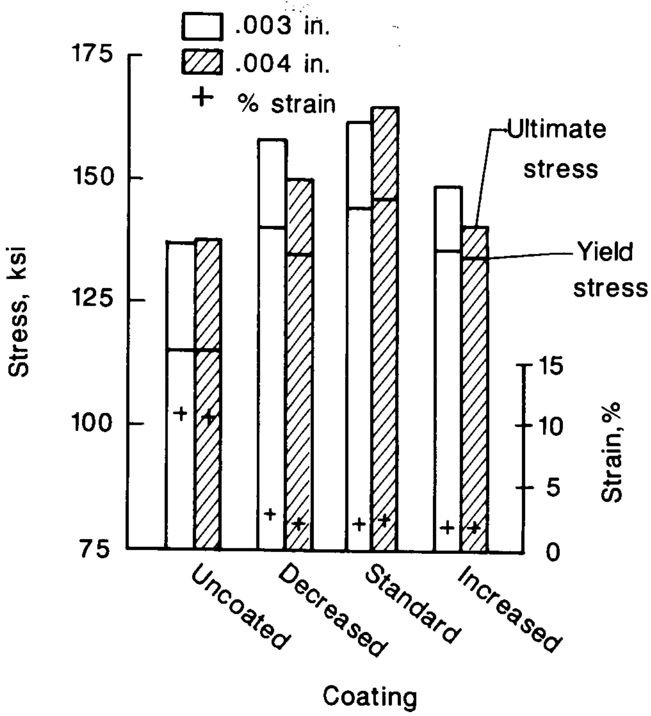
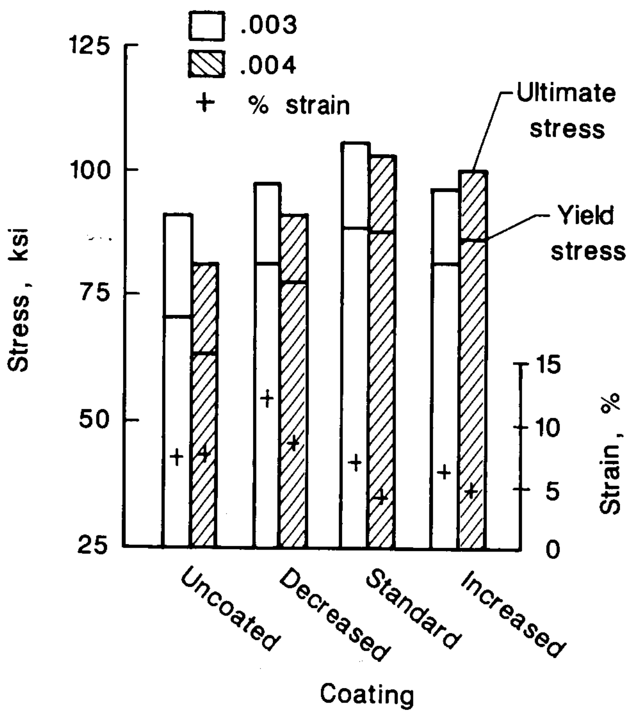
Figure 4. Elevated temperature tensile test apparatus.

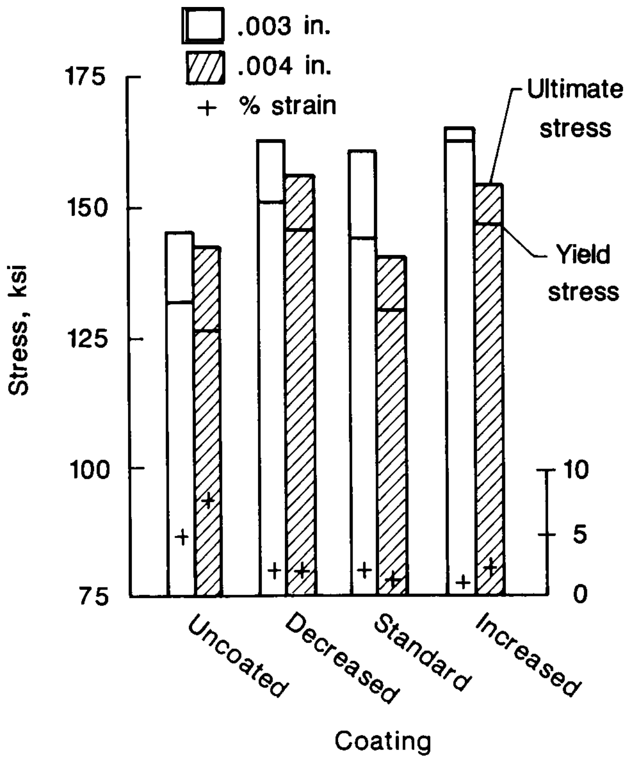


(a) Tested at room temperature.

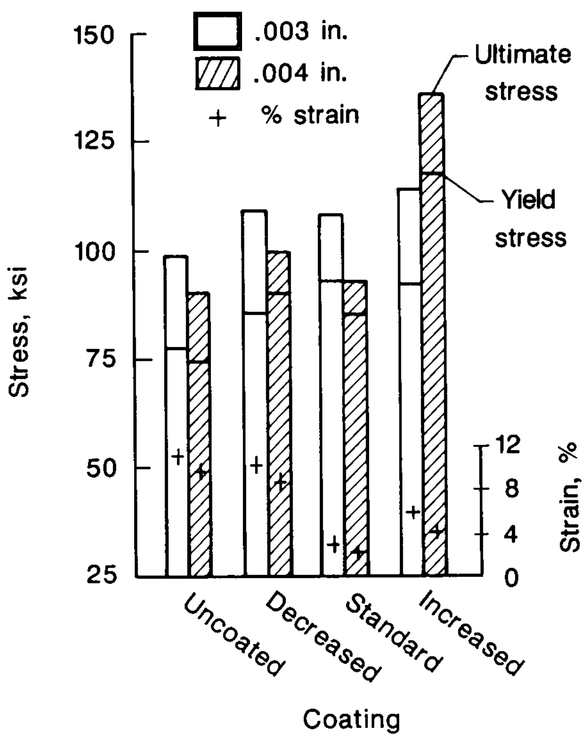


(b) Tested at 800°F.

Figure 5. Tensile test results for uncoated and fully coated specimens of Ti-6Al-4V.

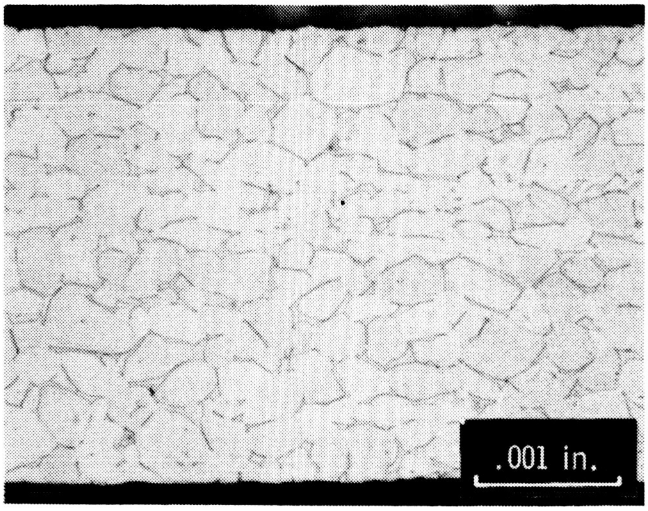


(a) Tested at room temperature.

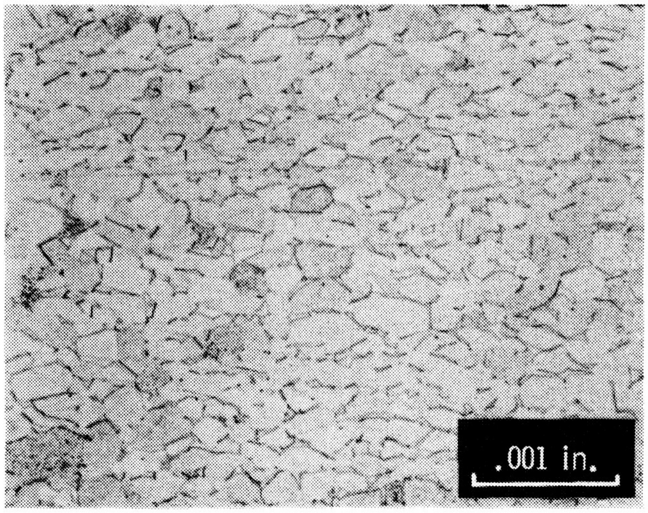


(b) Tested at 900°F.

Figure 6. Tensile test results for uncoated and fully coated specimens of Ti-6Al-2Sn-4Zr-2Mo.

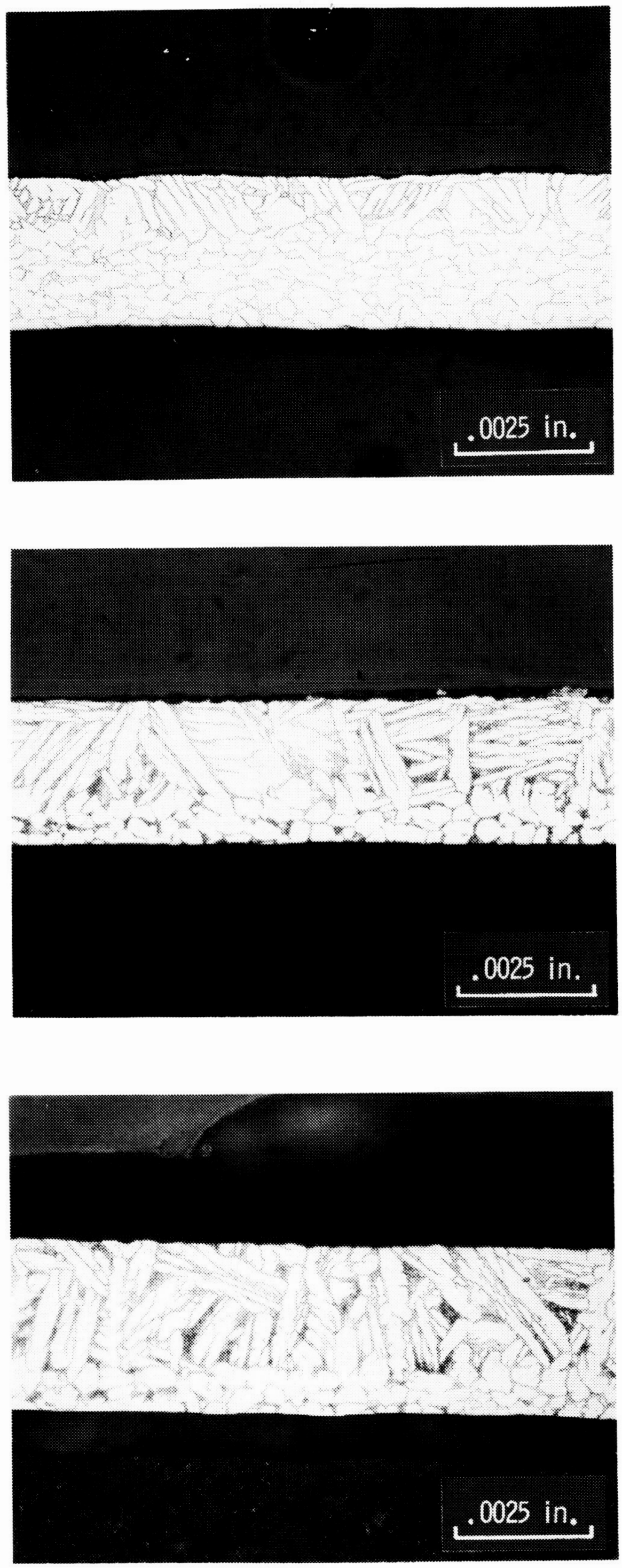


(a) 0.003-in. Ti-6Al-4V.



(b) 0.004-in. Ti-6Al-2Sn-4Zr-2Mo.

Figure 7. Photomicrographs of uncoated specimens.

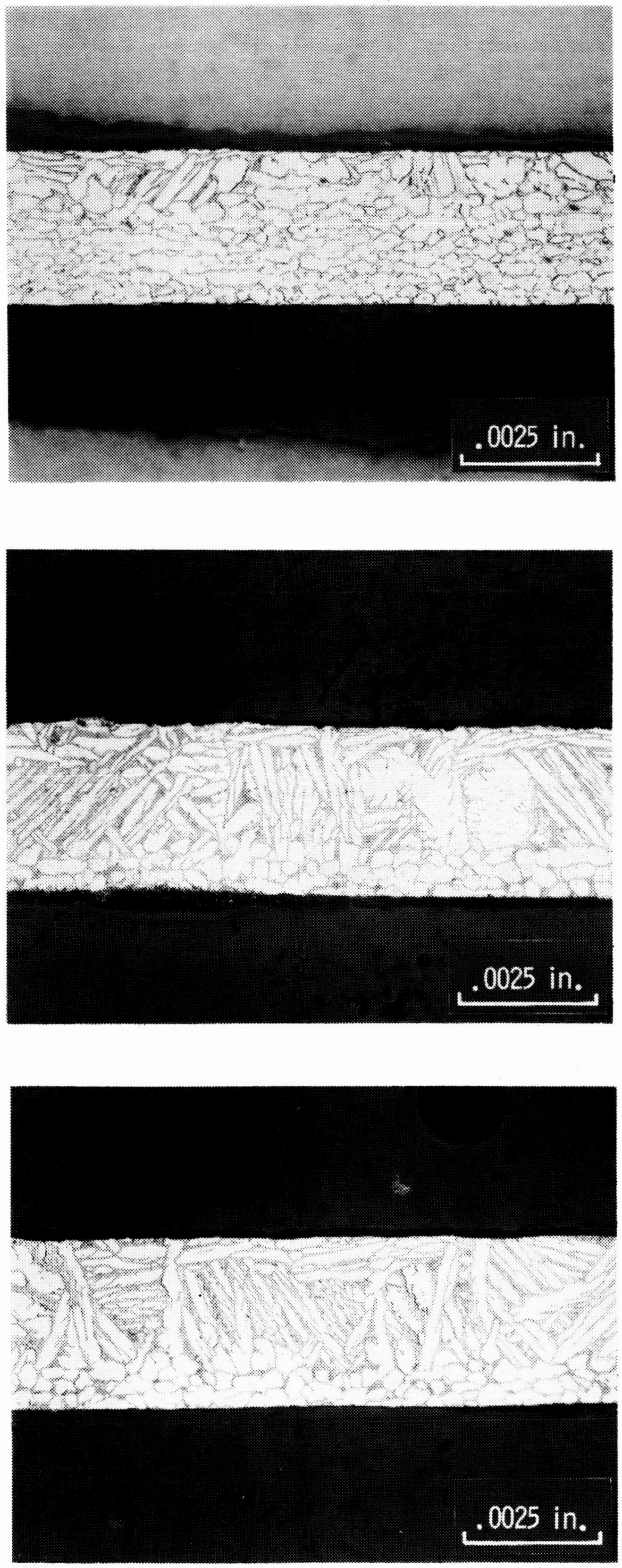


(a) Decreased.

(b) Standard.

(c) Increased.

Figure 8. Photomicrographs of specimens of 0.003-in. Ti-6Al-4V fully coated with varying amounts of LID filler metal.

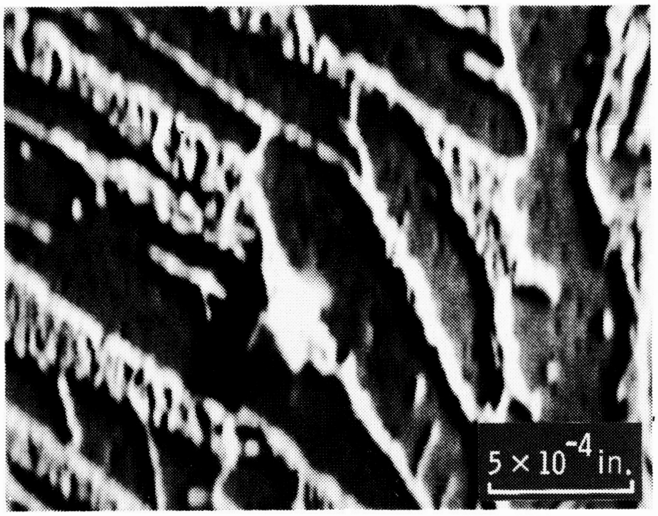


(a) Decreased.

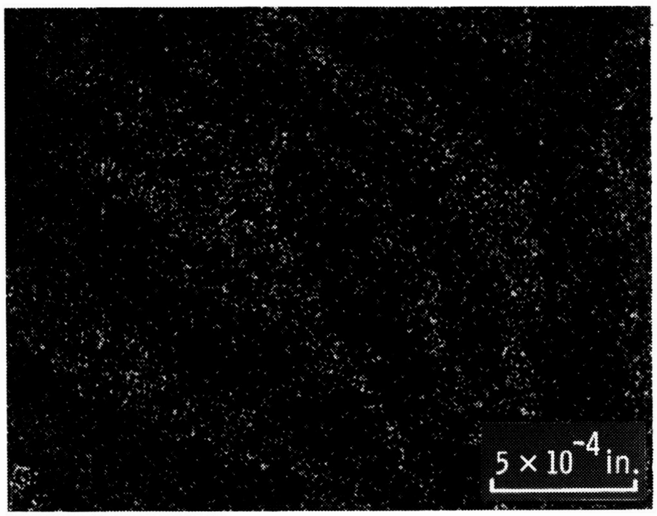
(b) Standard.

(c) Increased.

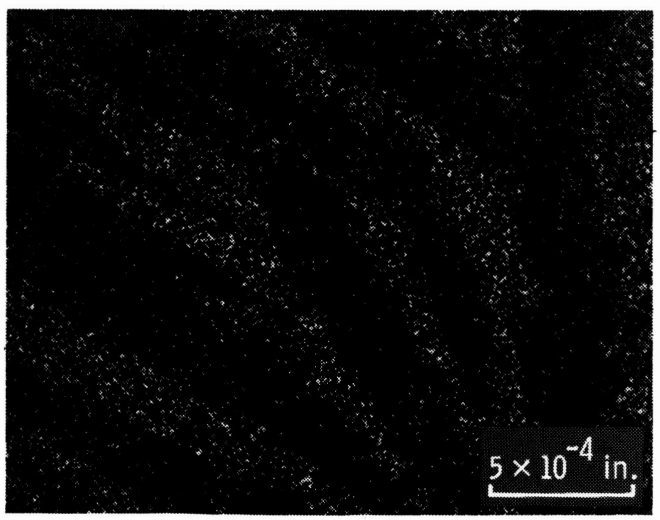
Figure 9. Photomicrographs of specimens of 0.003-in. Ti-6Al-2Sn-4Zr-2Mo fully coated with varying amounts of LID filler metal.



(a) Microstructure of scanned area.



(b) X-ray scan of area for Cu.



(c) X-ray scan of area for Ni.

Figure 10. Electron microprobe photomicrographs of specimen of 0.004-in. Ti-6Al-4V.

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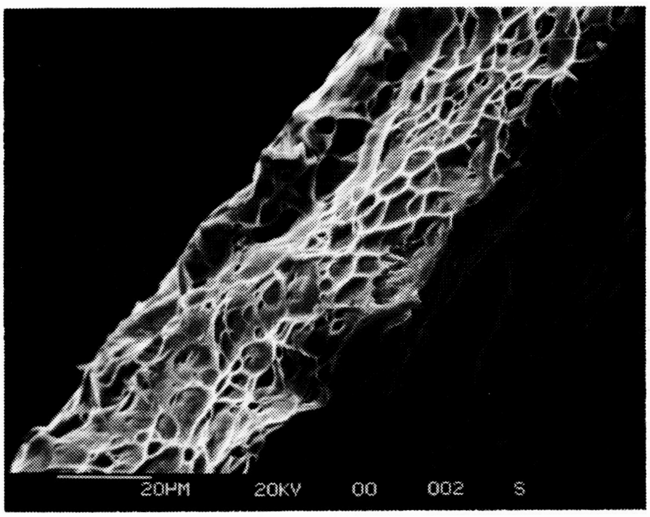
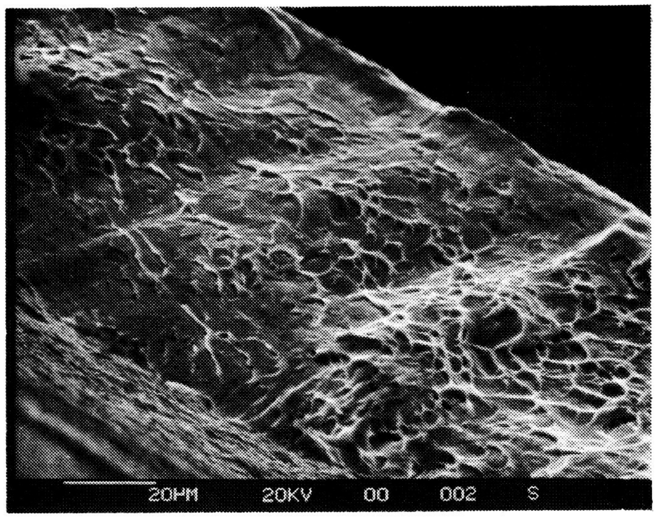
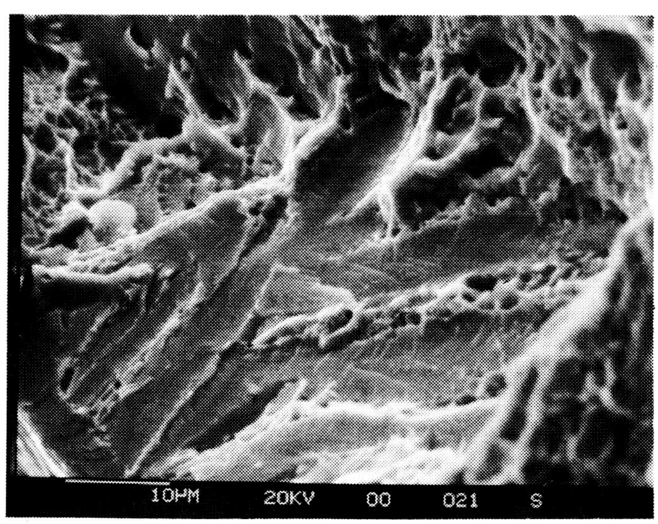


Figure 11. Fractograph of uncoated specimen of 0.003-in. Ti-6Al-4V.

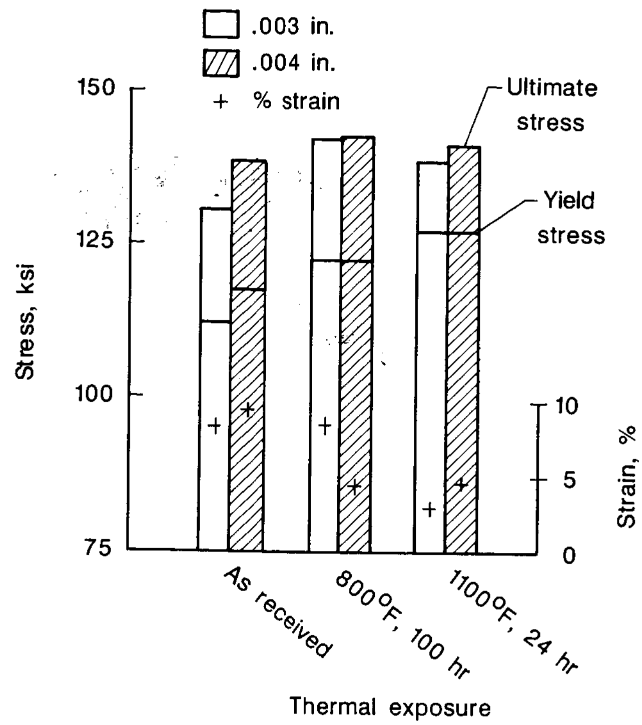


(a) Decreased.

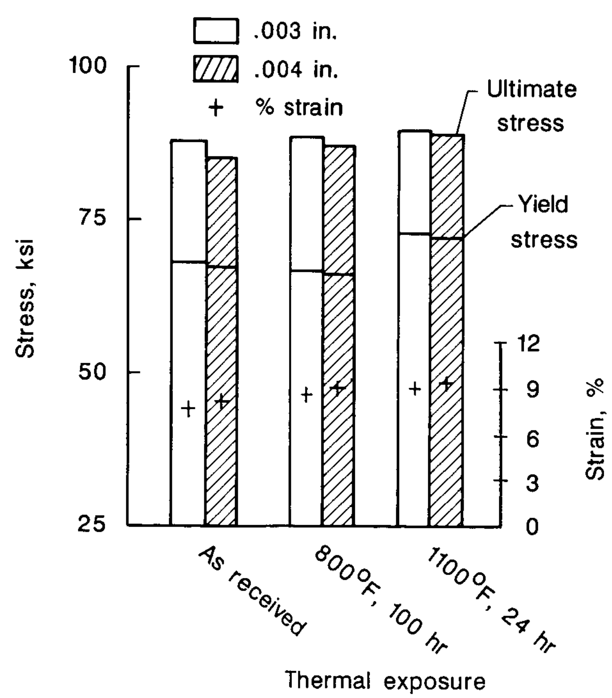


(b) Increased.

Figure 12. Fractographs of fully coated specimens of 0.004-in. Ti-6Al-4V with varying amounts of applied LID filler metal.

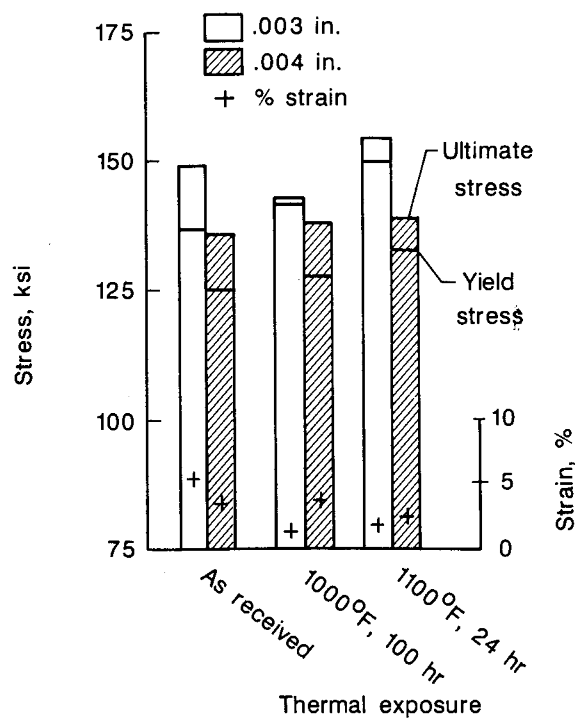


(a) Tested at room temperature.

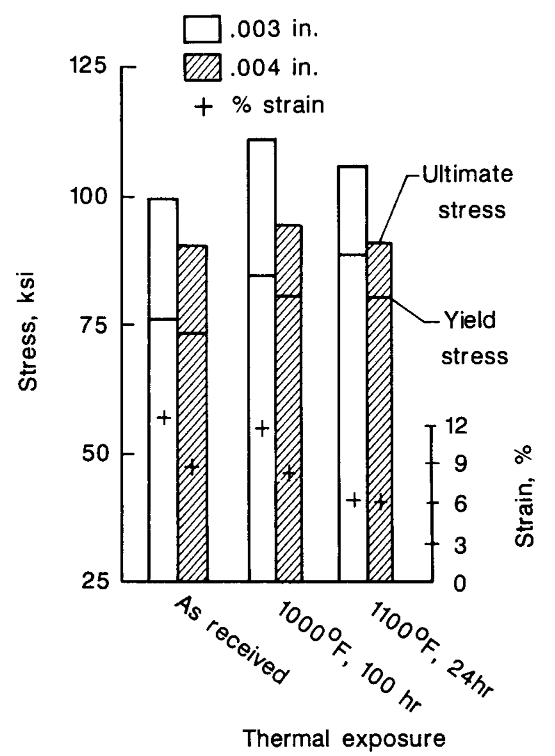


(b) Tested at 800°F.

Figure 13. Tensile test results for strip-coated specimens of Ti-6Al-4V.



(a) Tested at room temperature.



(b) Tested at 1000°F.

Figure 14. Tensile test results for strip-coated specimens of Ti-6Al-2Sn-4Zr-2Mo.

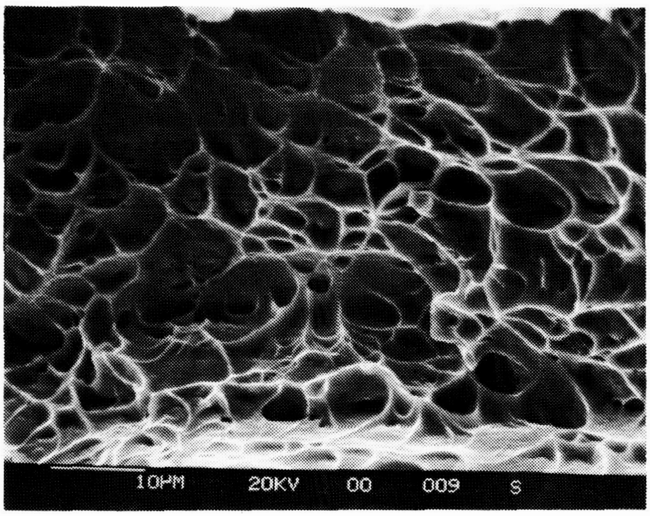


Figure 15. Fractograph of strip-coated specimen of 0.004-in. Ti-6Al-2Sn-4Zr-2Mo in the as-received condition. Specimen failed outside of strip.

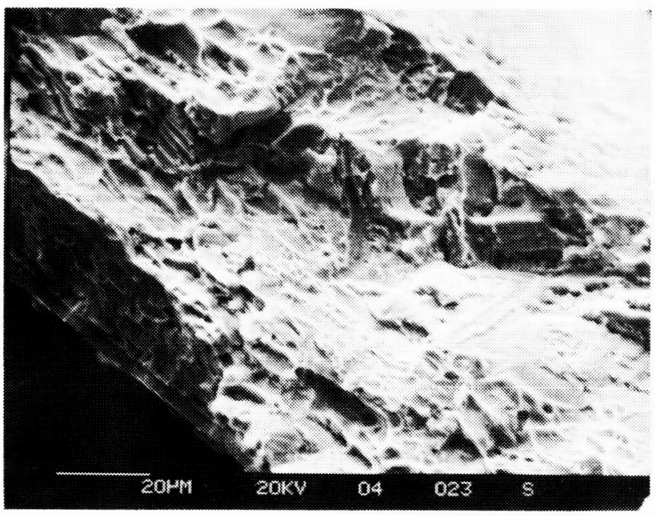


Figure 16. Fractograph of strip-coated specimen of 0.004-in. Ti-6Al-2Sn-4Zr-2Mo exposed to 1000°F for 100 hr. Specimen failed within strip.

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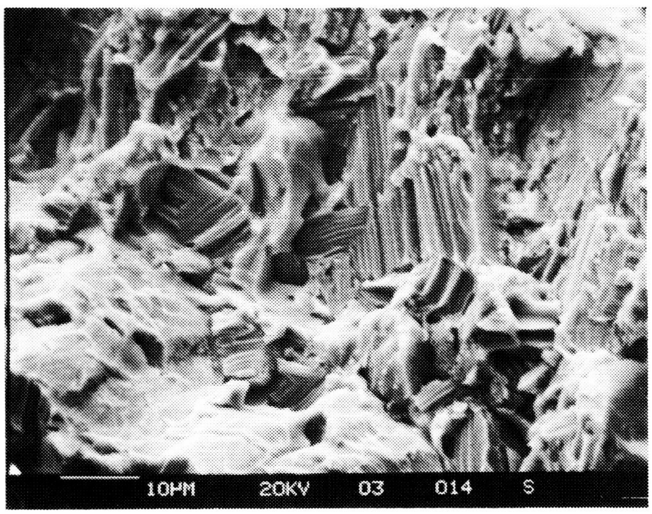

Figure 17. Fractograph of strip-coated specimen of 0.003-in. Ti-6Al-2Sn-4Zr-2Mo exposed to 1100°F for 24 hr. Specimen failed within strip.

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16. Abstract

A study was undertaken to determine the mechanical properties and microstructures resulting from Liquid Interface Diffusion (LID)® processing of foil-gauge specimens of Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo coated with varying amounts of LID material. In addition, the effects of various elevated temperature exposures on the concentration profiles of the LID alloying elements were investigated, using specimens with a narrow strip of LID material applied to the surface. Room and elevated temperature tensile properties were determined for both coated and uncoated specimens. Optical microscopy was used to examine alloy microstructures, and scanning electron microscopy to examine fracture surface morphologies. The chemical concentration profiles of the strip-coated specimens were determined with an electron microprobe.

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