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DIFFUSION BRAZING OF ALUMINUM ALLOYS

METALS AND PROCESSING BRANCH
METALS AND CERAMICS DIVISION

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AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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The diffusion brazing of butt joints in 6061 and 7075 aluminum alloys in a vacuum atmosphere with mechanical pressure perpendicular to the joint was investigated. Filler metals included silver, gold, copper, magnesium, zinc, Al12Si and Ag28Cu in the form of foil, powder, electroplated deposits, and vapor deposits. Joints were examined by metallography, bend tests, tensile tests, and other mechanical tests. No successful filler metal for 7075 aluminum was developed. Both silver and Al12Si filler metal in foil form produced joints

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in 6061 aluminum with the tensile strength of the base metal in the T6 condition. The tensile elongation and bend ductility was good in both as-brazed and T6 conditions.

FOREWORD

This report was prepared by Dr. G. Metzger, Metals and Processing Branch, Metals and Ceramics Division, Air Force Materials Laboratory (LLM), Wright-Patterson Air Force Base, Ohio. The research was performed under Project No. 7351, "Metallic Materials for Air Force Weapon System Components," Task No. 735102, "Welding and Brazing," Subtask No. 73510221, "Welding of Aerospace Materials."

The report covers work performed during the period January 1970 through December 1974.

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The author wishes to express his appreciation to Robert Leese, University of Dayton, for conducting the brazing experiments and associated tasks.

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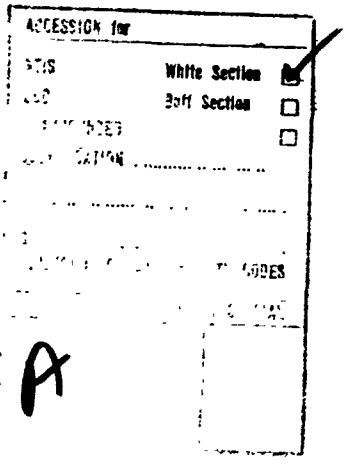

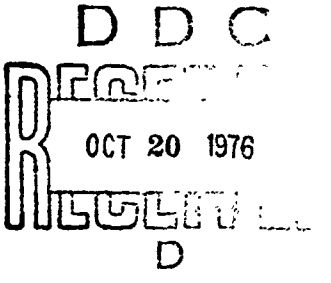

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SUMMARY

The brazing of 6061 and 7075 aluminum alloy butt joints in a vacuum atmosphere with mechanical pressure perpendicular to the faying surfaces was investigated. The diffusion brazing process was emphasized. In this process, interdiffusion of the base metal and a filler metal of a higher melting point than the brazing temperature form an alloy that melts at the brazing temperature.

The brazing of small sheet specimens at low pressures of 28 kPa (4 psi) to 1380 kPa (200 psi) indicated a number of filler metals which exhibited good wetting and flow; including Ag, Au, Cu, and Al12Si on 6061, Ag28Cu on 7075, and Mg and Zn on both 6061 and 7075. Indium and InZn alloys were poor on both base metals.

A simple test (consisting of splitting open small specimens) and a metallographic examination eliminated Au, Cu, Mg, and Ag28Cu as acceptable filler metals due to brittle behavior. Postbraze diffusion treatment did not significantly improve the results.

Filler metal in foil form proved to be superior to other filler metal forms such as: powder, electroplated deposits, and deposits from a metal vapor in a vacuum.

No successful filler metal for 7075 aluminum was developed.

Specimens of 6061 aluminum, brazed as butt joints with 8 μm Ag or 75 μm Al12Si filler metal at a pressure of 26 MPa (3.8 ksi), had a tensile strength equal to annealed base metal when in the as-brazed condition and equal to the base metal T6 condition when postbraze heat treated to the same condition. The tensile elongation and bend ductility in both as-brazed and T6 conditions was good.

The brazing temperature was 575°C for the Ag filler metal and 595°C for Al12Si filler metal.

SECTION I

INTRODUCTION

The present work is an outgrowth of an investigation to develop methods for the joining of aluminum-matrix fiber-reinforced composite materials. Brazing in vacuum was selected as a process which might be suitable for this purpose. As the major matrix material for the aluminum/boron composite, 6061 aluminum alloy was selected as one base material and 7075 aluminum alloy was added in an attempt to develop a brazing method for this important aircraft material.

Since most of the filler metals chosen for this investigation have a melting point near or above that of the base metal, the emphasis is on diffusion brazing. Conventional brazing uses a filler metal which melts below the brazing temperature and any diffusion which occurs is only incidental to the process. However, in diffusion brazing, inter-diffusion of base metal and filler metal is essential in order to form an alloy which will melt at the brazing temperature. In this process, preplacement of filler metal at the faying surfaces and pressure perpendicular to the joint is necessary.

SECTION II

BRAZING FURNACE AND BRAZING CONDITIONS

The brazing experiments were performed in the cold-wall vacuum furnace shown in Figure 1. The specimens are heated by radiation from resistance-heated molybdenum rods. Load may be applied to the specimen placed between the upper and the bottom platens through a hydraulically operated upper push rod sealed with an extension bellows. Not shown in Figure 1 are two hydraulic gages, one low range and one high range, for indicating ram load. High loads are applied through the hydraulic ram and low loads by dead weight.

Furnace temperature is controlled by a thermocouple output to a current-adjusting-type controller. This thermocouple is inserted into a hole drilled in the bottom platen. The output of a second thermocouple, located in or near the braze specimen is continuously recorded on a six-channel instrument. The specific location of this second thermocouple depends on the joining procedure and is given later in the description of each procedure. A third thermocouple was sometimes used to continuously record the temperature of the bottom platen.

The furnace has a nominal upper limit capability of 1200°C temperature, 44.5 kN (10,000 lb) load, 133 μPa (1×10^{-6} Torr) vacuum, and a working space of 30 cm (1 ft.) high by 30 cm (1 ft.) in diameter.

The brazing conditions were one hour in a vacuum of better than 1.33 mPa (1×10^{-5} Torr).

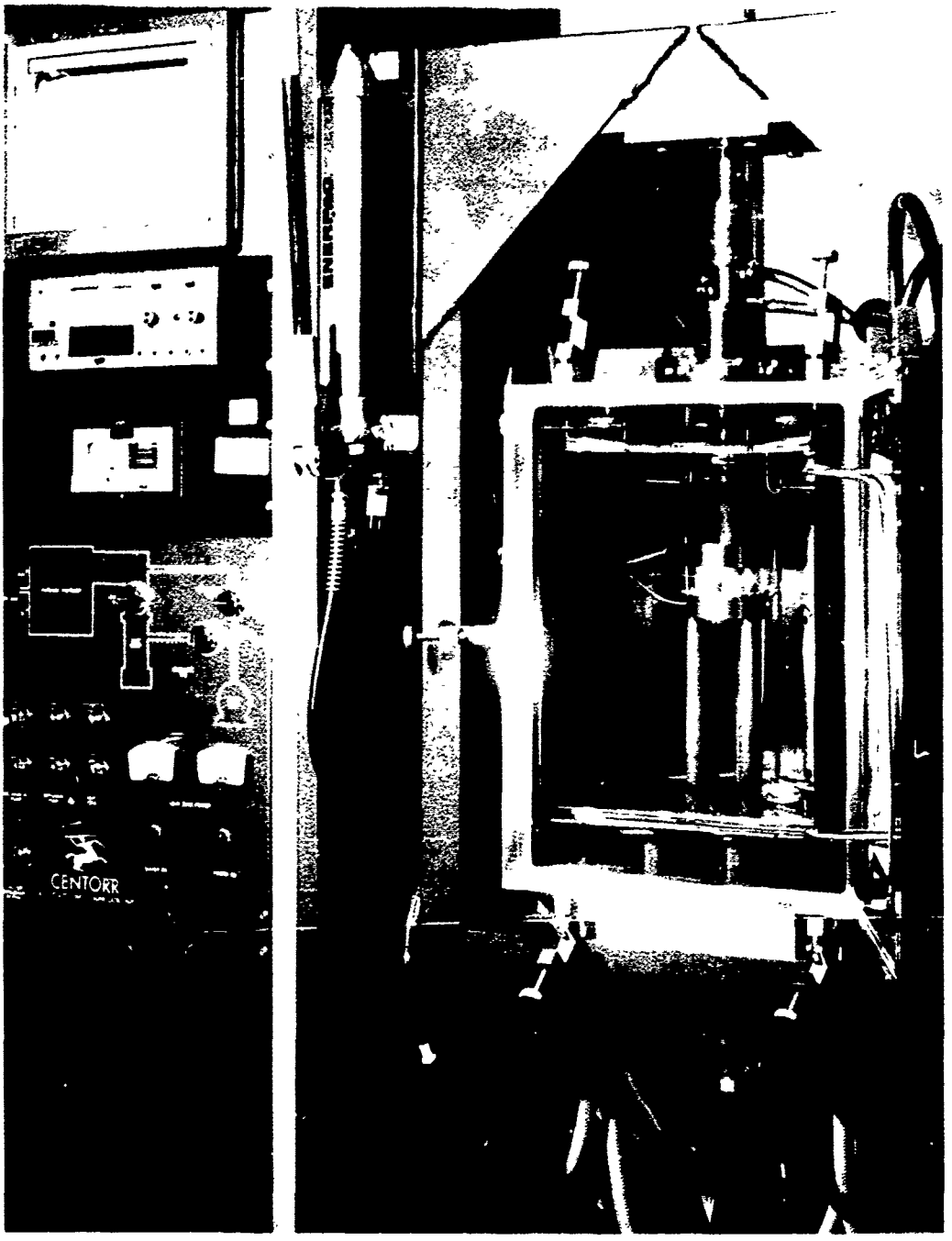

Figure 1. Brazing Furnace

SECTION III

BASE METALS

Base metals include 6061 and 7075 aluminum alloys in the form of 3.2 mm (0.125 in.) thick rolled sheet and 25.4 mm (1 in.) diameter extruded rod.

SECTION IV

FILLER METALS

The primary consideration in the selection of filler metals was their ability to form aluminum alloys with melting points lower than those of the base metals. Filler metals were in the form of rolled foil, powder, electroplated deposits, or deposits from a metal vapor in a vacuum.

The latter two filler-metal forms were deposited in equal thicknesses on both faying surfaces and the given filler-metal thickness represents the sum of the two deposits. Filler metals of more than one element were electroplated as multiple, alternate layers of the alloy components, but vacuum coating was done by direct deposition of the desired alloy. The surface preparation of base metals before coating by electroplating or vapor deposition was not controlled. Powder filler metals of more than one element were made by mechanically mixing the appropriate powdered elements.

Pertinent data on metals and alloys of interest to this investigation are given in Table 1. The solution temperature given for 7075 aluminum is the highest of temperatures recommended for the various wrought forms.

TABLE 1

SIGNIFICANT TEMPERATURES FOR METALS AND ALLOYS OF INTEREST

Metal or Alloy	Eutectic Comp. w/o	Temperature °C			
		Liquidus	Solidus	Solution	Braze
6061		649	582	530	590[a]
7075		638	476	490	
		Melting			
Ag		961			
Al		660			
Au		1063			
Cu		1083			
Mg		650			
Si		1410			
Zn		419			
In		156			
Ag/Al	70/30	566			
Ag/Cu	72/28	779			
Ag/Mg	48/52	471			
Al/Au	4/96	525			
Al/Cu	67/33	548			
Al/Mg	32/68	437			
Al/Si	88/12	577			
Au/Mg	38/62	576			
Au/Si	94/6	370			
Cu/Mg	31/69	485			

a. Filler metal A&12Si.

SECTION V

FILLER METAL WETTING AND FLOW

The first experiments were made with two 25.4 mm (1 in.) square pieces of 3.2 mm (1/8 in.) aluminum alloy sheet placed together under low mechanical pressure with an intermediate filler metal, to produce a brazed joint area of 25.4 mm by 25.4 mm (1 in. x 1 in.). Specimen temperature was recorded from a thermocouple inserted into a hole in a dummy square placed above or below the joint or joints being brazed. Oxidized stainless steel foil inserted between the dummy square and the braze specimen and between specimens, when more than one specimen was brazed in a vertical stack, prevented diffusion welding of specimens to each other. Surface preparation of the base metals consisted of an acid etch, followed by a water rinse and an alcohol rinse; except that the electroplated and vapor deposited specimens were brazed in either the as-coated condition or were cleaned with an alcohol rinse only. The etching solution was 38 v/o HNO_3, 12 v/o HF, and 50 v/o water for 6061 aluminum and 17 w/o H_2SO_4, 3 w/o CrO_3, and 80 w/o water for 7075 aluminum.

Preliminary evaluation of the brazed specimens consisted of visual examination to determine the extent of braze alloy flow at the joint periphery. This was followed by metallographic examination f a joint cross section and by simple qualitative mechanical tests, where this was justified by the results of the preliminary evaluation.

Brazing conditions and the results of the visual examination are shown in Table 2 for 6061 aluminum and in Table 3 for 7075 aluminum.

Several filler metals, including Ag, Au, Cu, Mg, Zn, and A&12Si demonstrated good wetting and flow on 6061 aluminum, but In or InZn alloys were not satisfactory. The results with electroplated and vapor-deposited filler metals were consistent with the foil results, except for the vapor-deposited Ag, which should have exhibited good wetting and flow at a thickness of 20 μm.

TABLE 2

WETTING EXPERIMENTS, 6061 ALUMINUM

Brazing Conditions						
Filler Metal						
Comp. w/o	Form	Thick. µm	Temp. °C	Pressure kPa	Pressure psi	Flow[a]
Ag	Foil	25	575	28	4	Excellent
	Foil	25	575	1380	200	Excellent
	Electro.[b]	1	575	1380	200	Poor
	Electro.	18	575	1380	200	Good
	Electro.	34	575	1380	200	Excellent
	Electro.	58	575	1380	200	Excellent
	Vapor[c]	2, 10 and 20	575	1380	200	Poor
Au	Foil	50	575	28	4	Excellent
Cu	Foil	12, 25 and 50	560	1380	200	Excellent
	Vapor	2	560	1380	200	Good
	Vapor	6	560	1380	200	Excellent
	Vapor	17	560	1380	200	Excellent
Mg	Foil	25 and 125	450	1380	200	Excellent
Zn	Foil	100	575	28	4	Excellent
In	Foil	50	575	28	4	Poor
In25Zn	Foil	50	575	28	4	Poor
In50Zn	Foil	100	575	28	4	Fair
In50Zn	Foil	50	360	28	4	Poor
Al12Si	Foil	75	595	28	4	Excellent

a. See text for further description.
b. Electroplated deposit.
c. Deposited from metal vapor in vacuum.

TABLE 3

WETTING EXPERIMENTS, 7075 ALUMINUM

Brazing Conditions						
Filler Metal						
Comp. w/o	Form	Thick. μm	Temp. °C	Pressure MPa	Pressure psi	Flow[a]
Mg	Foil	25,125	450	1.38	200	Good
		25	490	1.38	200	Good
	Vapor[b]	2, 10	490	1.38	200	Good
		2, 10	490	6.89	1000	Good
Ag28Cu	Foil	100	490	1.38	200	Erratic[d]
		100	490	6.89	1000	Erratic[d]
	Powder	2,12,25	490	0.07	10	Erratic[d]
		100	490	1.38	200	Erratic[d]
	Electro.[c]	1,2,3	490	1.38	200	Excellent
	Vapor	2	490	1.38	200	Good
		10, 20	490	1.38	200	Excellent
Ag26Cu5Zn	Powder	12	490	1.38	200	Excellent
		50	490	1.38	200	Poor
Ag25Cu10Zn	Powder	12	490	1.38	200	Good
		50	490	1.38	200	Fair
Ag26Cu5Mg	Powder	12	490	1.38	200	Good
		50	490	1.38	200	Good
Ag25Cu10Mg	Powder	12	490	1.38	200	Poor
		50	490	1.38	200	Excellent
Ag26Cu5Au	Powder	12	490	1.38	200	Good
		50	490	1.38	200	Poor
Ag25Cu10Au	Powder	12	490	1.38	200	Good
		50	490	1.38	200	Poor
Ag26Cu5Si	Powder	12	490	1.38	200	Excellent
		50	490	1.38	200	Poor
Ag25Cu10Si	Powder	12	490	1.38	200	Excellent
		50	490	1.38	200	Poor

TABLE 3 (CONT'D)

WETTING EXPERIMENTS, 7075 ALUMINUM

Brazing Conditions						
Filler Metal						
Comp. w/o	Form	Thick. μm	Temp. °C	Pressure MPa	Pressure psi	Flow[a]
Zn	Foil	100	400	0.03	4	Excellent
In50Zn	Foil	100	400	0.03	4	Poor
In25Zn	Foil	50	400	0.03	4	Poor

a. See text for further description.

b. Deposited from metal vapor in vacuum.

c. Electroplated deposit.

d. Varied from poor to excellent.

The wetting and flow on 7075 aluminum was much less successful, with only Mg and Zn showing consistent good results, with one exception. A specimen with vapor deposited Mg filler metal, reputed to be of 10 μm thickness, did not exhibit flow at the joint periphery; however, later metallographic examination indicated that insufficient Mg to form a brazed joint was actually present. The inZn alloys were poor and the AgCu-base alloys were erratic, with the alloys in powder form often showing better wetting and flow at the lesser filler metal thicknesses.

SECTION VI

POSTBRAZE DIFFUSION TREATMENT

Selected specimens from the wetting and flow experiments were cut into smaller squares and subjected to the time-temperature conditions given in Table 4 to investigate the feasibility of improving joint properties by diffusion of elements forming intermetallic compounds or other detrimental phases at the braze into the adjacent base metal. The diffusion treatment was carried out in an air atmosphere at all combinations of time and temperature shown in the table.

The brazing conditions for the diffusion treated specimens are given in Tables 2 and 3. For the first two items of Table 2, only those specimens brazed at 28 kPa (4 psi) were diffusion treated. For the first item of Table 3, specimens brazed at both 450° and 490°C were diffusion treated.

Evaluation consisted of metallographic examination and, in a few cases, simple qualitative mechanical tests, as described in Section VII.1, were made.

Some of the bend specimens (Section VII.3) were also diffusion treated, as described previously.

TABLE 4

POSTBRAZE DIFFUSION TREATMENT

Base Metal	Filler Metal Comp. w/o	Form	Thick. μm	Diffusion Conditions Temp.°C	Time Hours
6061	Ag	Foil	25	300,400,500	10,100,1000
		Vapor[a]	2,10,20	400,500	100
	Au	Foil	50	300,400,500	10,100,1000
	Cu	Foil	12,25,50	400,500	100,1000
		Vapor	2,6,17	400,500	100
	Al12Si	Foil	75	300,400,500	10,100,1000
7075	Mg	Foil	25 25	400 420,440, 460,480	10,100,1000 100
		Vapor	2, 10	450	100
	Ag28Cu	Vapor	2,10,20	500	100
	Zn	Foil	100	300,400,500	10,100,1000

a. Deposited from metal vapor in vacuum.

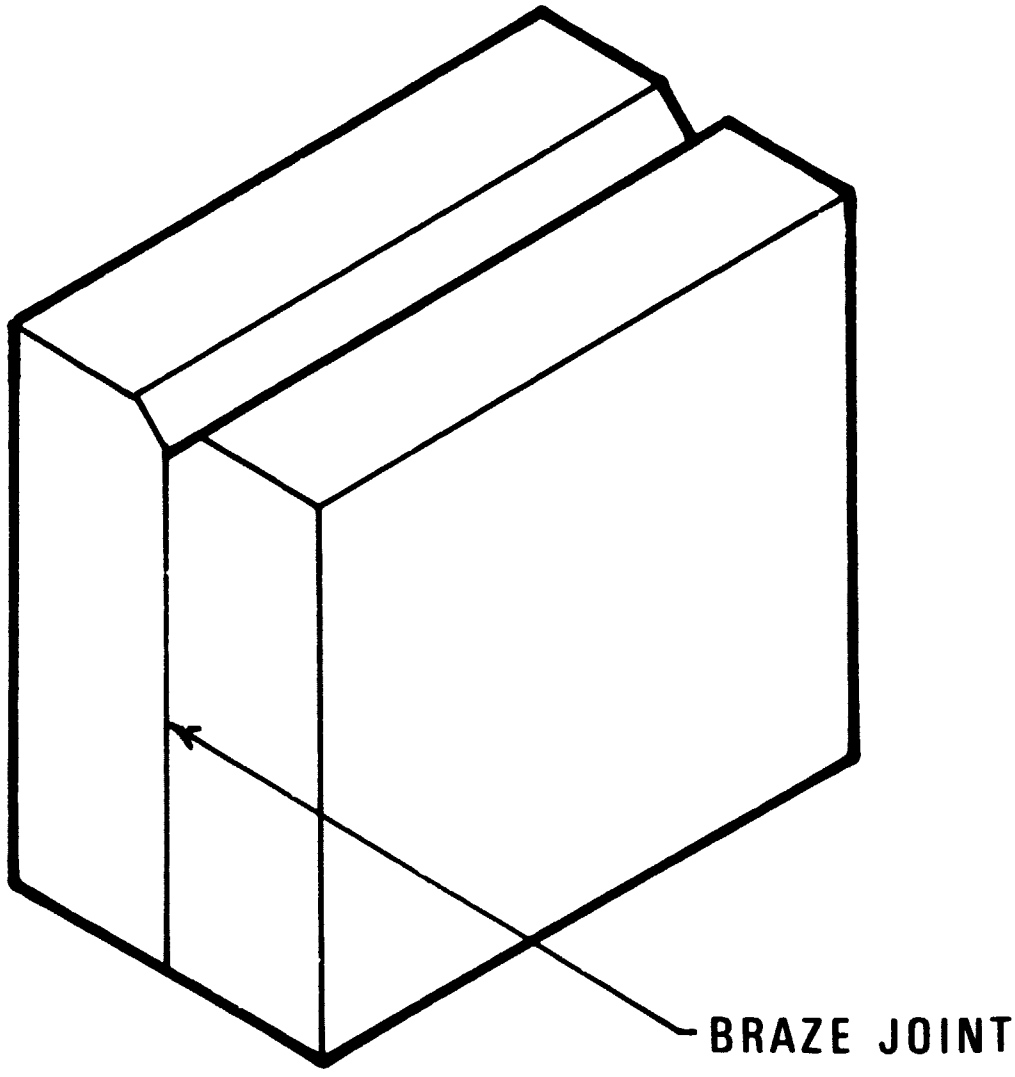

Figure 2. Specimen for Wedge Test

TABLE 5

WEDGE TEST RESULTS OF BRAZED JOINTS

1.38 MPa (200 PSI) BRAZING PRESSURE

Base Metal	Filler Metal Comp. w/o	Filler Metal Form	Filler Metal Thick. µm	Postbraze Heat Treat	Wedge Test[a] Ductility	Wedge Test[a] Strength
6061	Ag	Foil	25	None	High	High
				T6	Low	High
	Ag	Electro.[b]	1	None	High	High
				T6	Low	Low
	Ag	Electro.	18	None	High	High
				T6	Low	High
	Ag	Electro.	34	None	Low	High
				T6	Low	High
	Ag	Electro.	58	None	High	High
				T6	Low	High
	Cu	Foil	12,25,50	None	Low	Fair
				T6	Low	Low
	Mg	Foil	25, 125	None	Low	Low
				T6	Low	Low
7075	Mg	Foil	25	None	Low	Low
				T6	Low	Low
	Mg[c]	Foil	25	None	Low	Low
				T6	Low	Low
	Ag28Cu	Electro.	1,2,3	None	Low	Low
				T6	Low	Low

a. See text for description.
b. Electroplated deposit.
c. Specimens were diffusion treated at 400°C for times of 10, 100, and 1000 hours after brazing.

SECTION VII

MECHANICAL TESTING

1. WEDGE TEST

The first type of mechanical test specimen was made by cutting the previously described 25.4 mm (1 in.) square brazed specimens into smaller square pieces and filing a small notch at the braze joint along one side of the specimen, as shown in Figure 2. Testing was done with a hammer and double-bevel wedge chisel, placed at the filed notch. Evaluation of the results was by observing whether the specimen failed in a brittle or ductile manner and the relative amount of force needed to break open the joint. The results of this wedge test are presented in Table 5.

Silver foil was the only filler metal which showed promising results, with the exception of the low ductility in the T6 condition. Electroplated Ag yielded inconclusive results. The remaining filler metals, Cu, Mg, and Ag28Cu all produced brazes with both low ductility and low strength in both the as-brazed and the T6 condition.

Postbraze diffusion heat treatment of the 7075/Mg combination yielded no improvement in the wedge test results.

A series of 6061 square specimens were brazed and wedge tested to investigate the effect of pressure and the time of its' application on the braze properties. Brazing conditions were the same as those given for the first item of Table 5, except for the pressure.

Specimens were brazed with five different pressure cycles: (1) 70 kPa (10 psi) for the entire heating cycle from room temperature to brazing temperature and held for one hour, (2) 70 kPa during heat-up to brazing temperature when the pressure was increased to 1380 kPa (200 psi) and held for one hour, (3) 70 kPa during heat-up and for 15 minutes at brazing temperature, when the pressure was increased to 1380 kPa and held for the remainder (45 minutes) of the one hour at

brazing temperature, (4) same as the third cycle except the pressure was increased after 30 minutes at brazing temperature and held for 30 minutes, (5) 1380 kPa for the entire heating cycle, as described for the first pressure cycle.

The wedge test results were the same as those given for the first item of Table 5, with one exception. The specimen brazed with a pressure of 70 kPa (10 psi) during the entire heating cycle and heat treated to the T6 condition yielded a low strength braze, as well as one of low ductility.

2. TENSILE TEST

Butt joints were brazed with two 6061 aluminum cylinders in the die shown in Figure 3, which was designed for easy removal of the brazed joints. It consists of two matching conical cylinders with the inner cylinder split along its diameter. All parts of the die assembly were made of austenitic stainless steel. Specimen temperature was recorded from a thermocouple inserted into a close-fitting hole drilled in the wall of the outside conical cylinder of the die.

The brazing procedure consists of the following steps: (1) a close-fitting cylindrical plug is inserted into the bottom of the die cavity and fastened in place by a pin extending through the walls of the inner split conical cylinder and the plug, (2) this subassembly is placed in the outer conical cylinder resting on the bottom furnace platen, (3) two cylindrical aluminum specimens and filler metal are inserted into the die cavity, (4) a close-fitting cylindrical follower-plug is placed on top of the aluminum specimens, (5) the furnace is evacuated, (6) the specimens are heated to brazing temperature, and (7) load is applied to the follower-plug through the furnace rod.

Specimen deformation was controlled by the proper selection of original diameter for the aluminum specimens to produce a final

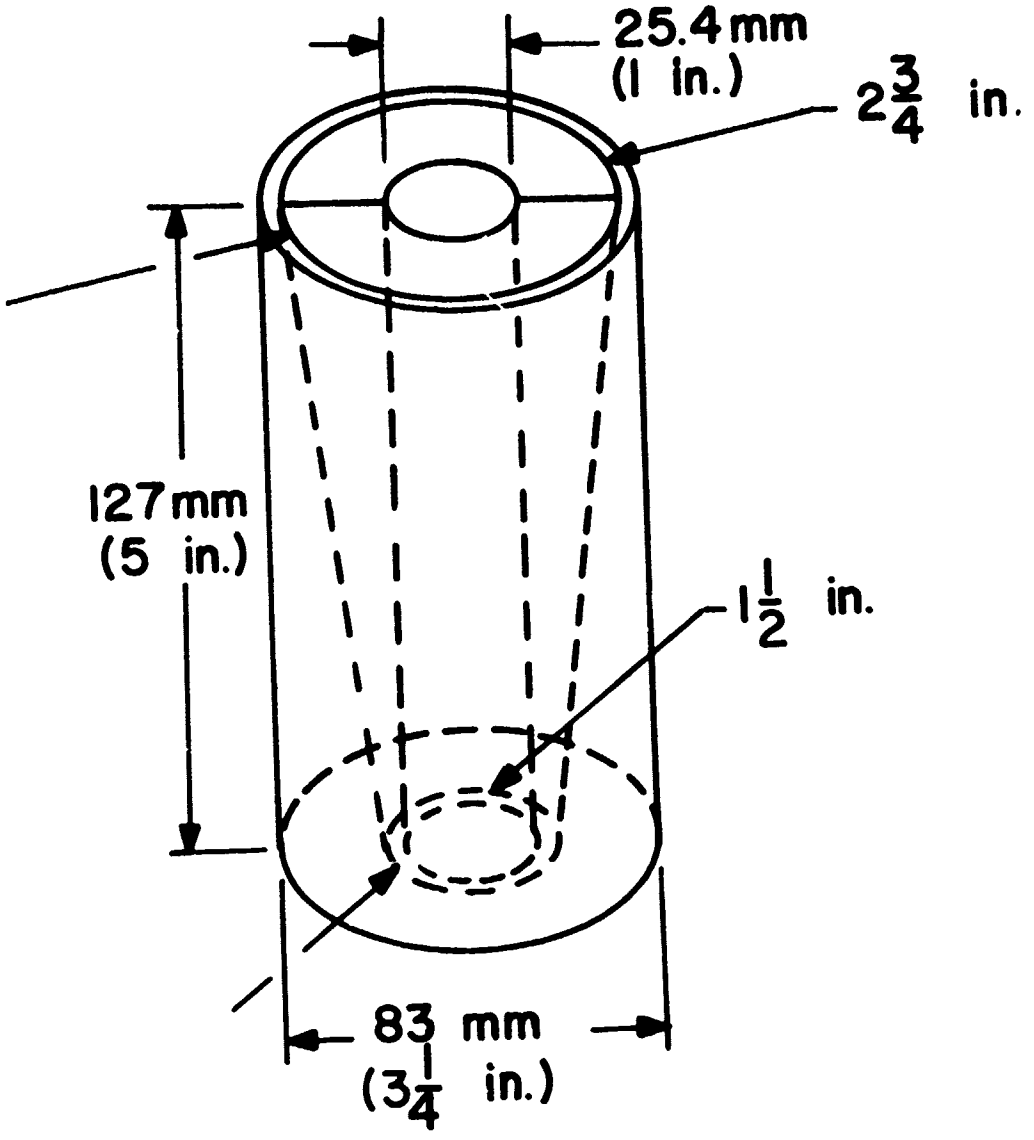

Figure 3. Brazing Die

diameter of 25.4 mm (1 in.). Specimen deformation was calculated by the following equation:

$$\delta = \frac{A_f - A_o}{A_o} (100)$$

where δ is percent braze deformation, A_o is the original faying surface area, and A_f is the final faying surface area. The length of the aluminum specimens was adjusted to yield a brazed cylinder with a length of about 44 mm (1 3/4 in.). Specimens, which were brazed with foil filler metal, were prepared by polishing with 5 μm diamond abrasive, followed by a water rinse and an alcohol rinse. The brazing pressure was 26 MPa (3.8 ksi) and the brazing temperature was 575°C for Ag filler metal and 590°C for Aℓ12Si filler metal.

The brazed specimens were sectioned longitudinally, as shown in Figure 4, and two subsize tensile specimens (Reference 1), with a reduced section diameter of 2.87 mm (0.113 in.) and a gage length of 12.7 mm (0.5 in.), from each of two brazed joints, were machined from pieces labeled "A". The gage length is a slight departure from that specified in Reference 1. One tensile specimen from each joint was tested in the as-brazed condition and one was heat treated to the T6 condition before testing. The results of the tensile tests are given in Table 6.

All brazing conditions produced joints with excellent tensile strengths in both the as-brazed and the T6 condition, with one exception among the vapor-coated filler metal specimens. However, there is a remarkable difference in tensile elongation values between the specimens brazed with vapor deposited filler metal and those with foil. All joints with vapor deposited filler metal exhibited poor elongation in both as-brazed and T6 conditions, while joints with 8 μm Ag foil and with Aℓ12Si foil yielded, in both as-brazed and T6 conditions, tensile elongations essentially equivalent to base metal properties. The one exception, braze joint No. 5, still had a respectable value of 5.4%.

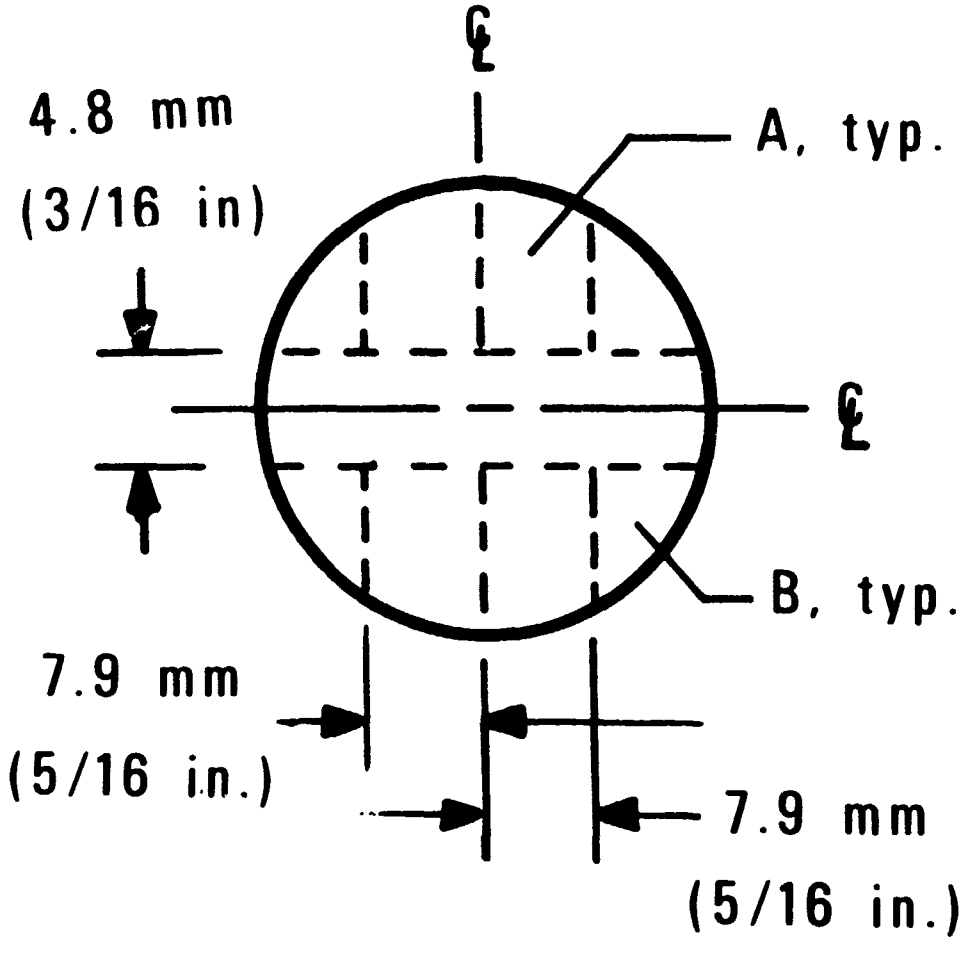

Figure 4. Sectioning Plan for 25.4 mm (1 in.) Diameter Brazed Cylinders.

TABLE 6

TENSILE TEST RESULTS OF BRAZED JOINTS

6061 ALUMINUM

26 MPa (3.8 KSI) BRAZING PRESSURE

Braze No.	Filler Metal Comp. w/o	Form	Thick. μm	Def.[a] %	Tensile Properties: Postbraze Heat Treatment: As-Brazed Tensile Strength MPa	ksi	El.[b] %	T6 Tensile Strength MPa	ksi	El.[b] %
	Ag	Vapor[c]	2	1	[d] 125	18.2	4.0	[d] 293	42.5	0.4
	Ag	Vapor	2	4	141	20.4	6.6	303	43.9	0.6
					144	20.9	9.2	270	39.2	0.2
	Ag	Vapor	10	1	128	18.5	3.8	207	30.0	0
					128	18.6	6.2	305	44.3	1.8
	Ag	Vapor	10	4	103	15.0	2.2	262	38.0	0
					124	18.0	3.8	287	41.6	0
1	Ag	Foil	8	1	145	21.3	23.8	325	47.2	18.4
2					147	21.1	23.0	330	47.8	19.6
3	Ag	Foil	25	1	[e]			287	41.6	2.0
4					145	21.0	22.0	316	45.9	2.2
5	Al12Si	Foil	75	1	145	21.1	26.8	304	44.1	5.4
6					147	21.3	21.8	321	46.6	18.4

a. Specimen deformation during brazing.
b. All specimens with less than 10% elongation failed at the joint. Those with greater than 10% failed in base metal.
c. Deposited from metal vapor in vacuum.
d. Specimen broke at the joint during machining.
e. Specimen destroyed by machining error. Specimen did not break.

3. BEND TEST

To obtain more significant information regarding the ductility of the brazed joints, bend tests were performed on the pieces labeled "B" in Figure 4, from the same brazed joints described in Section VII.2. The bend specimens were tested as cut by a band saw from the brazed cylinders, and were somewhat irregular and nonuniform in size and shape. The nominal specimen cross section was an approximate right-angle triangle with legs of 2.5 mm (3/32 in.) and 5 mm (3/16 in). Specimens were tested in the as-brazed, T6, and diffusion treated conditions.

The bend specimens were deformed by three-point bending into a bottom die with a vee-groove angle of 75° and a span width of 32 mm (1 1/4 in.) by a matching plunger with a 6 mm (1/4 in.) radius. The specimen bend angle (the supplement of the included angle between the two legs of the bent specimen) at failure was reported. If the specimen did not fail after full depression into the die, the bend angle of 100° was reported. Full conformance to the die would indicate a bend angle of 105°, but springback caused about a 5° difference.

The bend test results (given in Table 7) are consistent with the tensile test results of Table 6; i.e., the results are poor with the vapor-deposited Ag filler metals and the thicker Ag foil filler metal, but are excellent with the thinner Ag foil and with the Al12Si foil. The braze specimens, numbered 1 through 6 in Table 7, correspond to braze specimens of the same number in Table 6.

The diffusion treatment of joints brazed with vapor-deposited Ag filler metal yielded no improvement in bend ductility at a 500°C diffusion temperature or with specimens heat treated to the T6 condition. There was a significant increase of bend ductility with specimens diffusion treated at 400°C, when compared to the as-brazed specimens, but the bend ductility remained lower than for joints with foil filler metal.

TABLE 7

BEND TEST RESULTS OF BRAZED JOINTS

6061 ALUMINUM

26 MPa (3.8 KSI) BRAZING PRESSURE

Braze No.	Filler Metal Comp. w/o	Form	Thick. μm	Def.[b] %	Bend Angle, degree[a] Postbraze Heat Treatment As Brazed	T6	Diffusion Treatment, 100h 400C	500C	400C + T6	500C + T6
	Ag	Vapor[c]	2	1	15	0	25	10 15	0	0 10
	Ag	Vapor	2	4	15	0	30	10 30	0	0 0
	Ag	Vapor	10	1	20	0	50	5 10	0	0 0
	Ag	Vapor	10	4	5	0	35	0 0	0	0 0
1	Ag	Foil	8	1	100	100				
2					100	30				
3	Ag	Foil	25	1	60	10				
4					d	20				
5	Al12Si	Foil	75	1	100	100				
6					100	100				

a. Specimens with 100° bend angle did not fail. All others failed at the joint.
b. Specimen deformation during brazing.
c. Deposited from metal vapor in vacuum.
d. Specimen broke at the joint during cutting.

Eight bend test specimens, brazed with 8 μm Ag foil and Aℓ12Si foil did not fail, with the exception of one specimen in the T6 condition. The low value may have been due to an edge flaw in the braze joint, since the bend specimens were taken from the outer specimen annulus with no subsequent machining.

SECTION VIII

METALLOGRAPHIC RESULTS

1. 6061 ALUMINUM ALLOY

a. Silver Filler Metal

The microstructures of some of the 6061 aluminum joints brazed with silver foil to investigate the effect of pressure on the wedge test results (Section VII.1) are illustrated in Figures 5 through 8.

The grey, intergranular phases are much more in evidence in the joint brazed at 70 kPa (10 psi) (Figure 5) than in the joint brazed at 1380 kPa (200 psi) (Figure 6); both in the as-brazed condition. After heat treatment to the T6 condition, the specimen brazed at lower pressure has completely fractured (Figure 7) and the intergranular phases of the higher pressure specimen have been slightly reduced (Figure 8). Specimens brazed with the other pressure cycles (described in Section VII.1) contained lesser amounts of the grey phases than did the specimen brazed at 70 kPa, and localized microcracking was present in some specimens but no extensive cracking was observed. Other specimens brazed with silver foil at a pressure of 28 kPa (4 psi) also fractured when postbraze heat treated to the T6 condition.

The series of square specimens brazed with silver foil to determine the effect of postbraze diffusion treatment, represented by the first item of Table 4, revealed another deficiency of low pressure brazing. Photomicrographs of these specimens which were brazed at 28 kPa (4 psi), are shown in the as-brazed condition (Figure 9) and after diffusion treatment of 1000 hours at 400°C (Figure 10). The type of porosity illustrated was present in all specimens of the series and, in a number of cases, was more extensive than that shown. Since there was no correlation between the severity of the porosity and the temperature or time of diffusion treatment, it is apparent that the degree of porosity was not affected by the diffusion treatment.

Figure 5. 6061 Aluminum Brazed with 25 μm Silver Foil at 70 kPa (10 psi) Pressure, As-Brazed Condition. 250X 1% HF

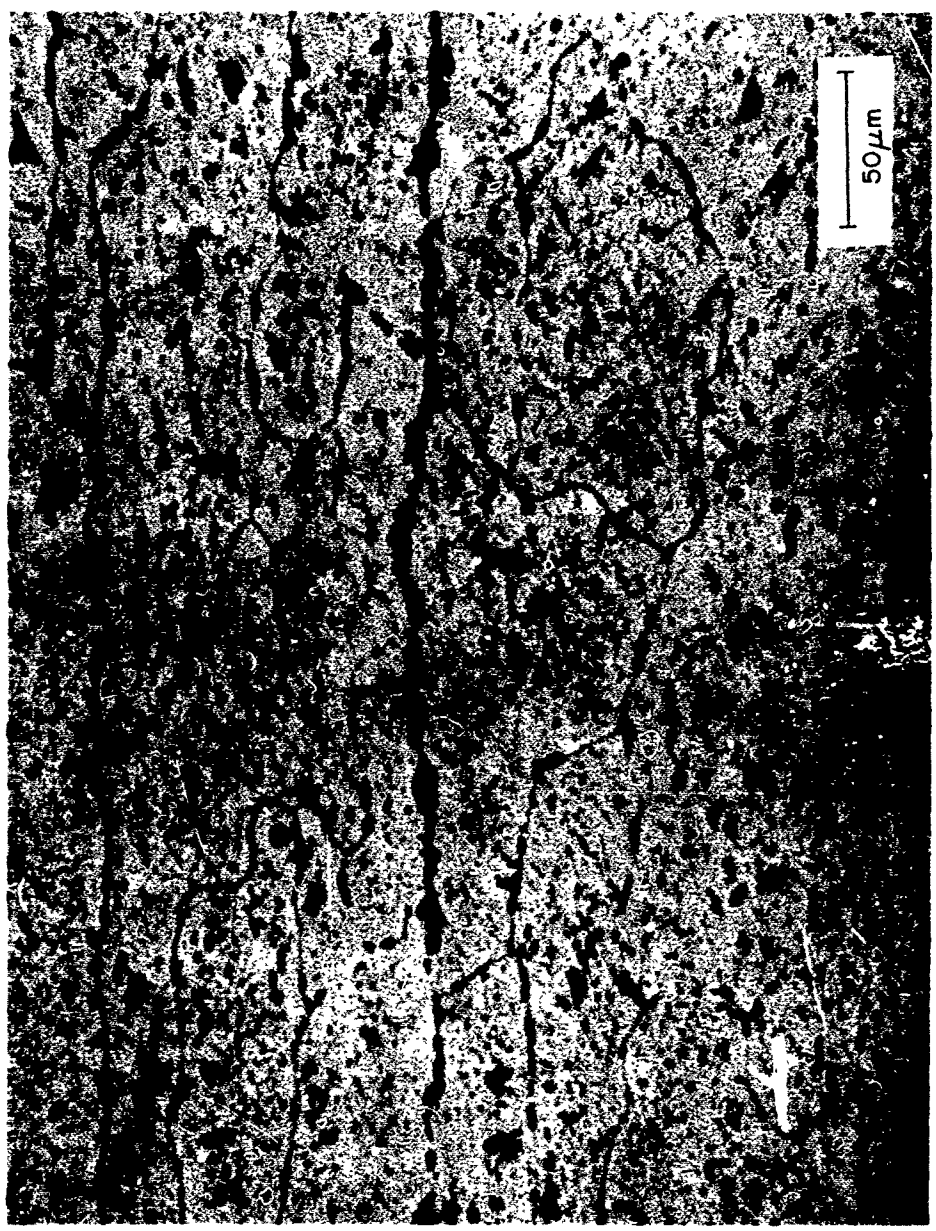

Figure 6. 6061 Aluminum Brazed with 25 μm Silver Foil at 1380 kPa (200 psi) Pressure, As-Brazed Condition. 250X 1% HF

Figure 7. 6061 Aluminum Brazed with 25 μm Silver Foil at 70 kPa (10 psi) Pressure, T6 Condition. 250X 1% HF

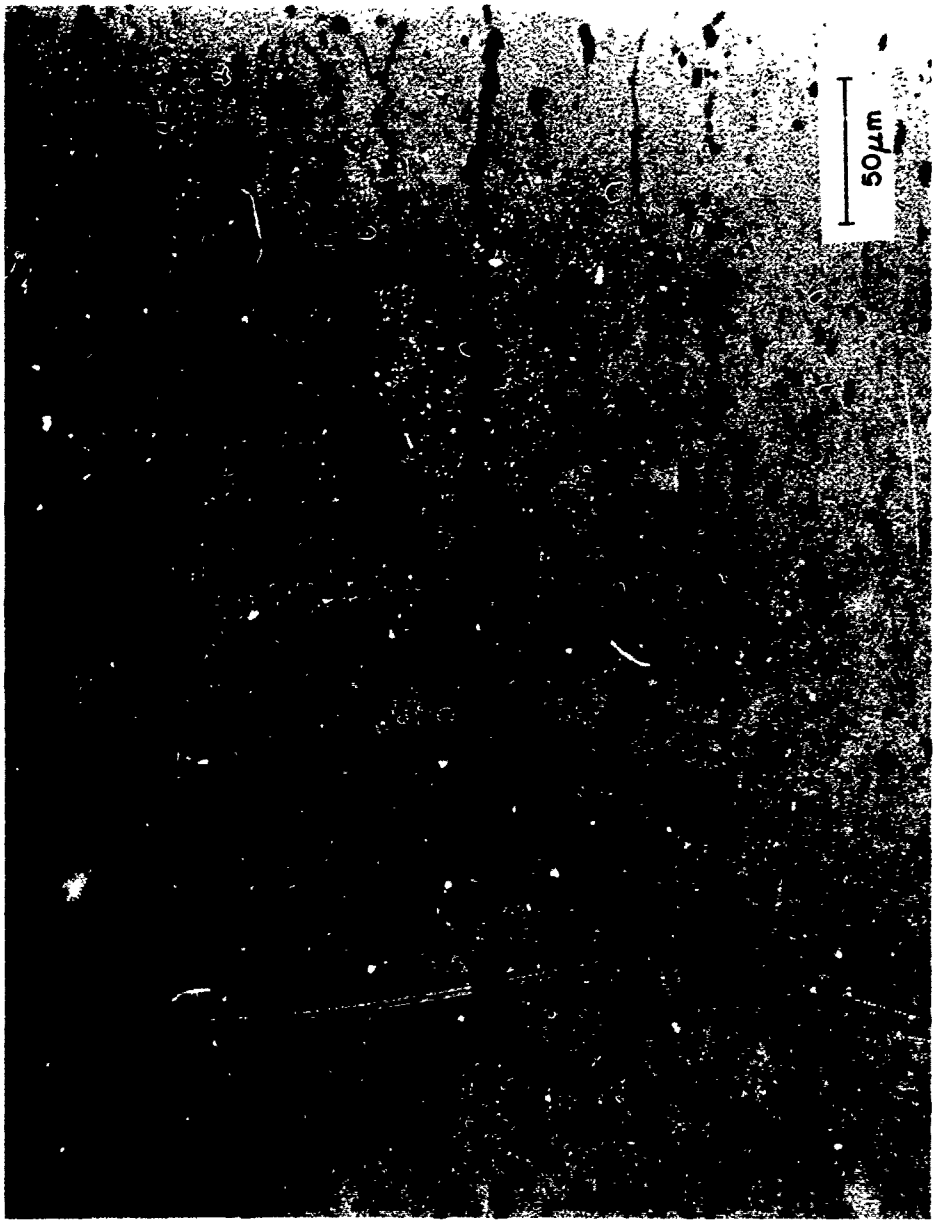

Figure 8. 6061 Aluminum Brazed with 25 μm Silver Foil at 1380 kPa (200 psi) Pressure, T6 Condition. 250X 1% HF

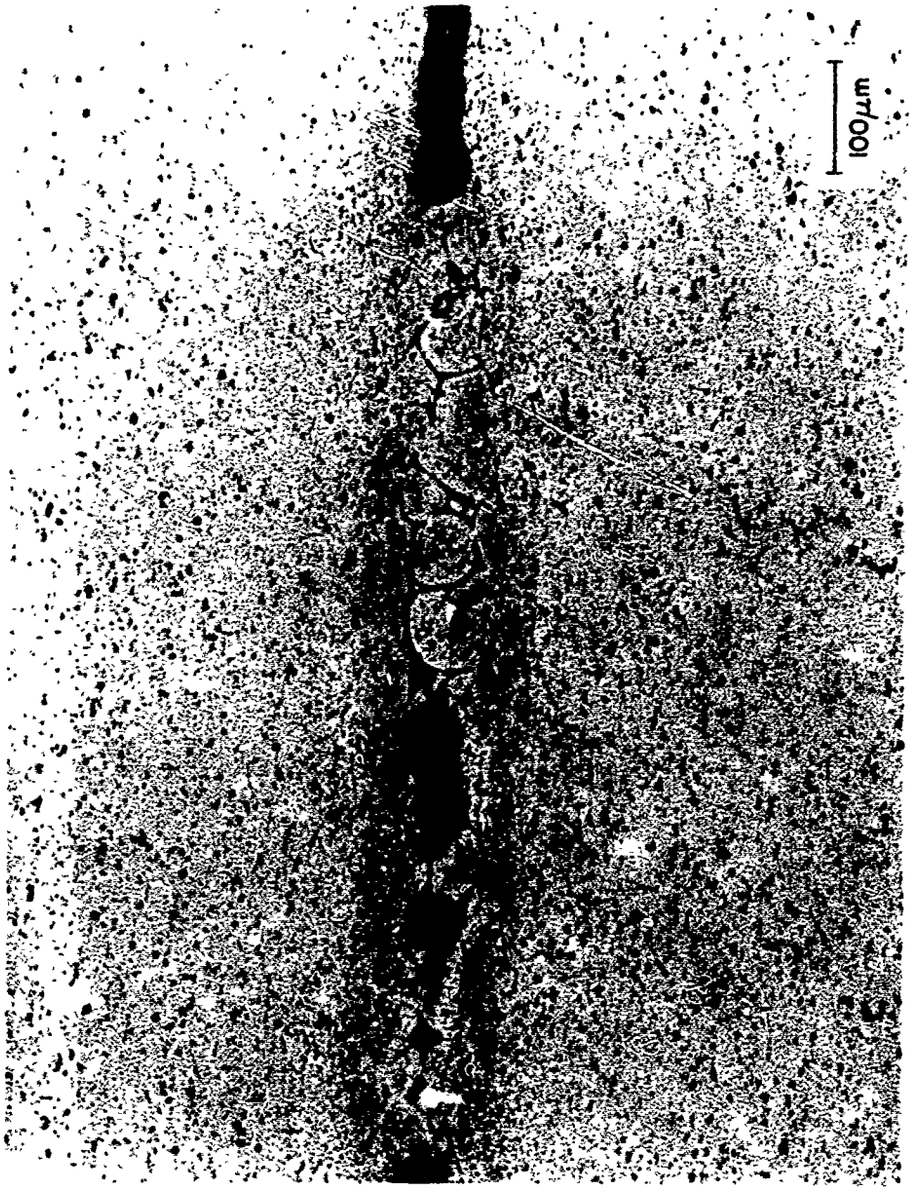

Figure 9. 6061 Aluminum Brazed with 25 μm Silver Foil at 28 kPa (4 psi) Pressure, As-Brazed Condition. 100X 20% NaOH

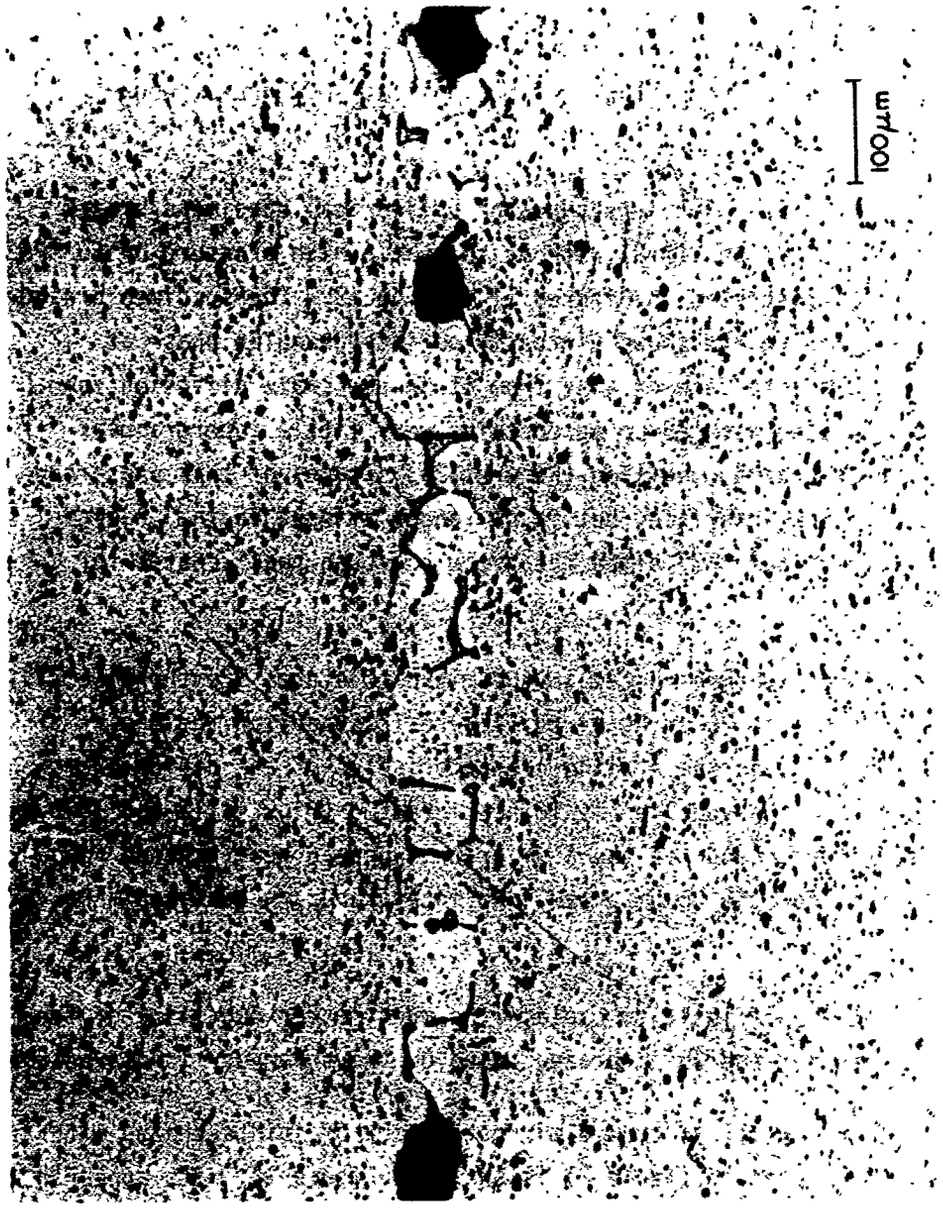

Figure 10. 6061 Aluminum Brazed with 25 μm Silver Foil at 28 kPa (4 psi) Pressure, Diffusion Heat Treated 1000 Hours at 400°C. 100X 20% NaOH

The microstructural difference between the as-brazed specimen (Figure 9) and the specimen diffusion treated 1000 hours at 400°C (Figure 10) was minimal, with only a change in the etching characteristics of the solid solution grains of the braze zone. At a diffusion temperature of 500°C, however, the grain boundary phase decreased with increased diffusion time until at 1000 hours, none remained.

The braze microstructures of cylindrical specimens brazed as butt joints (Section VII.2) with Ag foil at a high pressure of 26 MPa (3.8 ksi) are illustrated in Figures 11 through 13. The specimen brazed with 8 μm Ag (Figure 11) shows virtually no intergranular phase at either the braze interface or away from it in the braze diffusion zone. The specimen brazed with 25 μm Ag contains very little intergranular phase in the as-brazed condition (Figure 12). Traces of this phase can be detected at the interface, but is no longer evident in the braze diffusion zone (Figure 13) after the braze has been heat treated to the T6 condition.

Other features noted in the microstructures are the wider diffusion zone of the 25 μm Ag braze (Figure 12) than for the 8 μm braze (Figure 11), and the etching characteristics of the diffusion zone changes when the specimen is T6 heat treated (Figures 12 and 13). The microstructure change of the 8 μm braze, when T6 heat treated, was similar to that for the 25 μm braze. No intergranular phase could be detected.

It is difficult to explain the much better ductility of the 8 μm braze than for the 25 μm braze, based on the observed microstructures.

The typical as-brazed microstructure of joints brazed with 1 μm of electroplated Ag (Table 2) is shown in Figure 14. Its appearance is quite similar to joints brazed with 8 μm Ag foil at high pressure (Figure 11), except that the diffusion zone is not present. When heat treated to the T6 condition, the 1 μm electroplated Ag microstructure was not significantly different than in the as-brazed condition.

Figure 11. 6061 Aluminum Brazed with 8 μm Silver Foil at 26 MPa (3.8 ksi) Pressure, As-Brazed Condition. 150X 1% HF

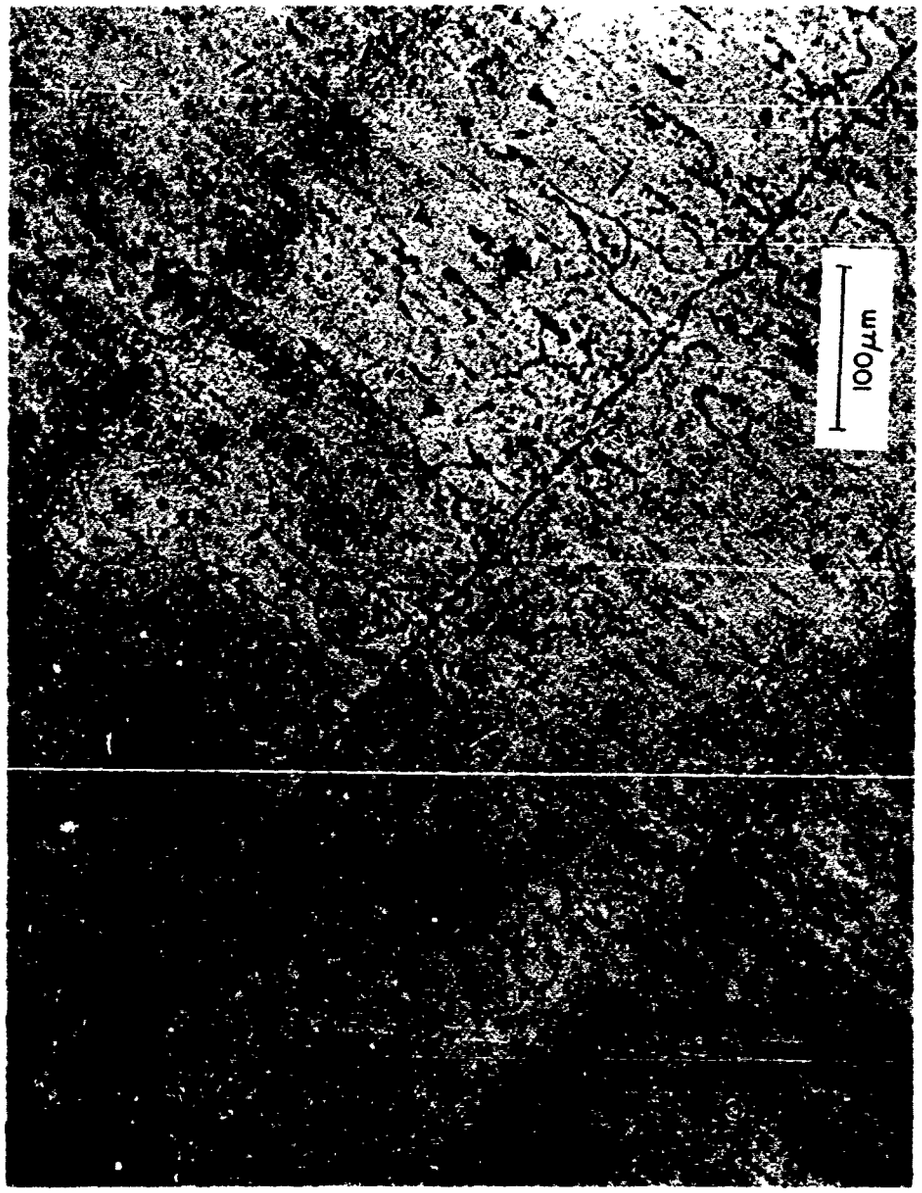

Figure 12. 6061 Aluminum Brazed with 25 μm Silver Foil at 26 MPa (3.8 ksi) Pressure, As-Brazed Condition. 150X 1% HF

Figure 13. 6061 Aluminum Brazed with 25 μm Silver Foil at 26 MPa (3.8 ksi) Pressure, T6 Condition. 150X 1% HF

Figure 14. 6061 Aluminum Brazed with 1 μm Electroplated Silver at 1380 kPa (200 psi) Pressure, As-Brazed Condition. 500X 20% NaOH

The 1 μm of Ag was obviously sufficient to form a brazed joint, as judged from the wedge test results of the as-brazed condition and the microstructure. The reason for the low ductility and low strength of the T6 specimens (when subjected to the wedge test (Table 5)) was not revealed by metallographic examination.

Joints brazed with 18, 34, and 58 μm electroplated Ag were all of a similar microstructure, despite the almost three to one ratio in the extremes of filler metal thickness. There was also, as with the 1 μm filler metal thickness, no significant difference between the as-brazed and the T6 conditions. Typical photomicrographs are shown in Figures 15 and 16. Intermetallic phases are clearly distinguishable along the braze, but the true character of the black, crack-like indications was not established; i.e., whether they are actually microcracks, contamination, or voids; or the result of the breaking out of a brittle phase. One exception to the similarity of the braze microstructures of the joints with 18, 34, and 58 μm of electroplated Ag, were elongated voids frequently present in the 58 μm braze joints, in both the as-brazed and T6 conditions, illustrated in the right half of Figure 16.

All microstructures of joints brazed at a pressure of 1380 kPa (200 psi) with vapor deposited Ag filler metal contained numerous linear and globular black indications. Neither the nature of these indications or their relationship to filler metal thickness or diffusion treatment was established. Figure 17 is a representative photomicrograph.

Figures 18 through 21 illustrate the microstructures of joints brazed at 26 MPa (3.8 ksi) with vapor deposited Ag filler metal. The black linear indications appear to be cracks; however, these metallographic specimens were removed from the same braze specimens as the tensile and bend specimens of Tables 6 and 7. It appears obvious that brazed joints, with cracks to the extent indicated in Figures 18 through 21, could not have yielded the high joint strengths of Table 6. On the other hand, brittle phases would explain the low elongations of Table 6 and the low bend angles of Table 7. It is concluded that the principal feature of the braze microstructures is a dark-etching britile phase or phases.

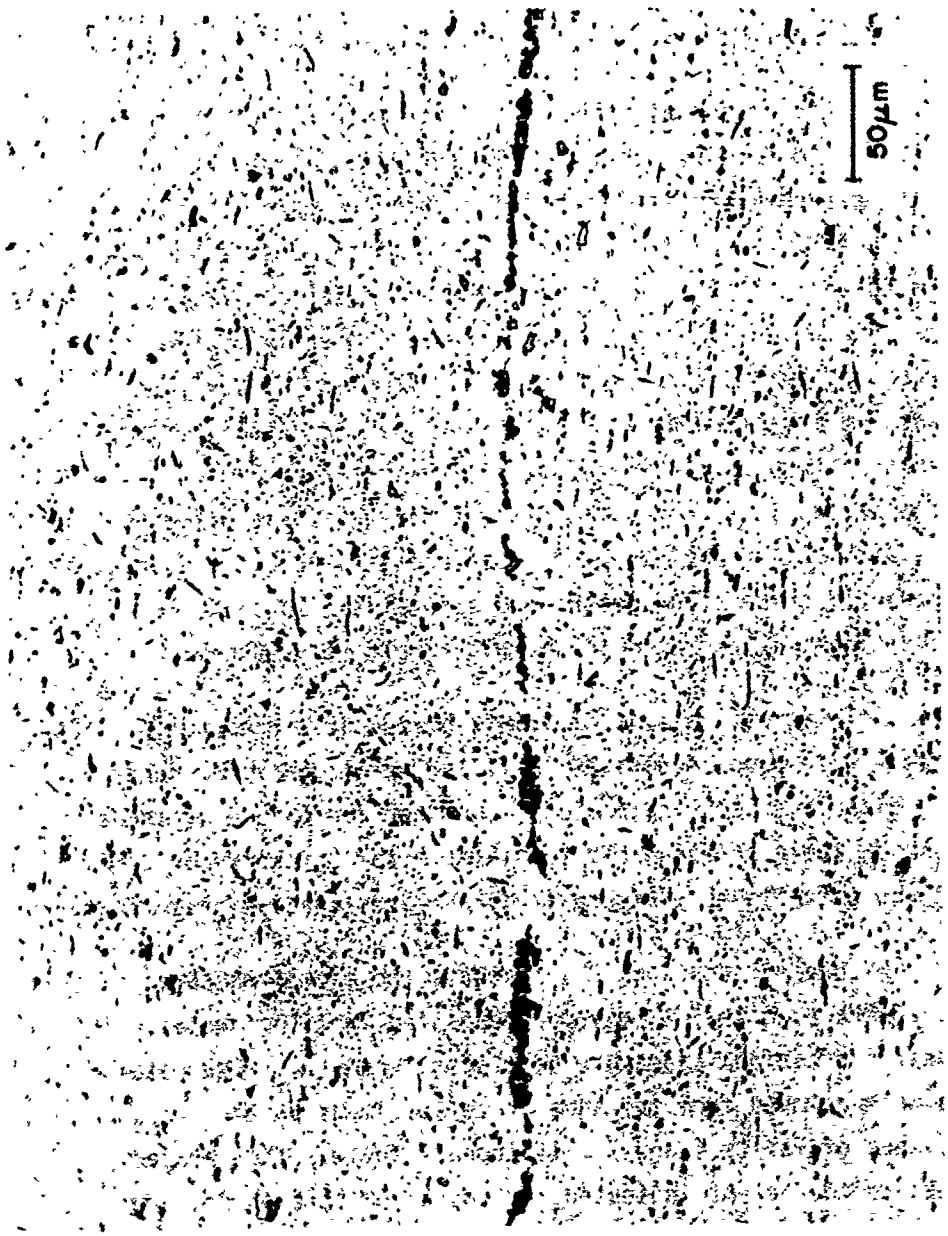

Figure 15. 6061 Aluminum Brazed with 34 µm Electroplated Silver at 1380 kPa (200 psi) Pressure, As-Brazed Condition. 200X 20% NaOH

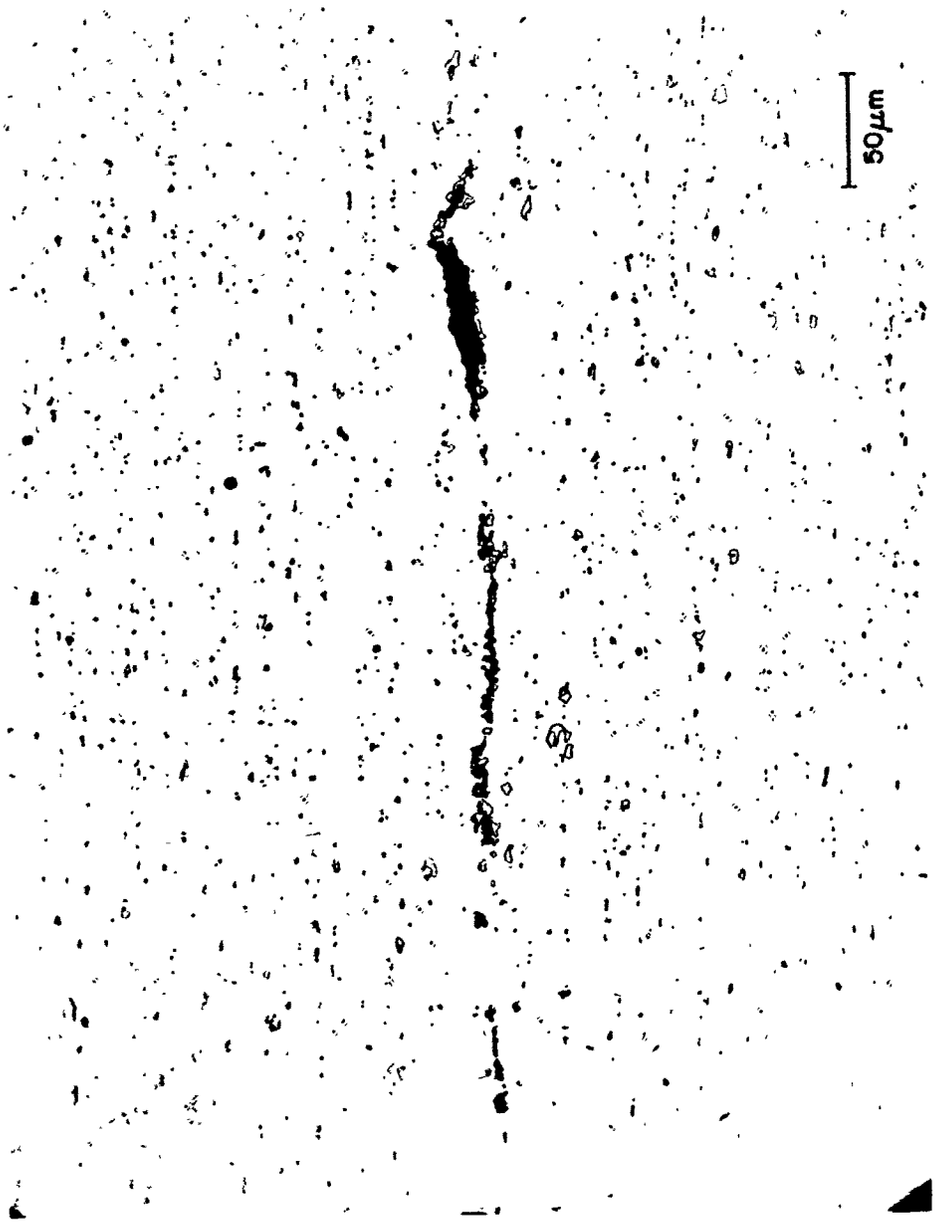

Figure 16. 6061 Aluminum Brazed with 58 µm Electroplated Silver at 1380 kPa (200 psi) Pressure, T6 Condition. 200X 20% NaOH

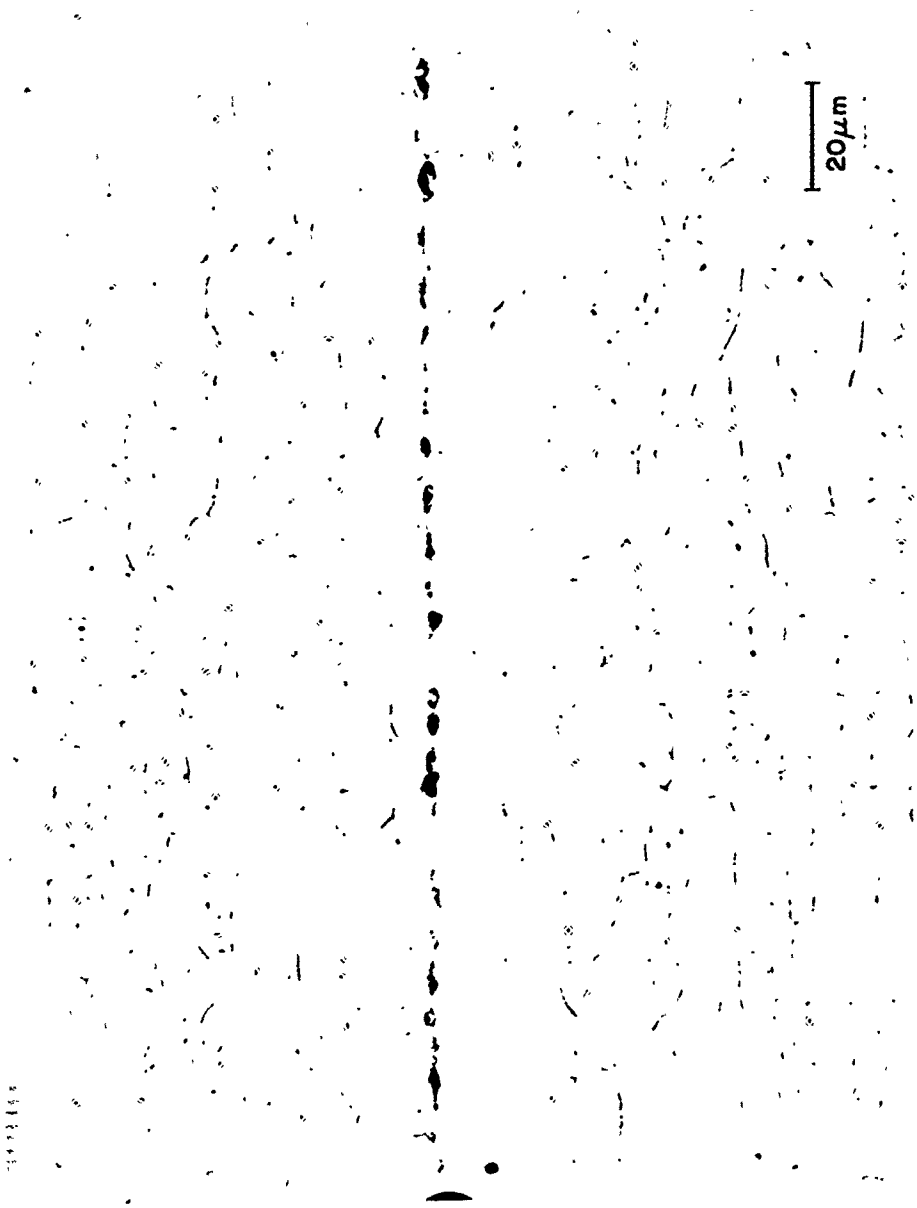

Figure 17. 6061 Aluminum Brazed with 10 μm Vapor Deposited Silver at 1380 kPa (200 psi) Pressure, As-Brazed Condition. 500X 0.5% HF

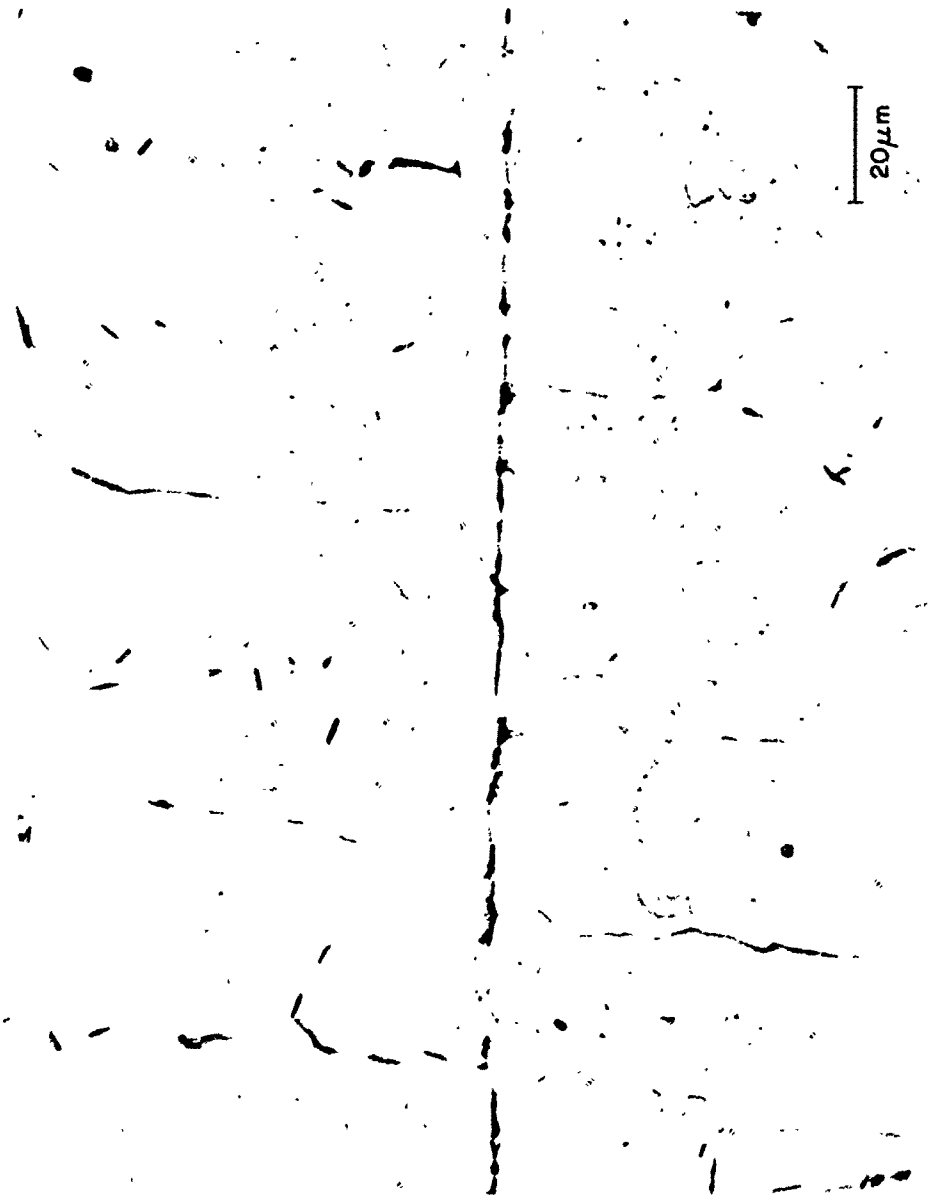

Figure 18. 6061 Aluminum Brazed with 2 μm Vapor Deposited Silver at 26 MPa (3.8 ksi) Pressure, As-Brazed Condition. 500X 1% HF

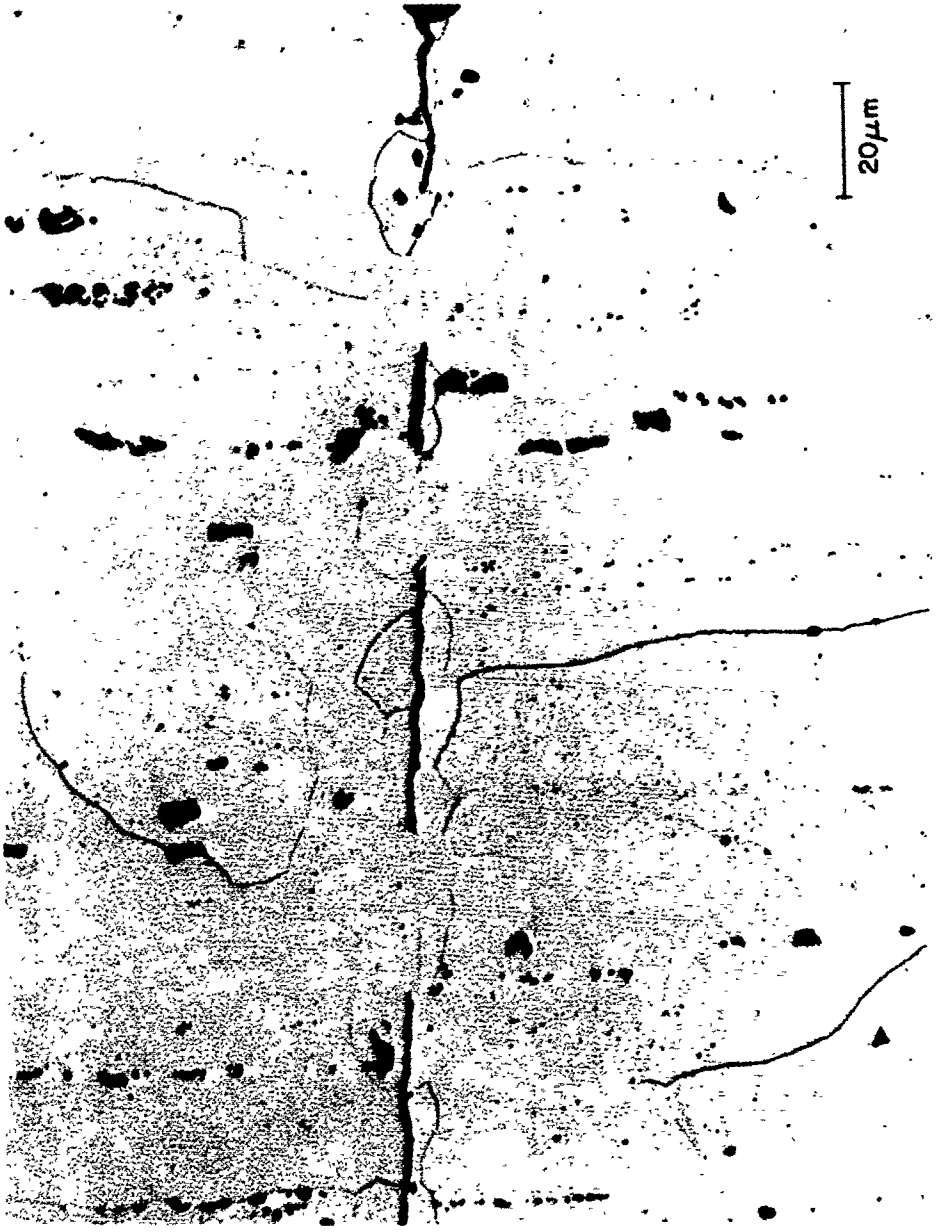

Figure 19. 6061 Aluminum Brazed with 2 μm Vapor Deposited Silver at 26 MPa (3.8 ksi) Pressure, T6 Condition. 500X 1% HF

Figure 20. 6061 Aluminum Brazed with 10 μm Vapor Deposited Silver at 26 MPa (3.8 ksi) Pressure, As-Brazed Condition. 500X 1% HF

Figure 21. 6061 Aluminum Brazed with 10 μm Vapor Deposited Silver at 26 MPa (3.8 ksi) Pressure, As-Brazed Condition. 500X 1% HF

b. Aℓ12Si Filler Metal

The microstructure of specimens brazed with Aℓ12Si filler metal at 28 kPa (4 psi) pressure is shown in Figure 22. The average width of the braze metal is about equal to the thickness of the filler metal foil; i.e., 75 μm, and silicon needles are visible. A typical result of the diffusion treatment is illustrated in Figure 23; little effect is noted, other than the disappearance of the silicon needles. With regard to porosity Figure 22 is atypical. Scattered porosity, as seen in Figure 23, was generally observed in all specimens, and did not appear to be affected by diffusion treatment.

Diffusion treatment at 300°C, even at 1000 hours, had no effect on the braze metal microstructure. At 400° and 500°C, for 10, 100, and 1000 hours, the microstructure was similar to Figure 23.

Specimens brazed at 26 MPa (3.8 ksi) pressure with the same filler metal foil (Tables 6 and 7) revealed a decrease in the braze width to about 35 μm, no porosity and no silicon needles (Figure 24). There is, however, evidence of a braze metal grain boundary phase. Heat treatment to the T6 condition causes the grain boundary phase to disappear and the inclusions at the braze metal-base metal interfaces to decrease in frequency (Figure 25).

c. Copper Filler Metal

The microstructure of joints brazed with 12 μm Cu foil in the as-brazed condition (as illustrated in Figure 26) exhibited dark needle-shape and grey blocky intermetallics at the braze. The latter compound also penetrated the grain boundaries immediately adjacent to the braze. Grain boundary and intragranular precipitates are visible at a greater distance from the braze, but were not present in the solution treated or diffusion treated specimens.

Figure 27 shows the microstructure after diffusion treatment at 500°C for 1000 hours. The needle-shape intermetallic compound has been removed and the blocky intermetallic is much less massive and is

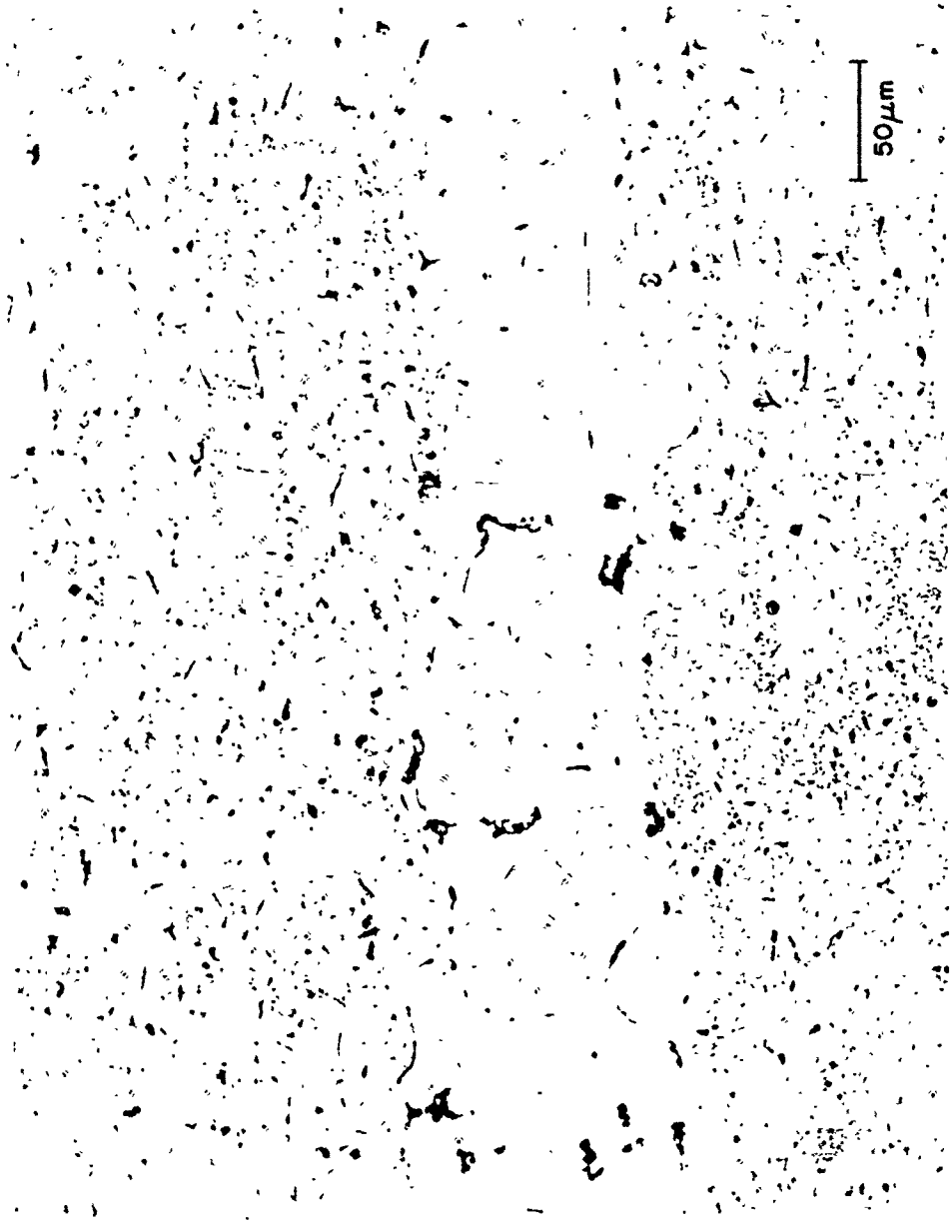

Figure 22. 6061 Aluminum Brazed with 75 um Aℓ12Si Foil at 28 kPa (4 psi) Pressure, As-Brazed Condition. 200X 20% NaOH

Figure 23. 6061 Aluminum Brazed with 75 μm Aℓ12Si Foil at 28 kPa (4 psi) Pressure, Diffusion Treated 100 Hours at 500°C. 200X 20% NaOH

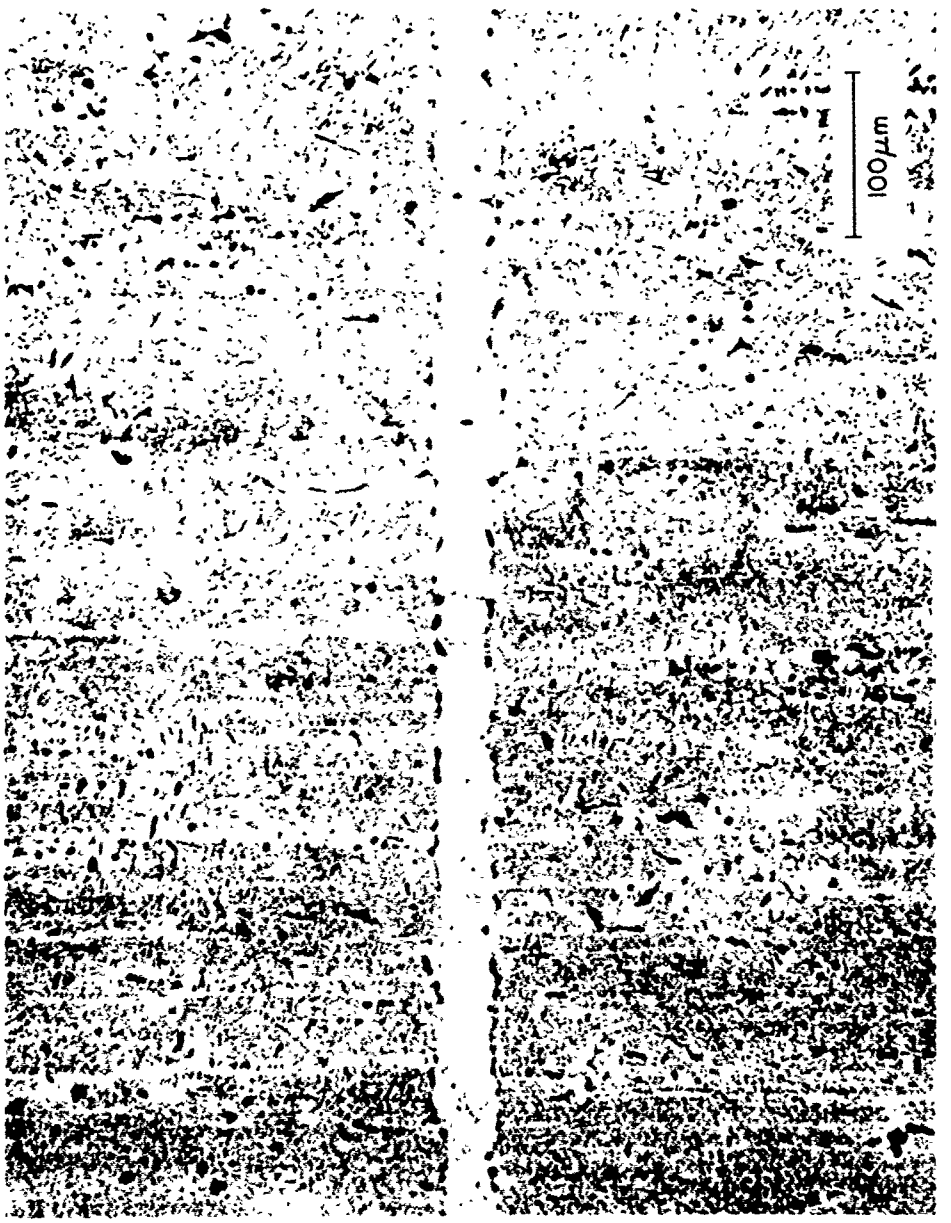

Figure 24. 6061 Aluminum Brazed with 75 μm Aℓ12Si Foil at 26 MPa (3.8 ksi) Pressure, As-Brazed Condition. 150X

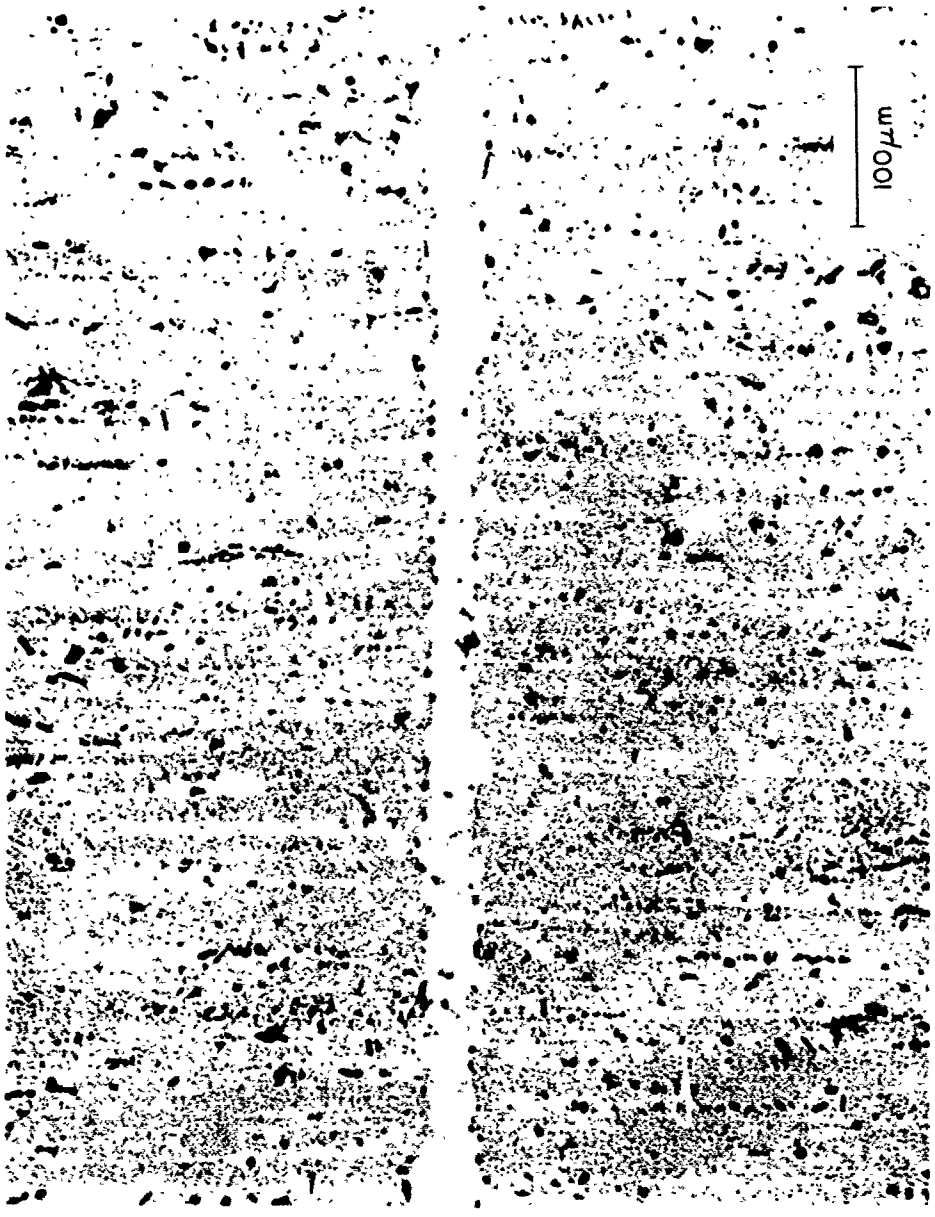

Figure 25. 6061 Aluminum Brazed with 75 μm Aℓ12Si Foil at 26 MPa (3.8 ksi) Pressure, T6 Condition. 150X

Figure 26. 6061 Aluminum Brazed with 12 μm Copper Foil at 1.38 MPa (200 psi) Pressure, As-Brazed Condition. 250X Kellers

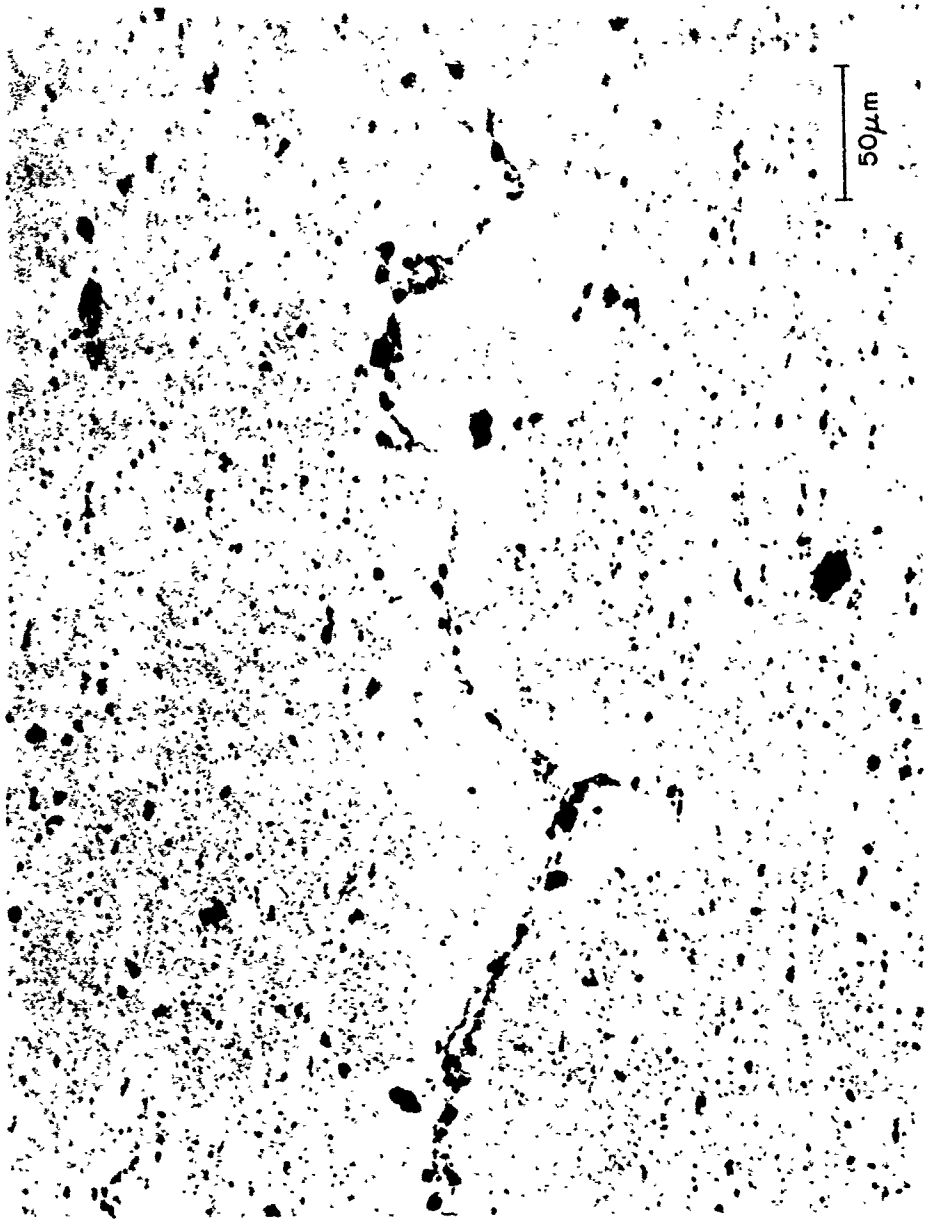

Figure 27. 6061 Aluminum Brazed with 12 μm Copper Foil at 1.38 MPa (200 psi) Pressure, Diffusion Treated 1000 Hours at 500°C. 250X Kellers

intermittent. Diffusion treatment at the same temperature for 100 hours was about the same as at 1000 hours, with slightly more intermetallics at the braze.

Specimens brazed with 25 μm and 50 μm Cu foil had microstructures similar to those with 12 μm, except the intermetallic compounds were thicker and more continuous. There was also Cu-Al eutectic in the as-braze condition and the joints brazed with 50 μm Cu fractured when solution heat treated. Diffusion heat treatment at 400°C had little effect on the microstructure.

A typical microstructure of joints brazed with vapor-deposited Cu is shown in Figure 28. No interdiffusion of Cu and Al was evident. Diffusion treatment at 500°C for 100 hours had no effect on the microstructure.

d. Gold Filler Metal

Four distinct phases were discernible in the joints brazed with Au filler metal. The photomicrograph (Figure 29) taken at the perimeter of the joint shows these phases most clearly. These are the intermittent light grey phase at the center (which is also one constituent of the matrix eutectic in the fillet area), then a lighter shaded phase, a dark grey phase, and finally a black phase at the interface of the braze metal and the 6061 aluminum.

The braze metal contained numerous microcracks in the center and also dark indications which were either pores or a breaking out of brittle phases. As illustrated in Figure 30, all of the diffusion treated specimens fractured.

e. Magnesium Filler Metal

The braze microstructure of joints with 25 μm Mg foil was without voids or cracks and contained two fine phases scattered along the joint, as shown in Figure 31. No significant difference was detected when the braze was heat treated to the T6 condition.

Figure 28. 6061 Aluminum Brazed with 6 μm Vapor Deposited Copper at 1.38 MPa (200 psi) Pressure, As-Brazed Condition. 250X 0.5% HF

Figure 29. 6061 Aluminum Brazed with 50 μm Gold Foil, As-Brazed Condition. 100X 20% NaOH

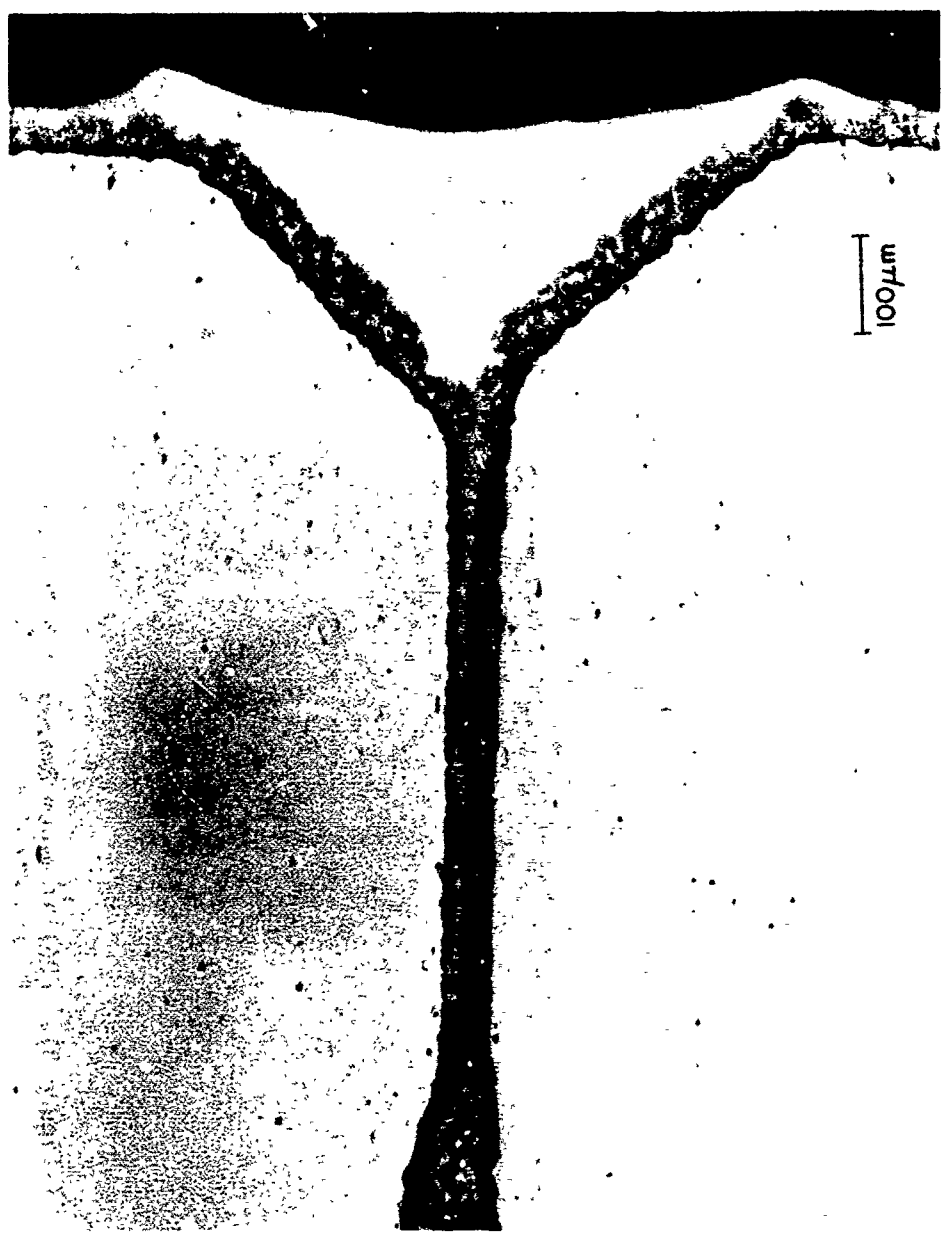

Figure 30. 6061 Aluminum Brazed with 50 µm Gold Foil, Diffusion Treated 1000 Hours at 300°C. 100X 20% NaOH

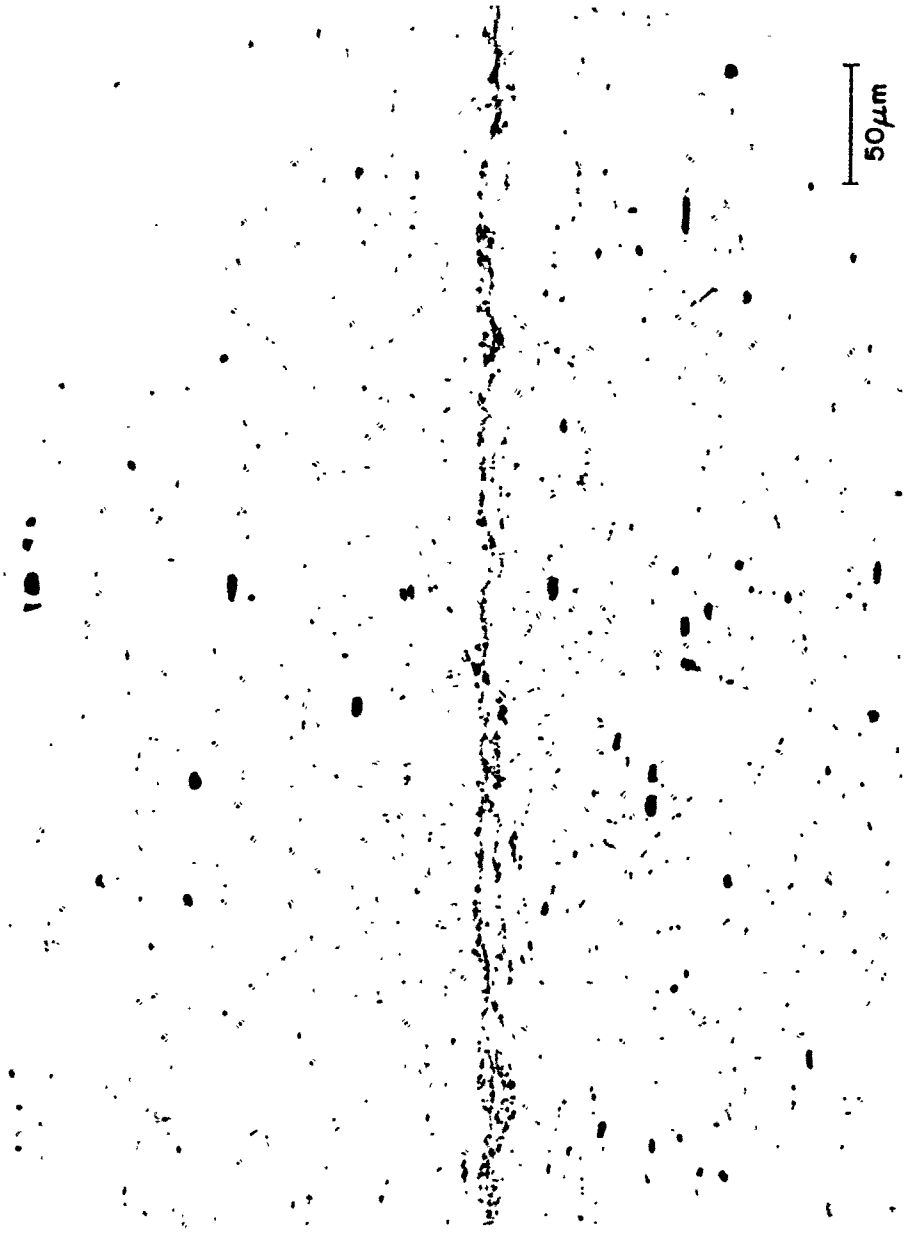

Figure 31. 6061 Aluminum Brazed with 25 μm Magnesium Foil at 450°C, As-Brazed Condition. 250X No Etch

When Mg filler metal foil of 125 μm thickness was used, the brazed joint had numerous voids. The microstructure was similar to that of the 25 μm joint, except that a semi-continuous dark-etching phase was present through the center of the joint and microcracks were visible in the braze fillet formed at the joint periphery. Heat treatment to the T6 condition caused the joint to fracture along its entire length.

2. 7075 ALUMINUM ALLOY

a. Magnesium Filler Metal

Specimens brazed with 25 μm Mg foil at 450°C had an as-brazed microstructure containing a center dark-etching phase, with fine, scattered phase particles on either side of the center phase. Numerous voids were present in the dark-etching phase, which formed either during brazing as porosity or during metallographic specimen preparation due to breaking out of a brittle phase. Heat treatment to the T6 condition caused complete fracture of the brazed joint through the center, dark-etching phase.

Diffusion treatment of the 25 μm Mg foil joints brazed at 450°C resulted in no improvement of the braze microstructure quality at lower temperatures and shorter times and a further deterioration at higher temperatures and longer times; i.e., more extensive void formation and cracking.

The as-brazed microstructure of specimens brazed with 25 μm Mg foil at 490°C indicated a sound joint of an almost continuous dark-etching phase, interspersed occasionally with an equiaxed grey phase, (Figure 32). The results of T6 heat treatment and diffusion treatment were essentially the same as for the specimens brazed at 450°C.

Joints brazed with 125 μm Mg foil contained a conglomerate of solid solution grains and a massive intermetallic phase, which also partially penetrated the solid solution grain boundaries. Frequent voids (as either pores or breaking out of a brittle phase) were also

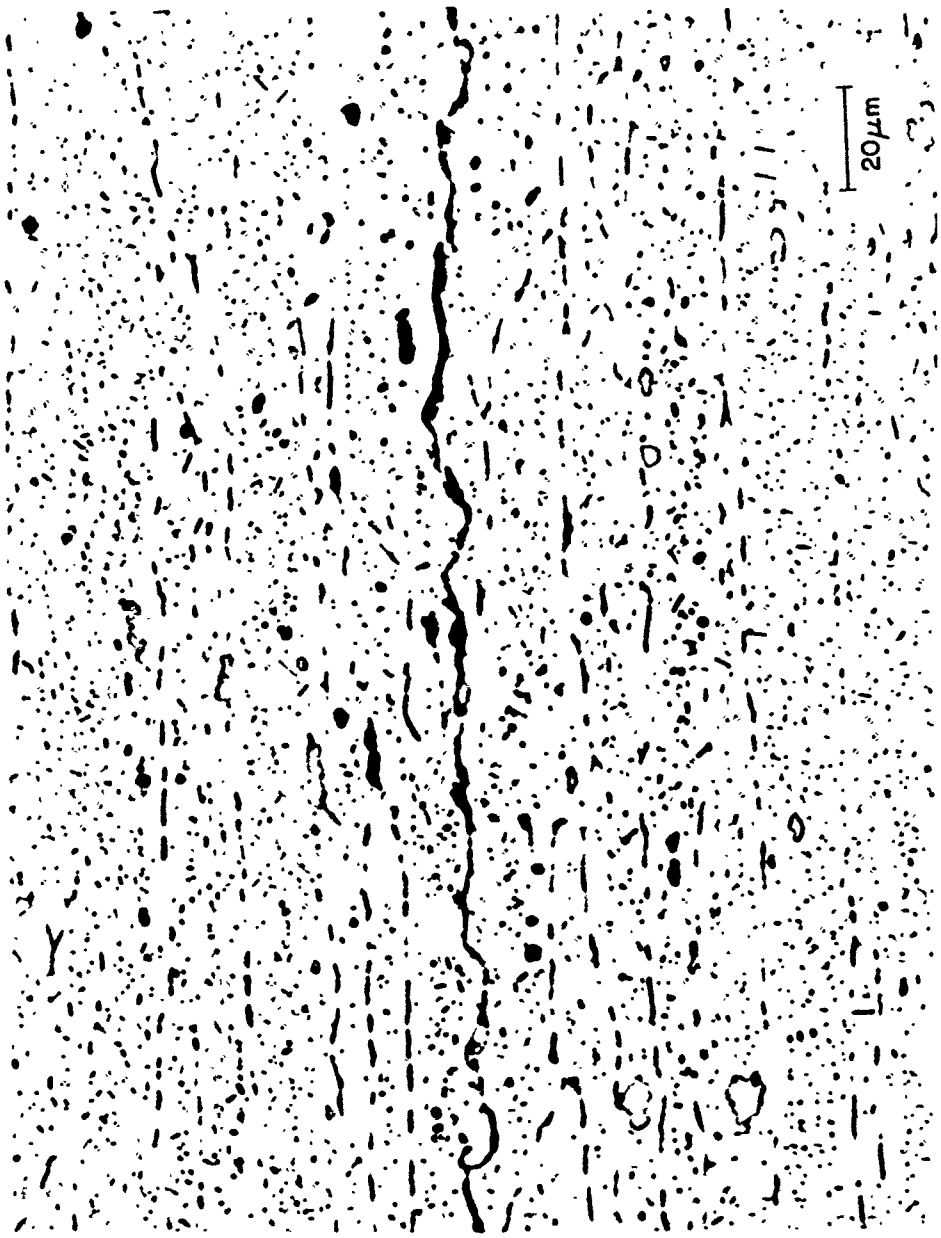

Figure 32. 7075 Aluminum Brazed with 25 μm Magnesium Foil at 490°C, As-Brazed Condition. 500X 0.5% HF

associated with the massive intermetallic phase. On either side of this center zone, scattered phase particles, with some tendency to concentrate at the base metal grain boundaries, was observed.

Where the massive intermetallic phase formed at the outer perimeter of the joint, brittle, chonchoidal-shaped microcracks were present. The joint broke open when heat treated to the T6 condition.

All of the joint microstructures of specimens brazed with vapor deposited Mg at either 2 μm or 10 μm thickness and at either 1.38 MPa (200 psi) or 6.9 MPa (1000 psi) pressure were quite similar. One exception was the specimen brazed with supposedly 10 μm Mg at 6.9 MPa (1000 psi), which metallographic examination showed to have much less than 10 μm filler metal, and was insufficient to form a brazed joint. This specimen has been eliminated from the following discussion.

A representative group of photomicrographs are presented in Figures 33 to 36. The as-brazed microstructures of Figures 33 to 35, all have an almost continuous grey phase of varying width with dark-etching indications, both globular and linear, of either microvoids, contamination, or a second phase. There was essentially no change in the microstructure caused by heat treatment to the T6 condition.

Diffusion treatment of the vapor deposited Mg brazed joints caused frequent microcracks, as illustrated in the center of Figure 36, to appear, both before T6 heat treatment and after. Some were much more extensive than in Figure 36.

b. Ag28Cu Filler Metal

The predominant phase found in all of the joints brazed with Ag28Cu electroplated filler metal is illustrated in Figure 37 as a massive grey phase. This phase is apparently brittle since all specimens cracked at the joint when solution heat treated.

Joints brazed with vapor deposited Ag28Cu filler metal also contained the brittle phase (Figure 38) in a more dispersed form, plus a

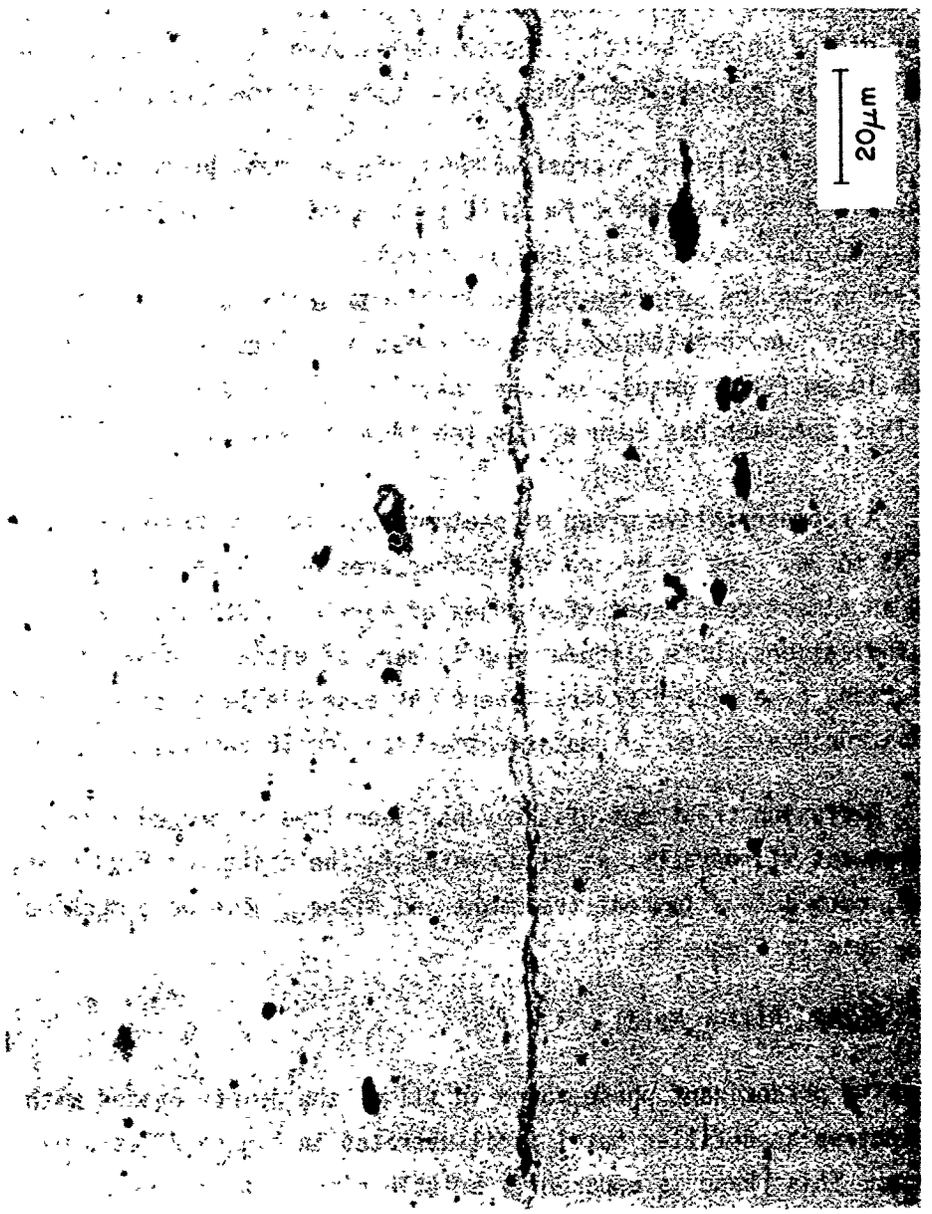

Figure 33. 7075 Aluminum Brazed with 2 μm Vapor Deposited Magnesium at 1.38 MPa (200 psi) Pressure, As-Brazed Condition. 500X No Etch

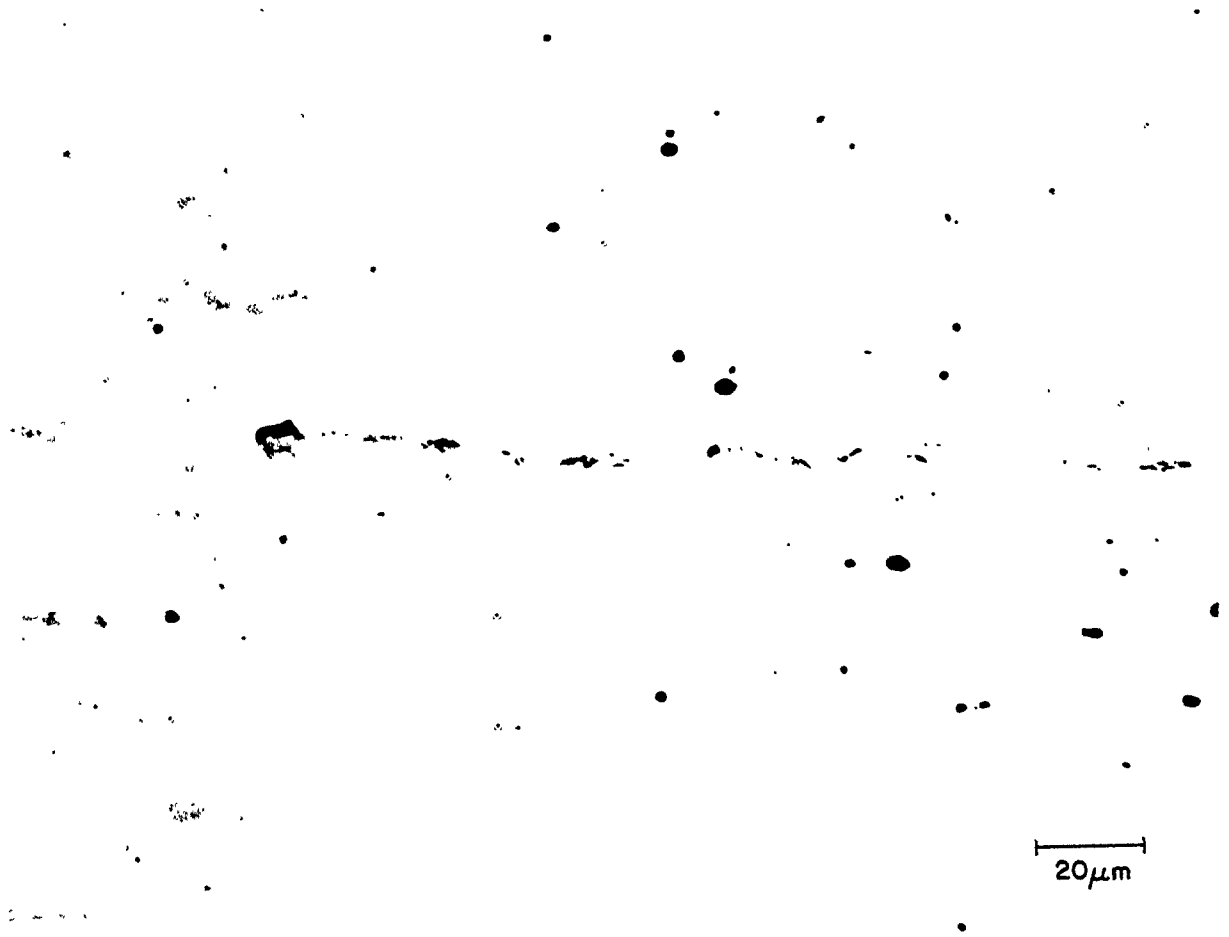

Figure 34. 7075 Aluminum Brazed with 10 μm Vapor Deposited Magnesium at 1.38 MPa (200 psi) Pressure, As-Brazed Condition. 500X No Etch

Figure 35. 7075 Aluminum Brazed with 2 μm Vapor Deposited Magnesium at 6.89 MPa (1000 psi) Pressure, As-Brazed Condition. 500X No Etch

Figure 36. 7075 Aluminum Brazed with 2 μm Vapor Deposited Magnesium at 6.89 MPa (1000 psi) Pressure, Diffusion Treated 100 Hours at 450°C, Followed by T6 Heat Treatment. 500X No Etch

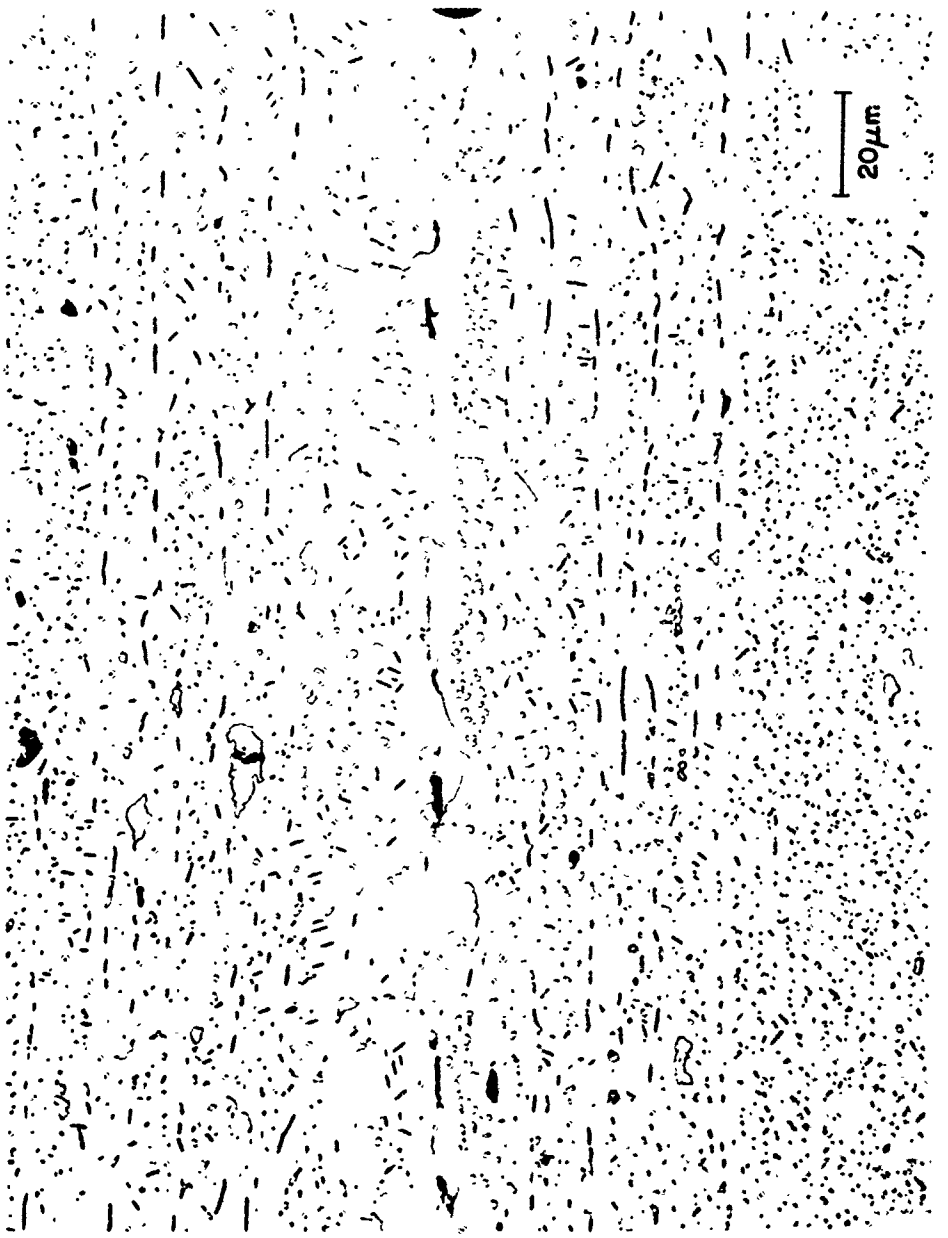

Figure 37. 7075 Aluminum Brazed with 1 μm Electroplated Ag28Cu Filler Metal at 1.38 MPa (200 psi) Pressure, As-Brazed Condition. 500X 20% NaOH

Figure 38. 7075 Aluminum Brazed with 2 μm Vapor Deposited Ag28Cu Filler Metal at 1.38 MPa (200 psi) Pressure, As-Brazed Condition. 500X 0.5% HF

thin, dark, almost continuous line. Cracking was more severe than with electroplated filler metal. Not only did all of the solution treated specimens fracture, but also those which were postbraze diffusion treated and the specimen in the as-brazed condition with 20 μm filler metal.

Because of the poor metallographic results with the electroplated and vapor deposited Ag28Cu filler metal and the erratic flow results with Ag28Cu filler metal in foil and powder form, braze specimens with the latter two filler metals were not metallographically examined.

c. Zinc Filler Metal

Both as-soldered and diffusion treated specimens contained many large voids. A grain boundary phase adjacent to the solder joint was present in the as-soldered specimens which was retained after diffusion treatment at 300°C. However, this phase was no longer present after diffusion treatment for 1000 hours at 400°C, or after 10 hours at 500°C.

SECTION IX

DISCUSSION

1. FILLER METALS

The most successful filler metals were silver (diffusion brazing) and Al2Si (conventional brazing). Both produced brazed joints in 6061 aluminum of excellent strength and good bend ductility. Other filler metals, including Au, Cu, Mg, and Ag28Cu were not suitable because of poor ductility. Indium and InZn alloys exhibited poor wetting. Zinc showed excellent wetting with both 6061 and 7075 aluminum but the 7075/Zn specimens had excessive porosity. The 6061/Zn specimens were not metallographically examined. Zinc was used only at low pressure, and higher pressures may have eliminated the porosity, as was the case with other filler metals. Further work with zinc appears to be justified, in particular with 7075 aluminum, since no brazing filler metal or high strength solder has been developed for this alloy.

Filler metal in foil form gave better results than other filler metal forms. Although the wetting behavior of electroplated Ag with 6061 was similar to Ag foil, the wedge test results were less favorable for the former. Metallographic examination did not reveal the reason for this difference, but it is probably due to the introduction of contaminants during electroplating.

The limited experiments with filler metal in powder form yielded poor results. Wetting of 7075 aluminum with Ag28Cu and Ag-Cu base alloys was erratic. Although Ag28Cu foil behaved in a like manner, electroplated and vapor deposited Ag28Cu filler metal exhibited excellent wetting. The least satisfactory form was vapor deposited filler metal. Wetting and brazed joint ductility with Ag foil was greatly superior to vapor deposited Ag. Braze cracking was more severe with vapor deposited Ag28Cu filler metal than with electroplated. It is believed that contamination during vapor deposition and uncertainty about filler metal thickness were major factors in the poor performance of this filler metal form. A discoloration of the vapor deposited

surface was often observed. An attempt to braze 7075 aluminum cylinders in the brazing die with a specified Mg filler metal thickness (that had been successful when brazing the square specimens) resulted in no braze joint. The latter result is believed to be due to less than the specified Mg thickness.

2. BRAZING PRESSURE

A number of observations indicated the effect of brazing pressure. Porosity in the 6061/Ag joints brazed at 28 kPa (4 psi) was eliminated by brazing pressures of 70 kPa (10 psi) and greater. The extensive intergranular phases in joints brazed at 70 kPa (10 psi), accompanied by gross cracking when heat treated to the T6 condition, were considerably reduced at higher pressures, and T6 treatment did not c use cracking.

Apparently, the reaction or diffusion kinetics are affected by pressure so that the elements of the intergranular phases are more completely dissolved in the aluminum matrix at higher pressures. This resulted in more of these phases being formed in specimens brazed at lower pressure. The thicker intergranular phases of the latter specimens can less readily accommodate the thermal stresses of heating and water quenching for the T6 treatment and the braze fractures.

Porosity and silicon phase in the braze metal of the 6061/Aℓ12Si joint brazed at 28 kPa (4 psi) were no longer present when a brazing pressure of 26 MPa (3.8 ksi) was applied.

Although the brazing pressure used to produce high strength joints was high (26 MPa (3.8 ksi)), it is probable that high quality joints could also be produced at some lower pressure.

3. DIFFUSION TREATMENT

Microstructural changes due to postbraze diffusion treatment were evident in all of the brazed joints, with the exception of the 7075/Mg joint. A minor increase in the bend ductility of 6061 joints brazed with vapor deposited Ag was the only improvement realized from diffusion

treatment. Cracking of the 6061/Au and 7075/Mg joints was made more severe by diffusion treatment.

4. METALLOGRAPHY

The conventional metallographic methods used in this investigation were often not adequate for a complete analysis of the microstructures. The factors which made metallographic examination difficult were the different polishing and etching behavior of base metal and braze metal, the very thin braze metal, the presence of brittle phases, and unfamiliar microstructures. It was often impossible to distinguish between microporosity, inclusions, microcracks, dark-etching phases, and voids left by the breaking out of brittle phases during specimen preparatior. A lengthy, detailed study of each base metal-filler metal combination, probably with more advanced metallographic techniques, would be necessary for a thorough understanding of the observed microstructures and their effect on the joint mechanical properties.

5. STRENGTH AND DUCTILITY OF BRAZED JOINTS

An extensive literature search revealed only a single article with information on the mechanical properties of brazed butt joints in aluminum alloys. Typical values for furnace brazed butt joints in 6061 aluminum (no further brazing details are given) of 234 MPa (34 ksi) tensile strength and 3% elongation have been reported (Reference 2). Both the tensile strength and the elongation would indicate that these specimens were given a postbraze T6 heat treatment.

The present work has demonstrated that brazed butt joints can be produced in 6061 aluminum with the tensile strength of heat treated and artificially aged base metal, accompanied by good tensile elongation and bend properties. The filler metals (silver and Al12Si) are equally suitable. The lower brazing temperature with silver filler metal permits a second brazing operation on parts which have previously been brazed with Al12Si filler metal.

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