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BRAZING TITANIUM STRUCTURES

PDO 6989263, Final Report

H. B. Pressly, Project Leader

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BRAZING TITANIUM STRUCTURES

BDX-613-1666 (Rev.), UNCLASSIFIED Final Report, Published
March 1977

Prepared by H. B. Pressly, D/814, under PDO 6989263

A vacuum furnace brazing process using Ag-5Al-0.5Mn brazing alloy has been developed for joining titanium alloy Ti-6Al-4V structures. Lap-shear strengths of the braze joints and the effects of the brazing thermal cycle on the tensile and bending properties of mill-annealed Ti-6Al-4V alloy sheet are reported. Nondestructive test methods were evaluated for detecting defects in these braze joints.

WPC-dvh

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SUMMARY

Brazing has been proposed as a process for joining annealed Ti-6Al-4V alloy structural hardware in a support assembly. A vacuum furnace brazing process was developed using Ag-5Al-0.5Mn brazing alloy, brazing temperatures between 850° and 870°C, and joint gaps between 0.05 and 0.15 mm (0.002 and 0.006 inch). Titanium turnings were used in the brazing furnace to prevent oxidation of the titanium during the brazing cycle.

The lap-shear strengths of braze joints made using this process ranged between 124 and 159 MPa (18 and 23 ksi). Cross sections of the joints showed sound metallurgical bonds. Tensile and yield strengths of the mill-annealed Ti-6Al-4V base metal were decreased slightly due to the brazing thermal cycle. Tensile strengths were reduced 4 to 5 percent and yield strengths were reduced 5 to 7 percent. Tensile elongations were not significantly affected. Although tensile and yield strengths did decrease, the Ti-6Al-4V base metal met the design requirements of 896 MPa (130 ksi) minimum tensile strength, 827 MPa (120 ksi) minimum yield strength, and 8 percent minimum elongation. Bend properties of the mill-annealed Ti-6Al-4V base metal were not adversely affected by the brazing thermal cycle. However, it was found that even a light oxide layer on the titanium surfaces would degrade the bend properties of the Ti-6Al-4V alloy.

A nondestructive test method, using an image analyzer to interpret radiographs, was used successfully to detect defects in the brazed joints.

DISCUSSION

SCOPE AND PURPOSE

This report describes the development of a vacuum furnace brazing process for joining mill-annealed titanium alloy Ti-6Al-4V structural hardware proposed for use in a support assembly.

ACTIVITY

Selection of Brazing Filler Alloys

A literature search was undertaken to select commercially available brazing filler alloys with useful brazing temperatures less than 900°C, lap-shear strengths greater than 103 MPa (15 ksi), and good corrosion and oxidation resistance.

Only brazing alloys with useful brazing temperature ranges below 900°C were considered so that the effects of the brazing cycles on the base metal properties of the mill-annealed Ti-6Al-4V alloy would be minimized. The alpha-beta annealing temperature range for this alloy is 755° to 900°C. Design requirements for the Ti-6Al-4V base metal were 896 MPa (130 ksi) minimum tensile strength, 827 MPa (120 ksi) minimum yield strength, and 8 percent minimum elongation.

Two brazing filler alloys were selected for this project: Ag-5Al-0.5Mn (a Convair-developed alloy known as "Dynabrazo B") and Ag-9Pd-9Ga (a Wesco-developed alloy known as "Gapasil 9"). Both of these brazing alloys were found to be commercially available in both wire and strip forms from Western Gold and Platinum Company (Wesco). Solidus, liquidus, and recommended brazing temperatures for these alloys are given in Table 1.

A factor in the selection of the Ag-5Al-0.5Mn alloy was the extensive engineering data reported for this alloy.^{1,2,3} Joints with lap-shear strengths in the range of 138 to 207 MPa (20 to 30 ksi) have been produced in Ti-6Al-4V laminated structures using this brazing alloy. These joints are essentially unaffected by exposure to salt spray corrosion tests for 50 hours or to 425°C oxidation tests for 100 hours. Good fatigue life when cycled at 34 MPa (5 ksi) shear stress and good stress corrosion resistance with a threshold stress between 28 and 83 MPa (4 and 12 ksi) have been reported. Data on mechanical properties of beta-annealed Ti-6Al-4V alloy have shown that tensile and yield strengths were slightly decreased, while ductility and toughness were unaffected by a simulated brazing thermal cycle of 15 minutes at 900°C.

Table 1. Recommended Brazing Temperatures

Composition	Name	Solidus	Liquidus	Recommended Brazing Range
Ag-5Al-0.5Mn	Dynabrazo B	775°C	815°C	830° to 885°C*
Ag-9Pd-9Ga	Gapasil 9	845°C	880°C	880° to 920°C

*Brazing Range of 845° to 905°C has also been recommended.

The Ag-9Pd-9Ga alloy, recently developed by Wesco, was selected on the basis of the technical data given in the manufacturer's literature.⁴ An average shear strength of 179 MPa (26 ksi), excellent oxidation resistance up to 315°C, and excellent salt spray and salt stress corrosion resistance up to 425°C have been reported for braze joints in titanium alloys using this brazing alloy.

Cleaning Titanium Surfaces

Brazing titanium alloys requires that the surfaces of the parts be solvent cleaned and chemically deoxidized prior to brazing. Chlorinated solvents are not recommended. The following standard cleaning procedure^{5,6} was used to prepare test specimens for brazing and the interval between cleaning and brazing was limited to 24 hours maximum:

Solvent wipe with reagent grade acetone,

Immerse in reagent grade acetone for 30 seconds,

Blow dry with compressed air,

Immerse in 30 percent HNO₃ plus 3 percent HF solution for 2 minutes,

Rinse in tap water for 2 minutes,

Rinse in deionized water for 2 minutes,

Immerse in reagent grade acetone, and

Blow dry with compressed air.

Wetting Characteristics of Brazing Alloys

The wetting characteristics of both brazing alloys were determined using Ti-6Al-4V alloy test specimens with four different surface finishes: as-rolled, sanded-320 grit, machined-63 rms, and machined and sanded. Three brazing temperatures for each brazing alloy were evaluated. Wetting tests were made in both vacuum and partial-pressure argon atmospheres in both a laboratory vacuum brazing furnace and a production vacuum brazing furnace.

The wetting characteristics of both Ag-5Al-0.5Mn and Ag-9Pd-9Ga brazing alloys were found to depend primarily on brazing temperature and brazing furnace atmosphere. For brazing temperatures equal to or greater than 900°C, good wetting was obtained using either brazing alloy, irregardless of whether or not the titanium surfaces were oxidized. For brazing temperatures equal to or less than 885°C, good wetting was obtained only when the furnace atmosphere was adequate to prevent oxidization of the titanium surfaces during the brazing cycle. Vacuum brazing cycles resulted in less oxidation on the titanium surfaces than partial-pressure argon brazing cycles. The production brazing furnace with graphite heating belts produced more oxidation on the titanium surfaces than the laboratory brazing furnace with molybdenum heating elements. Use of titanium turnings or zirconium foil, as "getters," in both laboratory and production brazing furnaces proved to be very effective in preventing oxidation of the titanium surfaces during the brazing cycle and thereby promoting wetting (Figure 1). Different surface finishes (as-rolled, sanded, machined, and machined and sanded) on the titanium alloy specimens did not significantly affect the wetting characteristics of either brazing alloy, except that specimens with machined surfaces exhibited somewhat greater flow of the Ag-9Pd-9Ga brazing alloy in the direction parallel to the machining grooves (Figures 1 and 2).

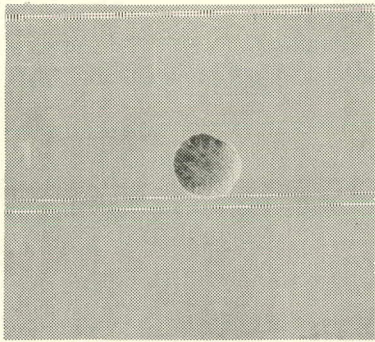
Lap-Shear Strength of Braze Joints

Joints with gaps of 0.05, 0.10, and 0.15 mm (0.002, 0.004, and 0.006 inch) were brazed at three temperatures within the recommended brazing range for each brazing alloy. In addition, some joints with zero gaps were made at selected brazing temperatures. The brazing was done in a production brazing furnace and titanium turnings were used as "a getter" in each furnace load. The following typical vacuum brazing cycle was used:

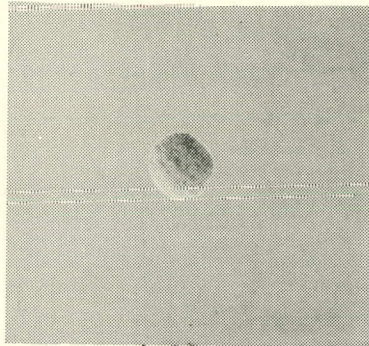
Evacuate to $<6.7 \text{ mPa}$ (5×10^{-5} torr),

Heat to 150°C,

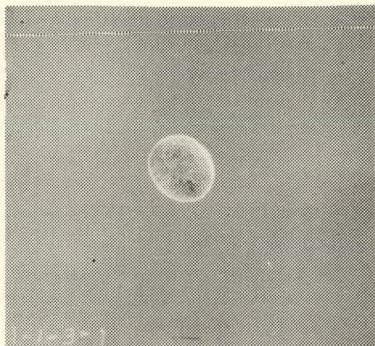
Backfill with argon,



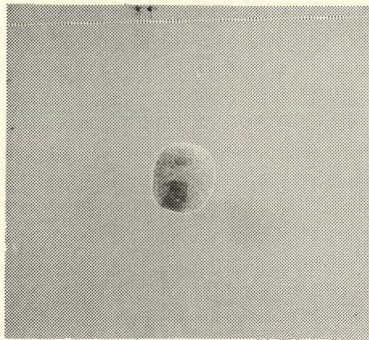
A. AS-ROLLED FINISH



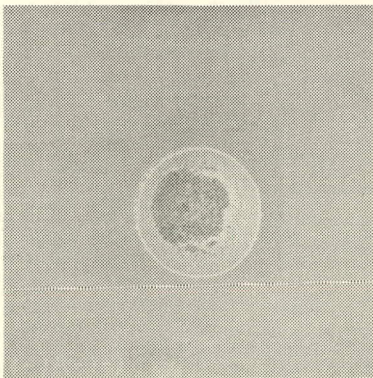
B. SANDED, 320 GRIT



C. MACHINED, 63 RMS

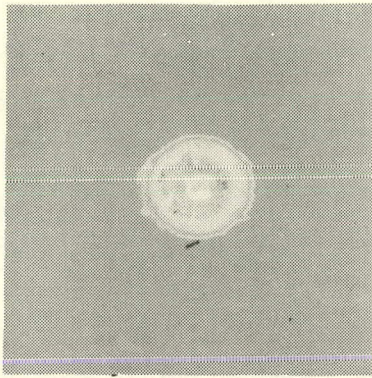


D. MACHINED AND SANDED

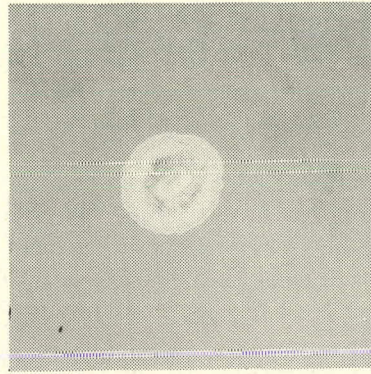


E. AS-ROLLED FINISH, USING Zr COVER

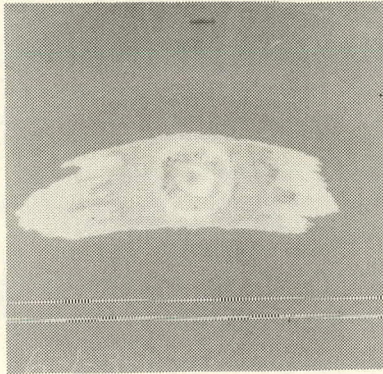
Figure 1. Wetting Characteristics of Ag-5Al-0.5Mn
Brazing Alloy (870°C Vacuum Brazing Cycle)



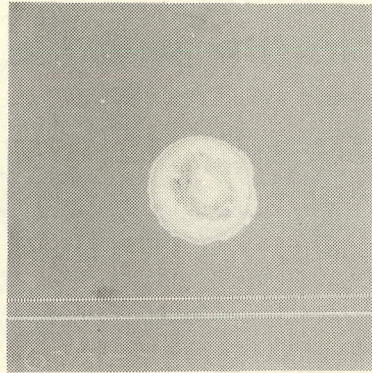
A. AS-ROLLED FINISH



B. SANDED, 320 GRIT



C. MACHINED, 63 RMS



D. MACHINED AND SANDED

Figure 2. Wetting Characteristics of Ag-9Pd-9Ga
Brazing Alloy (885°C Vacuum Brazing Cycle)

Evacuate to <6.7 mPa,

Heat to 705°C and hold at temperature for 30 minutes,

Heat to 870°C and hold at temperature for 15 minutes, and

Furnace cool under vacuum.

As shown in Figure 3, the braze joint consisted of a simple lap joint between two Ti-6Al-4V alloy panels, 3.2 by 28.6 by 127 mm (0.125 by 1.125 by 5 inches). The overlap was 6.4 to 7.9 mm (0.250 to 0.312 inch). Stainless steel shims were inserted in the overlap and gas-tungsten-arc tack welds were made along both sides of the joints to maintain the desired joint gap and alignment. Lap-shear test specimens (Figure 4) were machined from the braze joints and were tested in tension. Shear strengths of the braze joints were calculated and are reported in Table 2.

In general, braze joints made using Ag-5Al-0.5Mn filler alloy were stronger. Those joints which were brazed at 850° and 870°C with gaps of 0.05, 0.10, and 0.15 mm (0.002, 0.004, and 0.006 inch) were all visually acceptable and had shear strengths of 124 to 159 MPa (18 to 23 ksi). Joints brazed at 900°C with gaps of 0.10 and 0.15 mm (0.004 and 0.006 inch) had numerous voids and broke during machining, probably due to excessive alloying or insufficient braze alloy. Joints with zero gaps did not completely fill with braze alloy and either broke during machining or had low shear strengths.

Joints brazed with the Ag-9Pd-9Ga alloy had somewhat lower shear strengths. The shear strengths of all visually acceptable joints ranged between 96 and 152 MPa (14 and 22 ksi). For joints brazed at 890°C , the brazing alloy did not completely melt or flow adequately on all specimens. This was probably caused by temperature variations within the brazing furnace and because the brazing temperature was only 8°C above the liquidus of the braze alloy. Again, a joint with zero gap did not completely fill with braze alloy and had low shear strength.

Metallography of Braze Joints

Metallurgical cross sections were cut from both sides of each braze joint and were metallographically prepared and evaluated.

Sound braze joints were produced using the Ag-5Al-0.5Mn alloy at brazing temperatures of 850° and 870°C with joint gaps of 0.05, 0.10, and 0.15 mm (0.002, 0.004, and 0.006 inch). A typical cross section of these braze joints is shown in Figure 5. Only one alloy layer, approximately 0.005 to 0.013 mm (0.0002 to 0.0005 inch) thick, is evident between the silver-base brazing alloy and the titanium alloy base metal.

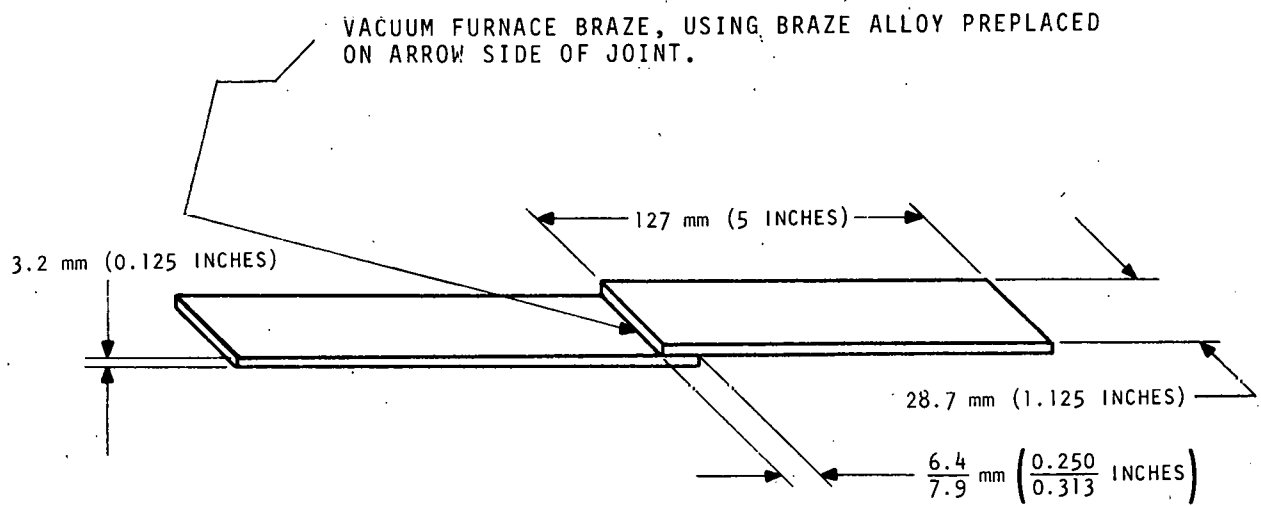
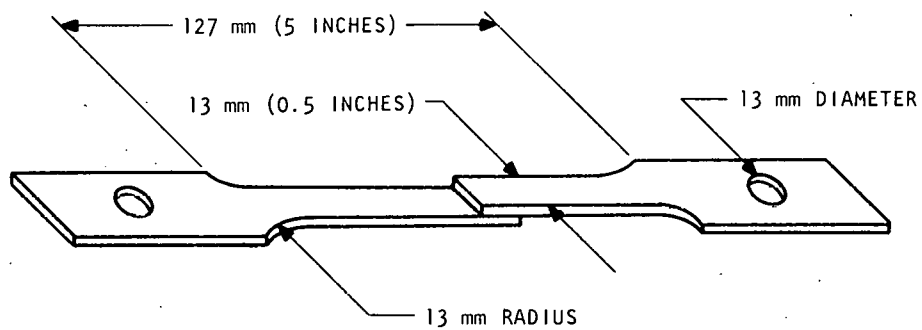


Figure 3. Braze Joint Design



(DIMENSIONS AND TOLERANCES PER AWS C 3.2 -- STANDARD METHOD FOR EVALUATING THE STRENGTH OF BRAZE JOINTS)

Figure 4. Shear Test Specimen

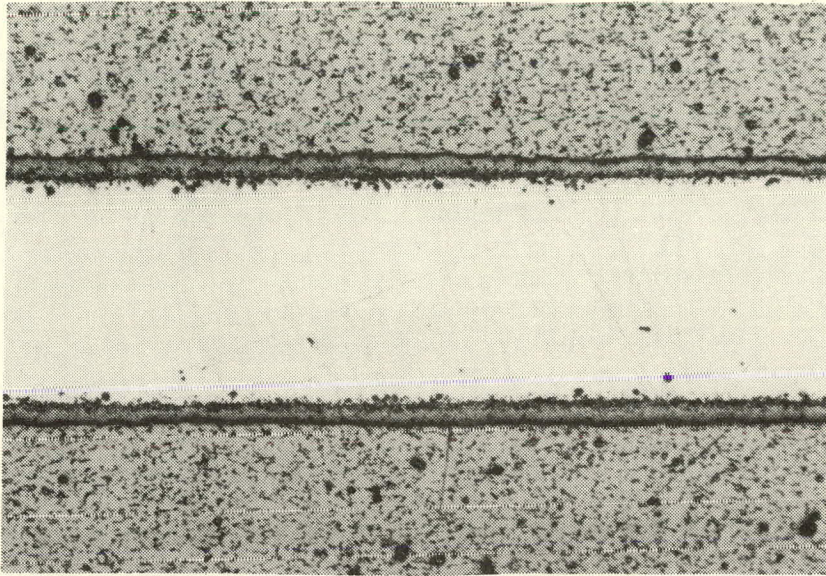
Table 2. Shear Strength of Braze Joints

Brazing Alloy	Brazing Cycle*	Joint Gap mm (Inches)	Shear Strength MPa (ksi)	Remarks
Ag-5Al-0.5Mn	850°C, 15 Minutes	0	**	80 Percent Unfilled Area***
Ag-5Al-0.5Mn	850°C, 15 Minutes	0.05 (0.002)	134 (19.4)	
Ag-5Al-0.5Mn	850°C, 15 Minutes	0.10 (0.004)	138 (20.0)	
Ag-5Al-0.5Mn	850°C, 15 Minutes	0.15 (0.006)	158 (22.9)	
Ag-5Al-0.5Mn	850°C, 28 Minutes	0.05 (0.002)	146 (21.2)	
Ag-5Al-0.5Mn	850°C, 28 Minutes	0.10 (0.004)	141 (20.5)	
Ag-5Al-0.5Mn	850°C, 28 Minutes	0.15 (0.006)	126 (18.3)	
Ag-5Al-0.5Mn	870°C, 15 Minutes	0.05 (0.002)	143 (20.8)	
Ag-5Al-0.5Mn	870°C, 15 Minutes	0.10 (0.004)	124 (18.0)	
Ag-5Al-0.5Mn	870°C, 15 Minutes	0.15 (0.006)	146 (21.2)	
Ag-5Al-0.5Mn	900°C, 15 Minutes	0	109 (15.8)	32 Percent Unfilled Area***
Ag-5Al-0.5Mn	900°C, 15 Minutes	0.05 (0.002)	126 (18.2)	
Ag-5Al-0.5Mn	900°C, 15 Minutes	0.10 (0.004)	**	Numerous small voids
Ag-5Al-0.5Mn	900°C, 15 Minutes	0.15 (0.006)	**	Numerous small voids
Ag-9Pa-9Ga	890°C, 15 Minutes	0	84 (12.2)	20 Percent Unfilled Area***
Ag-9Pa-9Ga	890°C, 15 Minutes	0.05 (0.002)	151 (21.9)	
Ag-9Pa-9Ga	890°C, 15 Minutes	0.10 (0.004)	123 (17.8)	
Ag-9Pa-9Ga	890°C, 15 Minutes	0.15 (0.006)	67 (9.7)	38 Percent Unfilled Area***
Ag-9Pa-9Ga	900°C, 15 Minutes	0.05 (0.002)	**	
Ag-9Pa-9Ga	900°C, 15 Minutes	0.10 (0.004)	131 (19.0)	
Ag-9Pa-9Ga	900°C, 15 Minutes	0.15 (0.006)	119 (17.3)	
Ag-9Pa-9Ga	915°C, 20 Minutes	0.05 (0.002)	101 (14.7)	
Ag-9Pa-9Ga	915°C, 20 Minutes	0.10 (0.004)	97 (14.0)	
Ag-9Pa-9Ga	915°C, 20 Minutes	0.15 (0.006)	105 (15.2)	

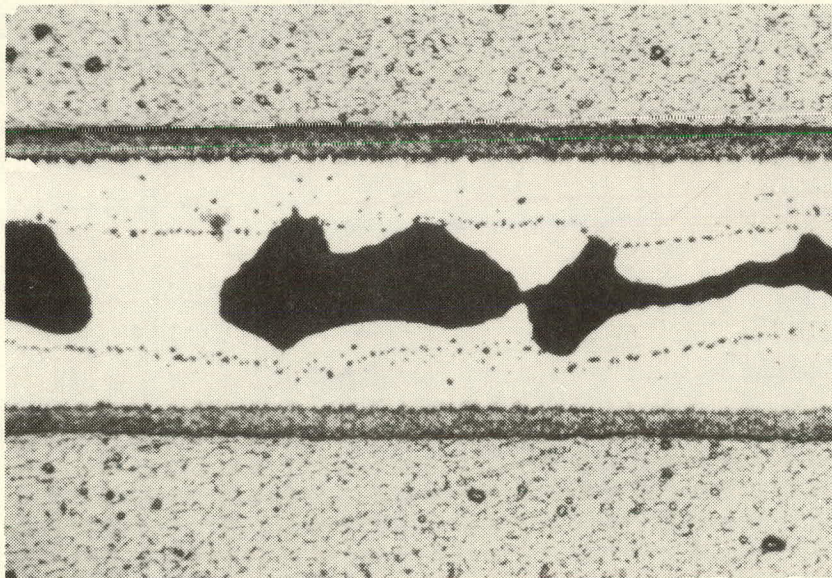
*Brazing cycles included preheating at 705°C for 30 minutes before brazing at the indicated temperature.

**Joints broke during machining.

***These braze joints were rejected by visual inspection.



850° AND 870°C BRAZING TEMPERATURES (200X)



900°C BRAZING TEMPERATURE (200X)

Figure 5. Cross Sections of Joints Brazed With Ag-5Al-0.5Mn Alloy

Joints brazed at 900°C with Ag-5Al-0.5Mn alloy had numerous voids (Figure 5). For this higher brazing temperature, the alloy layer was 0.020 to 0.023 mm (0.0008 to 0.0009 inch) thick.

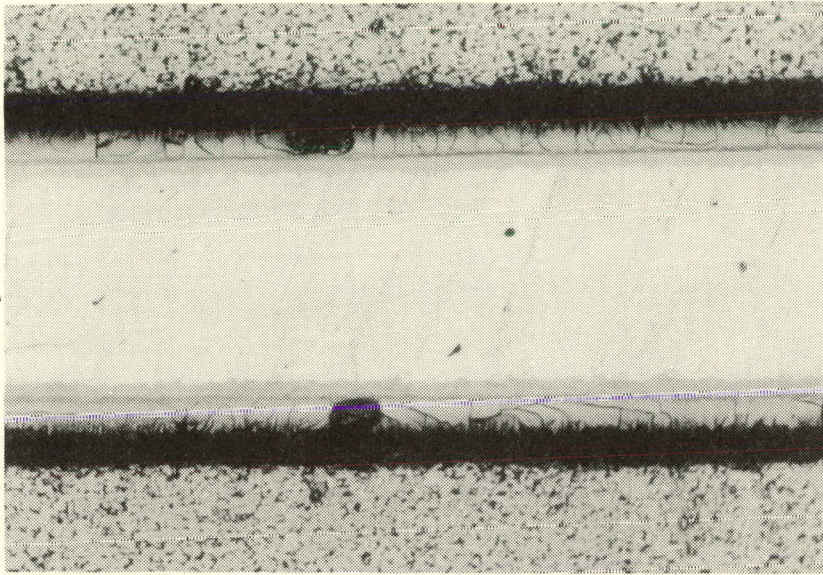
Microcracks were detected in most joints brazed with the Ag-9Pd-9Ga brazing alloy at 900°C and 915°C, as shown in Figure 6. The cross section shows three or four alloy layers between the silver-base brazing alloy and the titanium base metal. The total thickness of the alloy layers ranged from 0.041 to 0.051 mm (0.0016 to 0.0020 inch).

Effects of Brazing Cycles on Base Metal Properties

Tensile and bend properties of the annealed Ti-6Al-4V base metal were determined after exposure to various brazing cycles. These properties were determined on both bare and braze alloy coated specimens. Tensile tests were conducted in accordance with ASTM E8 using standard 13 mm (0.5 inch) wide sheet-type specimens. The bend test consisted of bending specimens, 1.6 by 28.6 by 82.6 mm (0.062 by 1.125 by 3.25 inches), at room temperature through 180 degrees around a radius equal to 4.5 times the nominal thickness, with the axis of bend parallel to the direction of rolling. After bending, the specimens were examined at 20X magnification for evidence of cracking or tearing.

Tensile properties of the base metal after exposure to various brazing cycles are given in Table 3. The effect of brazing temperature on tensile properties of the base-metal is illustrated in Figure 7. Tensile strengths were reduced approximately 4 percent at the lowest brazing temperature and approximately 6.5 percent at the highest brazing temperature. Yield strengths were reduced approximately 5 percent at the lowest brazing temperature and approximately 9 percent at the highest brazing temperature. Elongations were not significantly changed. For the lower brazing temperatures of 850° and 870°C, at which the strongest braze joints were produced, tensile strengths were reduced approximately 4 to 5 percent and yield strengths were reduced approximately 5 to 7 percent. Even though tensile and yield strengths were reduced slightly by exposure to these brazing cycles, the Ti-6Al-4V base-metal met design criteria of 896 MPa (130 ksi) minimum tensile strength, 827 MPa (120 ksi) minimum yield strength, and 8 percent minimum elongation (Figure 7).

The data in Table 3 show that braze alloy coatings did not degrade the tensile properties of the titanium base metal. Tensile specimens coated with braze alloy on one side were as strong or stronger than the uncoated specimens for any given brazing cycle.



900° and 915°C BRAZING TEMPERATURE (200X)

Figure 6. Cross Section of Joint Brazed With Ag-9Pd-9Ga Alloy

Bend properties of the mill-annealed Ti-6Al-4V base metal were not adversely affected by exposure to various brazing thermal cycles, except when the titanium surfaces were oxidized during the brazing cycle. Even a light oxide (gray discolorization) on the titanium surfaces caused bend test failures due to microcracks.

Specimens coated with the Ag-5Al-0.5Mn braze alloy passed the bend test; whereas, specimens coated with the Ag-9Pd-9Ga braze alloy failed the bend tests due to microcracks in the braze alloy coatings.

Nondestructive Testing of Braze Joints

All braze joints were nondestructively tested using both ultrasonic and radiographic inspection techniques. The results were correlated with shear strength and fracture analysis data.

Ultrasonic inspection showed clear indications of voids and porous areas in the braze joints. However, false indications of poor bonds were obtained for some braze joints which had high shear strengths and did not exhibit defects on fracture surfaces. Improved ultrasonic inspection equipment has been purchased and will be available for future evaluation.

Table 3. Tensile Properties of Ti-6Al-4V Alloy Mill-Annealed Sheet After Exposure to Various Brazing Cycles

Brazing Alloy*	Brazing Cycle**	Tensile Strength MPa (ksi)	Yield Strength 0.2% Offset MPa (ksi)	Elongation in 50.8 mm (Percent)
None	None	961 (139.4)	899 (130.4)	15.0
None	None	975 (141.4)	926 (134.3)	14.5
None	850°C, 15 Minutes	931 (135.0)	868 (125.9)	11.5†
None	850°C, 28 Minutes***	926 (134.3)	856 (124.1)	13.0
None	870°C, 15 Minutes	923 (133.9)	851 (123.4)	13.5
None	900°C, 15 Minutes	914 (132.5)	848 (123.0)	13.0
None	890°C, 15 Minutes	921 (133.6)	852 (123.5)	13.5
None	900°C, 15 Minutes	917 (133.0)	848 (123.0)	13.5
None	915°C, 20 Minutes	908 (131.7)	828 (120.1)	13.0
Ag-5Al-0.5Mn	850°C, 15 Minutes	936 (135.8)	871 (126.3)	15.5
Ag-5Al-0.5Mn	850°C, 28 Minutes***	936 (135.7)	863 (125.1)	11.0††
Ag-5Al-0.5Mn	870°C, 15 Minutes	947 (137.4)	883 (128.1)	10.0††
Ag-5Al-0.5Mn	900°C, 15 Minutes	935 (135.6)	861 (124.9)	12.5††
Ag-9Pd-9Ga	890°C, 15 Minutes	938 (136.1)	863 (125.2)	12.0††
Ag-9Pd-9Ga	900°C, 15 Minutes	935 (135.6)	859 (124.6)	11.0††
Ag-9Pd-9Ga	915°C, 20 Minutes	925 (134.1)	831 (120.6)	13.5†††

The Ti-6Al-4V alloy was purchased according to AMS 4911C: 924 MPa (134 ksi) minimum tensile strength, 869 MPa (126 ksi) minimum yield strength, and 8 percent minimum elongation.

*Braze alloy melted on one side of specimens during exposure to brazing cycle.

**Brazing cycles included preheating at 705°C for 30 minutes before heating to the indicated brazing temperature.

***Heating rate and total time above 760°C, recommended by Key, Burnett, and Inouye.²

†Specimen broke near one of the gage marks.

††Specimen broke near one of the gage marks and also outside the braze alloy coated area.

†††Specimen broke outside of the braze alloy coated area.

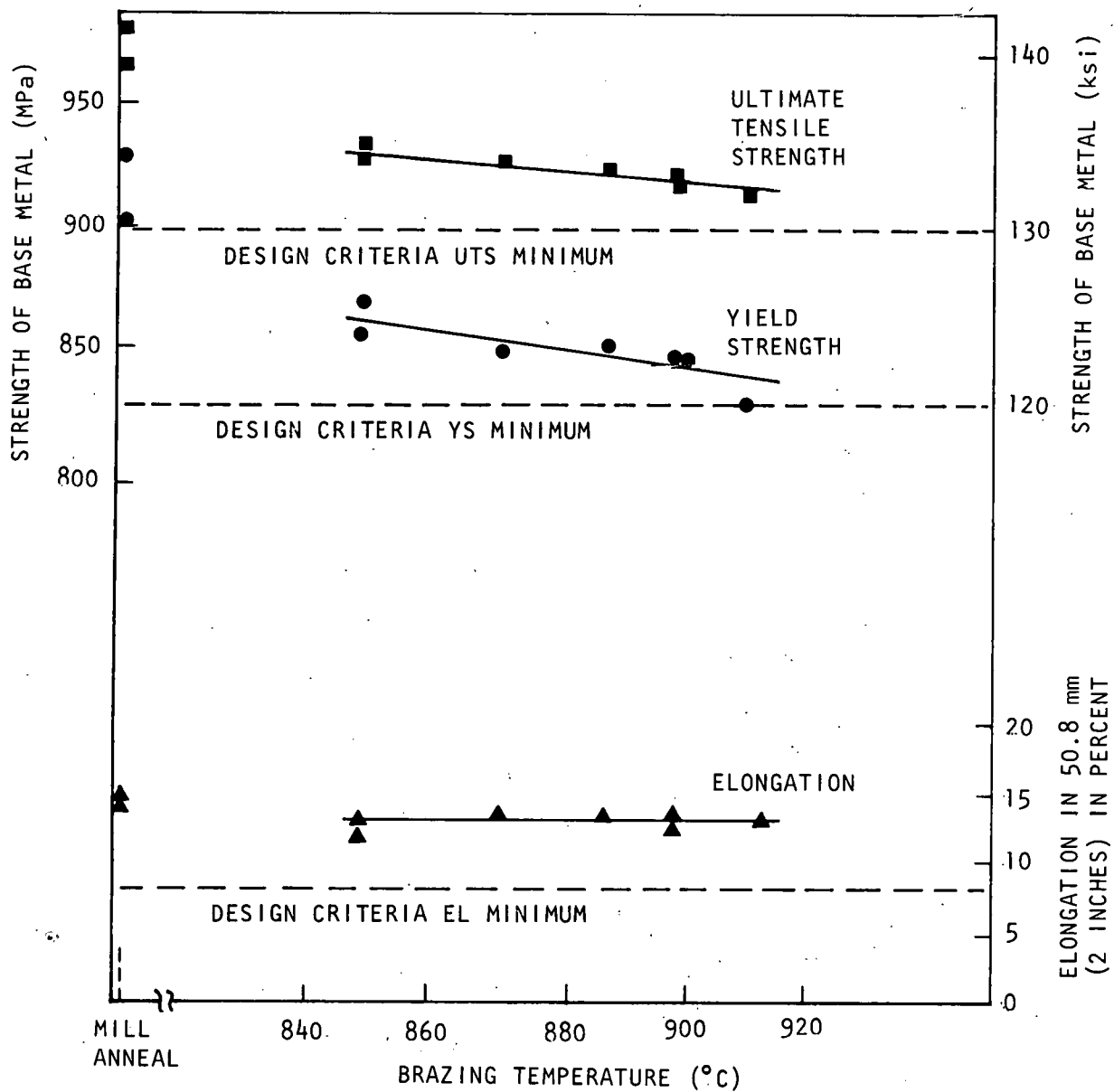


Figure 7. Tensile Properties of Ti-6Al-4V Base-Metal Versus Brazing Temperature

Radiography interpreted by reading of X-ray film did not clearly show all defects. However, when the radiographs were interpreted by using an V-P8 Image Analyzer (Interpretation Systems Incorporated), clear indications of voids and porous areas in joints with gaps of 0.05 mm (0.002 inch) and greater were obtained (Figure 8). The primary functions of the image analyzer were to magnify the radiographs and to contrast areas which had only slightly different X-ray densities.

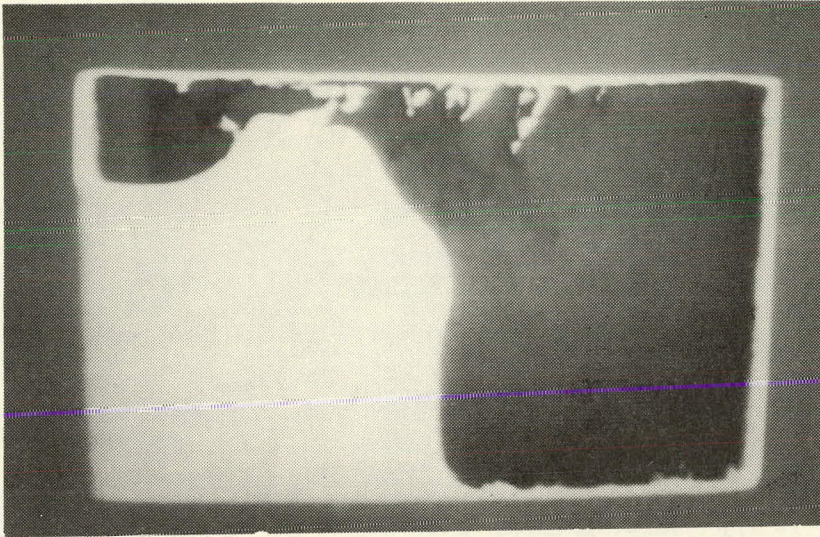
ACCOMPLISHMENTS

A vacuum furnace brazing process, developed for joining titanium alloy Ti-6Al-4V structures, was shown to produce sound, strong braze joints. The brazing process includes: using Ag-5Al-0.5Mn braze alloy, controlling brazing temperature between 850° and 870°C, and fixturing to control joint gap spacing between 0.05 and 0.15 mm (0.002 and 0.006 inch). Use of titanium turnings as a "getter" in the brazing furnace proved to be very effective in preventing oxidation of the titanium surfaces during the brazing cycle.

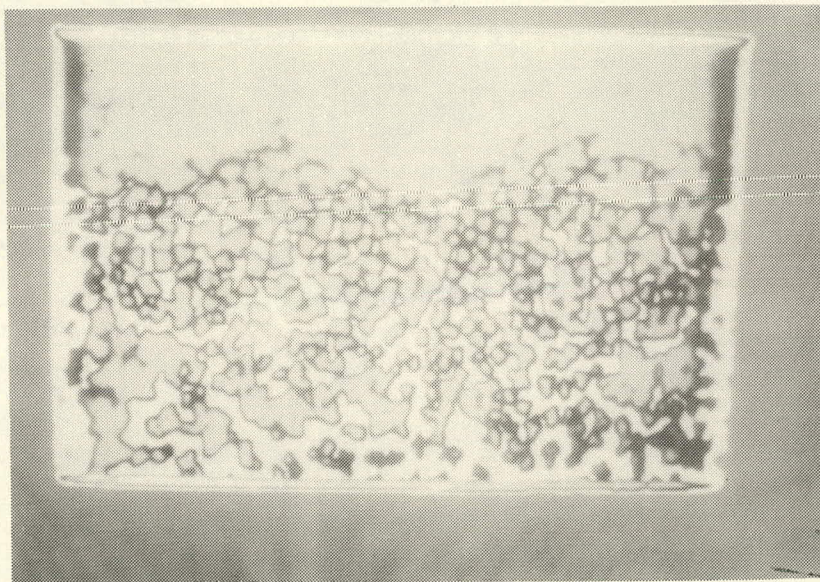
A nondestructive test method was established to detect defects in the braze joints. Radiographs were interpreted using an image analyzer and showed clear indications of voids and porous areas in braze joints with gaps of 0.05 mm (0.002 inch) and greater.

FUTURE WORK

Future work on brazing of titanium is planned to be done under process development project *Titanium Fabrication*. This vacuum brazing process will be applied to joining of Ti-6Al-4V alloy structures. Fixturing will be evaluated to minimize distortion. Mechanical and corrosion properties of the brazed joints will be determined.



LARGE VOID AREA, LIGHT AREA (7X)



POUROUS AREAS, LIGHT AREAS (7X)

Figure 8. Image Analyzer Representations of Braze Joint Radiographs

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⁴"Gapasil 9, A Brazing Filler Metal for Joining Titanium and Its Alloys," Western Gold and Platinum Company, *Technical Bulletin*, January, 1975.

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