Infrared Brazing Cu and Ti Using a 95Ag-5Al Braze Alloy

R.K. SHIUE, S.K. WU, and C.H. CHAN

Dynamic wetting angle measurements, microstructural evolution, reaction kinetics, and shear strength of infrared brazing Cu and Ti using a 95Ag-5Al braze alloy are evaluated. The specimen infrared brazed at 900 °C consists mainly of Cu_2Ti and Cu_4Ti. Both CuTi and Cu_4Ti_3 are observed at the interface between the braze and Ti substrate. Microstructures of Ti/95Ag-5Al/Cu joints infrared brazed at 830 °C and 850 °C are very different from that of the joint infrared brazed at 900 °C, because the dissolution of both substrates significantly decreased as the brazing temperature decreased. Specimens infrared brazed at 830 °C and 850 °C are primarily comprised of Ag-Cu eutectic and the Cu-rich phase. Two interfacial reaction layers, including Ti_2Cu and $AlCu_2Ti$, are found in the experiment. The shear strengths of infrared brazed specimens at 830 °C and 850 °C are between 160 and 198.5 MPa, and are fractured along the interfacial reaction layers, $AlCu_2Ti$ and Ti_2Cu, between the braze alloy and Ti substrate. The use of the infrared brazing provides an effective way to inhibit the growth of intermetallics at the interface between the braze alloy and substrate.

I. INTRODUCTION

THE joining of pure titanium and copper currently is applied for the production of titanium targets used in physical vapor deposition (PVD) infrastructures. In this process, it is desirable that the high-purity titanium target is bonded with the water-cooled oxygen-free copper substrate without significant loss of its thermal conductivity. Brazing is often one of the best choices in manufacturing of the Ti target due to the high thermal conductivity of the brazed joint as compared with adhesive bonding.[1,2] It has been reported that the titanium alloy can be successfully brazed with several silver-based braze alloys,[2–6] and 95Ag-5Al in weight percent is a type of silver-based braze alloy. The melting point of pure Ag is significantly decreased with 5 wt pct Al additions, resulting in solidus and liquidus temperatures of 95Ag-5Al braze being 780 °C and 810 °C, respectively.[2]

Infrared heating is a novel technique characterized by an extraordinary fast heating rate up to 3000 °C/min.[7] Thus, the interfacial reaction among the molten braze and substrates during infrared brazing may be greatly decreased due to the rapid thermal history. Accordingly, there are many successfully infrared-brazed joints demonstrated in previous studies.[7–10] This research investigates infrared brazing Cu and Ti using the 95Ag-5Al braze alloy. Dynamic wetting angle measurement, microstructural evolution, reaction kinetics across the brazed joint, and shear strength are comprehensively evaluated in the experiment.

II. MATERIAL AND EXPERIMENTAL PROCEDURES

The base metals used in the experiment were commercially pure titanium plate and oxygen-free copper plate. 95Ag-5Al alloy was chosen as the brazing filler metal, and braze alloy foil with thickness of 100 μm was used throughout the experiment.

Figure 1(a) illustrates the schematic diagram of the wetting angle measurement device. The instrument was composed of three major parts, an infrared vacuum furnace, a specimen holder, and the image analysis system. The ULVAC*

SINKO-RIKO RHL-P816C infrared furnace was used as the main body of the vacuum furnace. The measurement was performed in a vacuum of 5×10^{-5} mbar throughout the experiment. Infrared rays were generated from the infrared lamps, transmitting through a transparent quartz tube and focused on the specimen holder. One end of the quartz tube was attached to the specimen holder, and the other end could transmit the signal into the image analysis system. An enlarged diagram of the specimen holder is shown in Figure 1(b). The filler metal was located on the substrate (Cu or Ti), and a thermocouple was simultaneously in contact with the substrate. A graphite holder below the substrate was used in order to enhance the absorptivity of the infrared rays.

The braze alloy (95Ag-5Al, wt pct) with near spherical shape used in the wetting angle test was prepared from the foil by vacuum arc remelting with the operation voltage of 60 V and 50 to 60 A. The weight of each sphere was kept to approximately 0.12 g. There was an alumina plate next to the filler metal and substrate. The alumina plate was used as the background of the filler metal image during the wetting angle measurements. The image of the molten braze on the substrate was captured simultaneously by a charge coupled device (CCD) at a constant frequency of 20 frames per second. The active pixels of the CCD camera were 768 (H) × 494 (V). The CCD images were then saved in a computer for further analyses.

The heating rate was set at 900 °C/min throughout the experiment. All samples were preheated to 500 °C for 90 seconds before heating to the brazing temperature. Table I summarizes all process variables used in infrared brazing copper and titanium. After infrared brazing, the cross section of the brazed specimens was examined using either a LEO*

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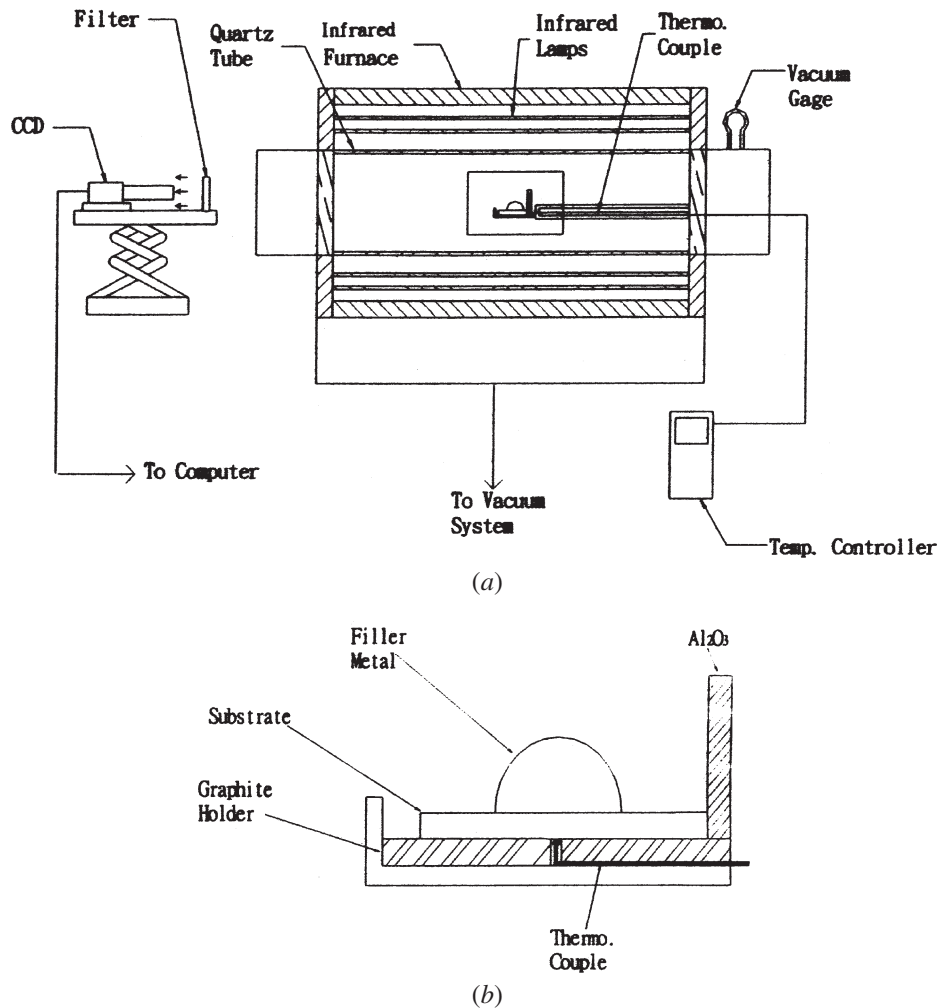Manuscript submitted December 12, 2003.

Fig. 1—Schematic diagram of (*a*) wetting angle measurement facility and (*b*) specimen holder in (a).

Table I. Process Variables Used in the Infrared Brazing

Filler Metal (Wt Pct)	Time (s)	830 °C	850 °C	900 °C
95Ag-5Al	60	M/S	M/S	M
	300	M/S	M/S	M

M: metallographic observation specimen, and S: shear test specimen.

1530 field emission scanning electron microscope (FESEM) or a PHILIPS* XL-30 scanning electron microscope (SEM)

*PHILIPS is a trademark of Philips Electronic Instruments Corp., Mahwah, NJ.

with an accelerating voltage of 15 kV. Quantitative chemical analyses were performed using a JEOL** JXL-8600SX

**JEOL is a trademark of Japan Electron Optics Ltd., Tokyo.

electron probe microanalyzer (EPMA) with an operation voltage of 20 kV and spot size of 1 μm.

Shear tests were performed in order to evaluate the bonding strength of selected infrared-brazed specimens.[6,7,9] A Shimadzu*

*Shimadzu is a trademark of Shimadzu Corp., Japan.

AG-10 universal testing machine compressed the infrared-brazed specimen with a constant speed of 1 mm/min. The fractured surface after the shear test was examined by SEM followed by a structural analysis. The structural analysis was performed using a PHILIPS PW1710 X-ray diffractometer with Cu K_α selected as the X-ray source. The X-ray scan rate was set at 4 deg/min, and its range was between 20 and 90 deg.

III. RESULTS AND DISCUSSION

A. *Dynamic Wetting Angle Measurements of 95Ag-5Al on Both Ti and Cu Substrates*

The image capture rate of the CCD was kept at 20 frames per second, so there were 6000 frames during 0 to 300 seconds. Additionally, there were two wetting angles between the molten braze and the substrate observed from each CCD captured image. The contact angle was obtained from averaging both right-side and left-side wetting angles of every CCD captured image. Figure 2 shows the time-dependent contact angle of 95Ag-5Al braze on Ti substrate at 830 °C, 850 °C, and 900 °C for various time periods, respectively. It should be noted that the time period (*X*-axis in Figure 2) is counted after the 95Ag-5Al braze alloy is melted during the test. According to Figure 2, the wetting angle of the
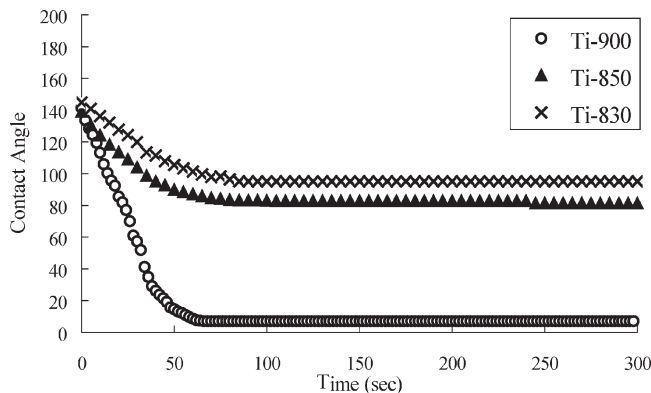
Fig. 2—Time-dependent contact angle of 95Ag-5Al braze on Ti substrate.
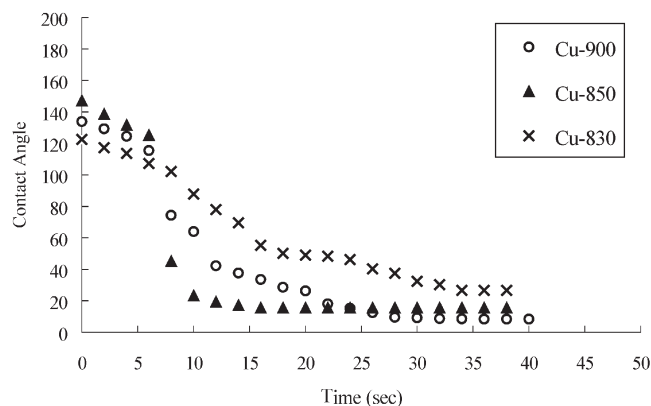

Fig. 3—Time-dependent contact angle of 95Ag-5Al braze on Cu substrate.

molten braze on the Ti substrate tested at 830 °C is as high as 100 deg. The wetting angle decreases with an increase in the testing temperature. It is also noted that the wetting angle decreases significantly in the first 50 seconds for the specimen tested at 900 °C, and the molten 95Ag-5Al braze can completely wet the Ti substrate after 65 seconds.

Figure 3 displays the time-dependent contact angles of 95Ag-5Al braze on Cu substrate at 830 °C, 850 °C, and 900 °C, respectively. In contrast to Figure 2, the molten braze demonstrates excellent wettability on the Cu substrate for all testing temperatures. For instance, the Cu substrate is readily wetted by the molten 95Ag-5Al braze at 900 °C after 10 seconds. It is also noted that the fluctuation of wetting angles for the Cu substrate is much more prominent than that of Ti substrate, as can be seen from a comparison of Figures 2 and 3. This is probably caused by high reflectivity of the Cu substrate during infrared heating, which may result in high temperature fluctuations during the wetting angle measurement. Consequently, the fluctuation in wetting angle measurement of the Cu substrate is much more prominent than that of Ti substrate.

B. *Microstructural Evolution of the Infrared-Brazed Specimen*

Figure 4 shows the SEM backscattered electron images (BEIs) of Ti/95Ag-5Al/Cu specimens that were infrared brazed at various brazing conditions. The microstructure of

infrared-brazed Ti/95Ag-5Al/Cu joints at 900 °C is very different from that of Ti/95Ag-5Al/Cu joints infrared brazed at 830 °C and 850 °C since cracks are observed from the infrared brazed joint at 900 °C, as illustrated in Figures 4 (e) and (f). In contrast, sound joints are formed for the specimens infrared brazed at 830 °C and 850 °C. The EPMA chemical investigations have been performed in order to identify various phases in the brazed joint.

Figure 5 shows the SEM BEI and EPMA results of the Ti/95Ag-5Al/Cu joint infrared brazed at 900 °C for 60 seconds. The microstructure of the Ti/95Ag-5Al/Cu joint is very similar to that of previously investigated Ti/Ag/Cu joints.[11] The infrared-brazed joint mainly consists of Cu_2Ti (marked as D) and Cu_4Ti (marked as E). There are at least three interfacial phases, including Ti-rich (marked as A), CuTi (marked as B), and Cu_4Ti_3 (marked as C), as illustrated in Figure 5. It is unusual that the Ag-rich phase is not observed across the infrared-brazed joint based on the experimental observations. The Ag-Cu-Ti ternary alloy phase diagram is cited here in order to explain the disappearance of the Ag content in the brazed joint.

Figure 6 shows the liquidus projection of the Ag-Cu-Ti ternary alloy phase diagram in atomic percent and weight percent, respectively.[12,13] According to Figure 6(a), there is a huge miscibility gap among the liquids for temperatures above 850 °C, with point c_1 at approximately 850 °C.[11,12] The molten braze tends to separate into two liquids, an Ag-rich liquid and a liquid rich in Cu and Ti for temperatures exceeding 850 °C. For instance, there are two immiscible liquids, L_1 and L_2, at 900 °C, and the reaction scheme is as formulated as[12]

$$L_1'' + CuTi \leftrightarrow L_2'' + Cu_4Ti_3 \quad (900 \text{ °C}) \qquad [1]$$
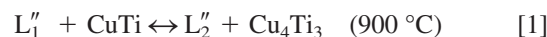
The L_1'' liquid is rich in Cu and Ti, while L_2'' liquid is Ag rich. According to the experimental observations, the Ag-rich liquid (L_2'') overflows out of the joint, so only the liquid rich in Ti and Cu (L_1'') is left in the joint. It is deduced that the overflow of the Ag-rich liquid (L_2'') results from the existence of the miscibility gap in the Ag-Cu-Ti ternary phase diagram. In addition, both CuTi and Cu_4Ti_3 are observed at the interface between the braze and Ti substrate, as illustrated in Figure 5. The binary Cu-Ti phase diagram is quoted here, because the infrared-brazed joint is mainly comprised of Cu and Ti. According to the Cu-Ti phase diagram, a series of invariant reactions upon cooling of the liquid are found:[11,14]

$$Cu_4Ti_3 + L \leftrightarrow Cu_2Ti \quad (\text{peritectic, } 890 \text{ °C} \pm 10 \text{ °C}) \, [2]$$

$$L \leftrightarrow Cu_2Ti + \beta Cu_4Ti \quad (\text{eutectic, } 875 \text{ °C} \pm 10 \text{ °C}) \, [3]$$

If the solidification of molten braze obeys the previous equations, then the residual molten braze is completely solidified into Cu_2Ti and Cu_4Ti. Accordingly, the experimental results, as demonstrated in Figure 5, are in accordance with the Cu-Ti binary alloy phase diagram.

Figure 7 displays the SEM BEIs and EPMA chemical analysis results of the Ti/95Ag-5Al/Cu specimen infrared brazed at 850 °C for 300 seconds. It is noted that there is no interfacial reaction layer between the braze and Cu substrate. However, at least two reaction layers are observed at the interface between the braze and Ti substrate, and the presence of reaction layers probably impairs the dissolution of substrate. Based on the EPMA chemical analyses, the infrared-brazed joint is primarily comprised of Cu-rich and
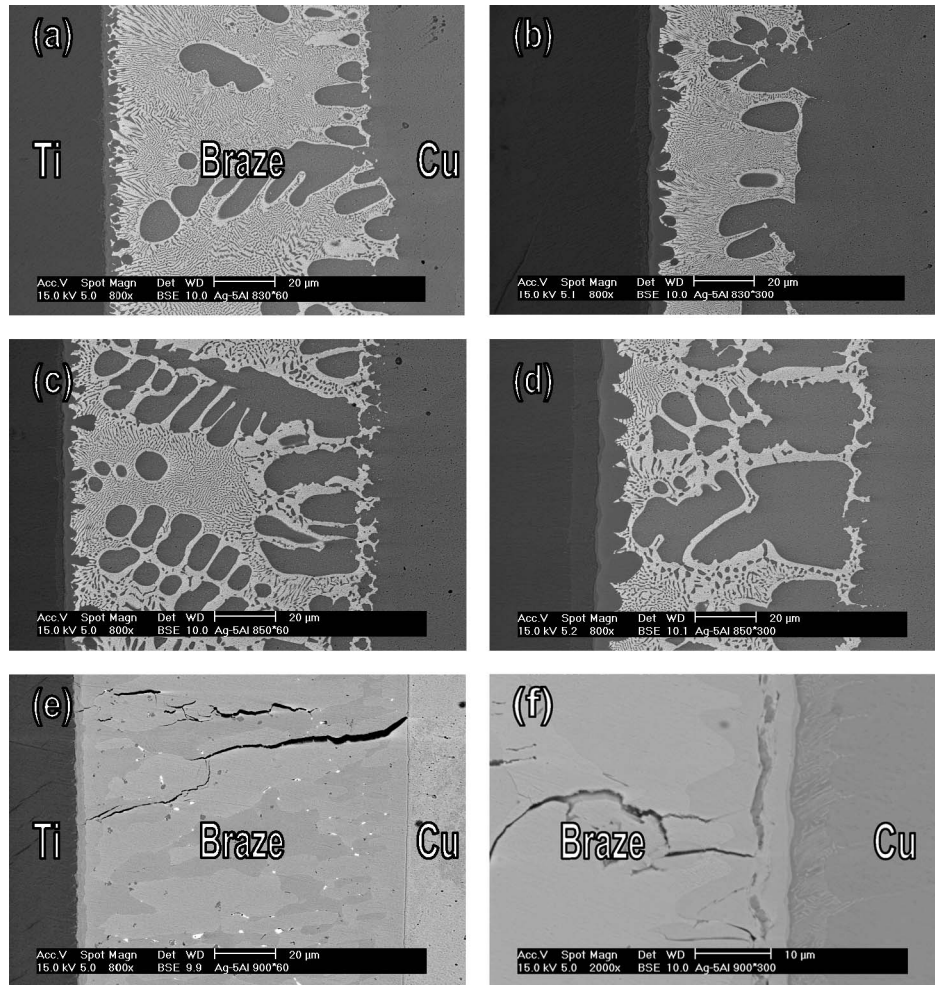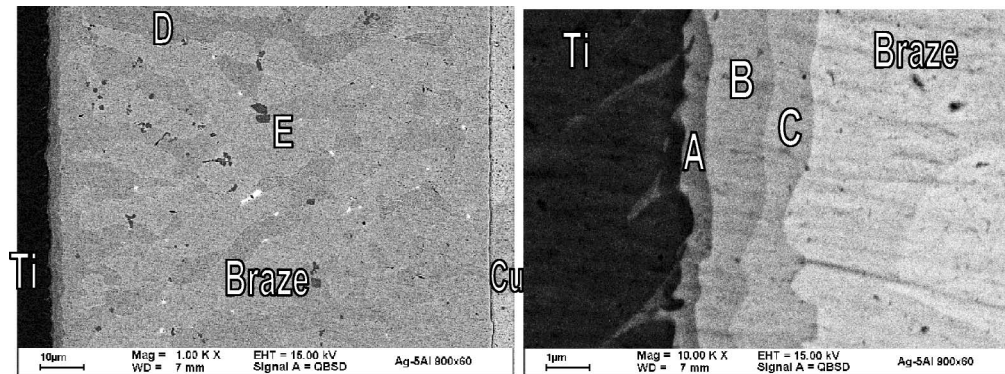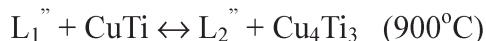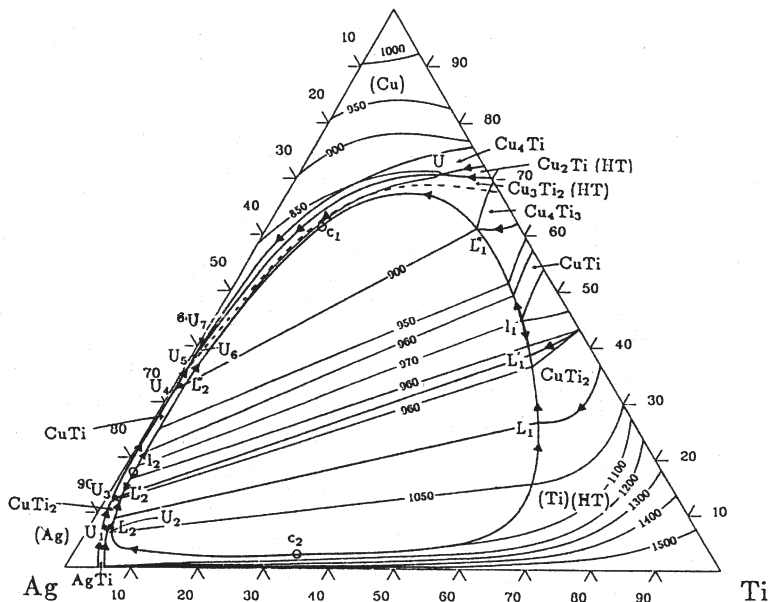
Fig. 4—SEM BEIs of Ti/Ag-5Al/Cu joints infrared brazed at (*a*) 830 °C, 60 s; (*b*) 830 °C, 300 s; (*c*) 850 °C, 60 s; (*d*) 850 °C, 300 s; (*e*) 900 °C, 60 s; and (*f*) 900 °C, 300 s.
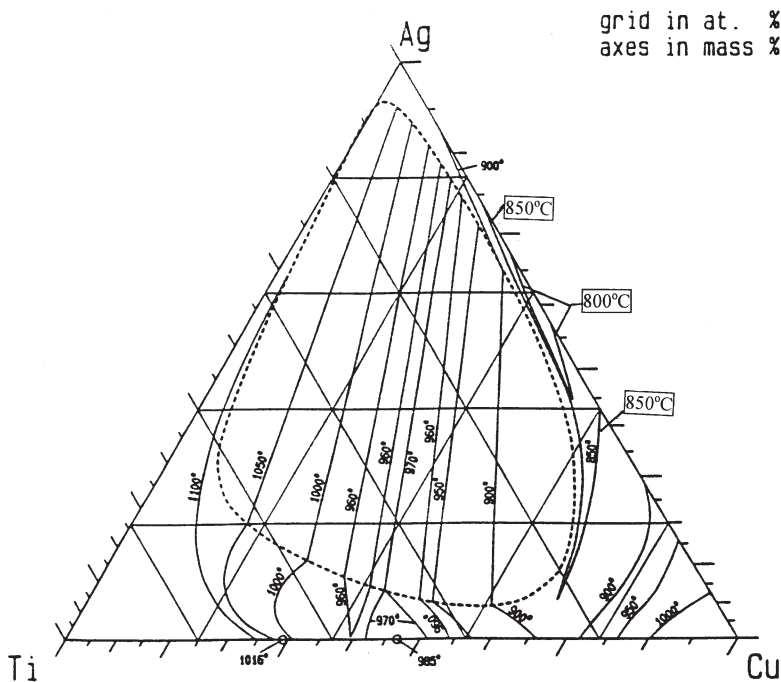

at%	A	B	C	D	E
Al	0.0	0.4	0.0	0.0	0.0
Ag	0.3	0.3	0.5	1.0	0.3
Cu	29.4	49.9	54.7	65.4	78.4
Ti	70.3	49.4	44.8	33.6	21.3
Phase	(Ti-rich)	CuTi	Cu$_4$Ti$_3$	Cu$_2$Ti	Cu$_4$Ti

Fig. 5—SEM BEI and EPMA results of Ti/95Ag-5Al/Cu joint infrared brazed at 900 °C for 60 s.

$$L_1'' + CuTi \leftrightarrow L_2'' + Cu_4Ti_3 \quad (900^{\circ}C)$$

(a)

(b)

Fig. 6—Liquidus projection of Ag-Cu-Ti ternary alloy phase diagram in (a) atomic percent and (b) weight percent.[12,13]

Ag-Cu eutectic as marked by D and E in Figure 7, respectively. Figure 8 shows the isothermal section of the Ag-Al-Cu ternary alloy phase diagram in atomic percent at 575 °C.[12] Both Ag and Cu can dissolve very large amounts of Al, up to 20 at. pct. In contrast, the maximum solubility of Ti in a Cu matrix is less than 1 at. pct at 500 °C, and the maximum solubility of Ag in Cu matrix is approximately 2 at. pct at 600 °C.[14] Therefore, it is expected that both the primary Cu-rich phase and Ag-Cu eutectic are alloyed with much more Al than Ti, which is consistent with the experimental results (Figure 7). In general, the infrared-brazed joint at 850 °C is comprised of a primary Cu-rich phase and Ag-Cu eutectic.
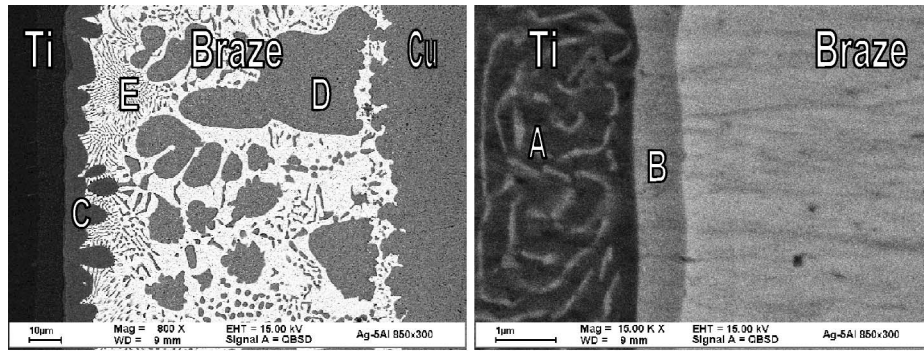
at%	A	B	C	D	E
Ag	0.5	1.2	0.8	7.9	60.7
Al	3.0	3.0	23.9	15.7	6.7
Cu	8.0	32.2	50.0	75.7	31.7
Ti	88.5	63.6	25.3	0.7	0.9
Phase	Ti-rich	Ti$_2$Cu	AlCu$_2$Ti	Cu-rich	Ag-Cu eutectic

Fig. 7—SEM BEI and EPMA chemical analysis results of the Ti/95Ag-5Al/Cu joint infrared brazed at 850 °C for 300 s.
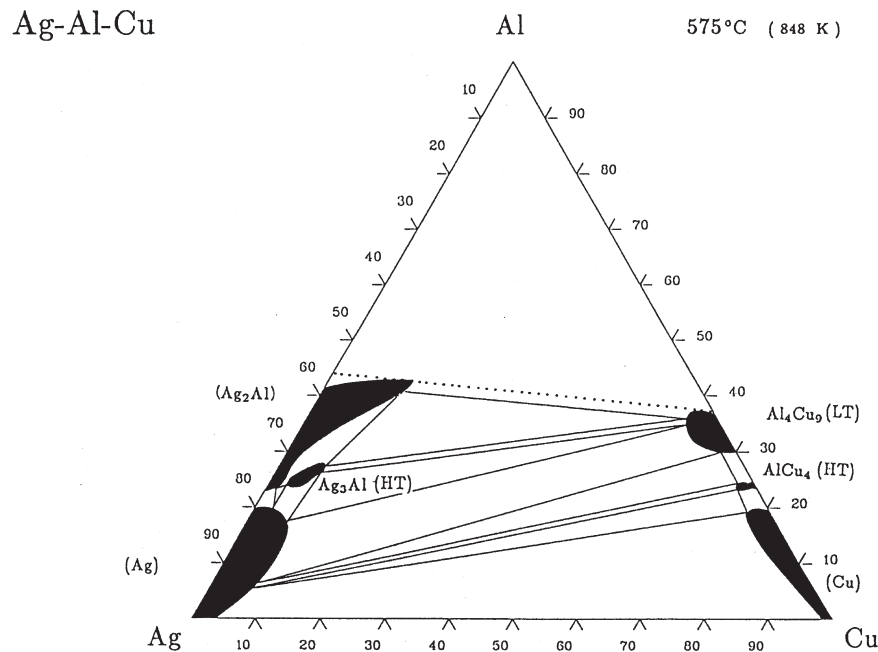

Fig. 8—Isothermal section of Ag-Al-Cu ternary alloy phase diagram at 575 °C.[12]

The change of braze alloy composition from 95Ag-5Al into Ag-Cu is caused by significant dissolution of Cu substrate into the molten braze during infrared brazing at 850 °C. In contrast, the dissolution of Ti substrate is much less prominent as compared with that of Cu substrate. This can be explained by limited solubility of Ti in Ag-Cu molten braze below 850 °C (Figure 6(b)) or the formation of interfacial reaction layer(s) between the molten braze and Ti substrate (Figure 7).

Based on the EPMA chemical analysis, there are at least two interfacial reaction layers in the joint, as shown in Figure 7. The stoichiometric ratio of Ti and Cu in phase B is close to Ti$_2$Cu. Similarly, the stoichiometric ratio between Al, Cu, and Ti of phase C is close to AlCu$_2$Ti. The formation of AlCu$_2$Ti phase indicates that Ti preferentially reacts with Al and Cu, instead of with Ag in the molten braze alloy. It has been previously reported that the AlCu$_2$Ti phase is observed at the TiAl boundary in brazing TiAl and INCONEL* 909

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*INCONEL is a trademark of INCO Alloys International, Hutington Woods, WV.

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using the 72Ag-28Cu (wt pct) braze alloy.[15] This was formed by the reaction of Ti, Al, and Cu during brazing, and it had a very high hardness of Hv 700,[15] which is in agreement with the experimental observations of this work.
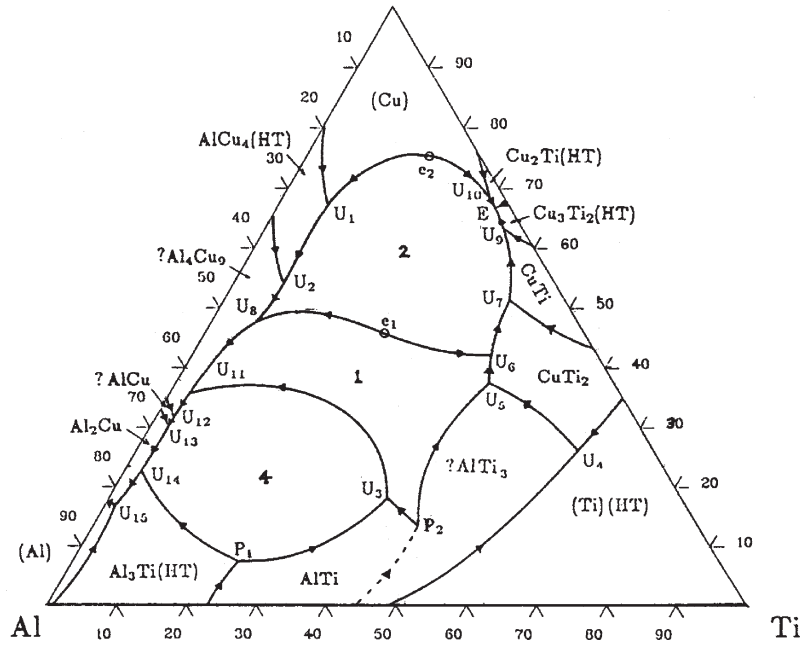
Fig. 9—Liquidus projection of Al-Cu-Ti ternary alloy phase diagram in atomic percent.[7,12]
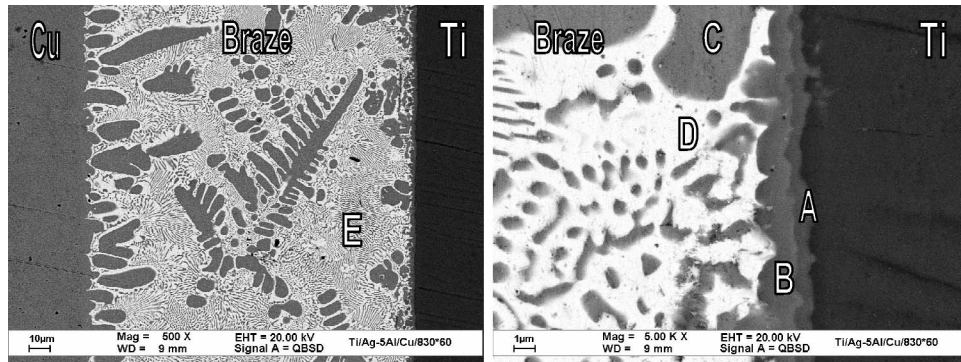
At%	A	B	C	D	E
Ag	1.2	0.8	2.7	80.9	54.4
Al	3.0	23.9	18.1	4.7	6.8
Cu	32.2	50.0	78.6	13.1	38.1
Ti	63.6	25.3	0.6	1.2	0.7
Phase	(Ti$_2$Cu)	AlCu$_2$Ti	Cu-rich	Ag-rich	Ag-Cu eutectic

Fig. 10—SEM BEI and EPMA chemical analysis results of the Ti/95Ag-5Al/Cu joint infrared brazed at 830 °C for 60 s.

Figure 9 illustrates the liquidus projection of Al-Cu-Ti ternary alloy phase diagram in atomic percent.[7,12] Because the equilibrium temperatures of all invariant reactions close to AlCu$_2$Ti phase far exceed 850 °C, the interfacial AlCu$_2$Ti reaction layer is solidified from the molten braze during infrared brazing at 850 °C (or 830 °C). This is evidenced by the irregular morphology of the AlCu$_2$Ti phase (marked as C), as illustrated in Figure 7. It also can be noted that the morphology of AlCu$_2$Ti phase is very different from that of the interfacial Ti$_2$Cu phase, as marked by B in Figure 7. According to Figure 9, both AlCu$_2$Ti and Ti$_2$Cu phases share boundary curve, as do the Ti$_2$Cu phase and Ti substrate. There are no other phases other than Ti$_2$Cu between AlCu$_2$Ti and Ti. The average cooling rate is approximately 20 °C/min after infrared brazing. Thus, it is

reasonable to deduce that the Ti$_2$Cu phase with the smooth interface is probably the result of the solid-state interdiffusion between AlCu$_2$Ti phase and the Ti substrate.

Figure 10 shows both the SEM BEI and EPMA chemical analysis results of the Ti/95Ag-5Al/Cu joint infrared brazed at 830 °C for 60 seconds. Similar to the specimen infrared brazed at 850 °C for 300 seconds, the brazed joint is mainly comprised of the Ag-Cu eutectic and Cu-rich phase, as marked by points C through E in Figure 10. There are at least two interfacial reaction layers, Ti$_2$Cu (marked as A) and AlCu$_2$Ti (marked as B), as illustrated in the figure. The thickness of the interfacial AlCu$_2$Ti phase is greatly decreased as the brazing condition changes from 850 °C, 300 seconds to 830 °C, 60 seconds According to Figure 6(b), dissolution of the Ti substrate into the molten braze is significantly decreased by decreasing the brazing temperature from 850 °C to 830 °C. Accordingly, the growth of interfacial AlCu$_2$Ti phase is inhibited due to insufficient Ti transport from Ti substrate into the molten braze during infrared brazing. Although the use of the infrared brazing cannot completely eliminate formation of the interfacial reaction layer(s), infrared brazing provides an effective way to inhibit the growth of intermetallics at the interface between the braze alloy and substrate. Additionally, the dissolution of both substrates during infrared brazing can be greatly decreased because of its rapid thermal history.

C. *Wetting Behavior of 95Ag-5Al Braze on Cu and Ti Substrates*

As discussed earlier, the molten braze demonstrates excellent wettability on the Cu substrate for all testing temperatures. However, the wetting angle of the molten braze on the Ti substrate tested at 830 °C is as high as 100 deg, but its wetting angle is decreased as the testing temperature increases. Accordingly, the molten 95Ag-5Al braze can effectively wet the Ti substrate at 900 °C, and the dissolution of the substrate into the molten braze plays an important role in the wetting behavior of the 95Ag-5Al braze alloy.

Figure 6(b) displays the liquidus surface of the Ag-Cu-Ti ternary alloy phase diagram in weight percent.[13] The reaction scheme below 850 °C is very different from that of 900 °C, because there is no miscibility gap below 850 °C. Both Cu and Ti substrates are dissolved into the molten 95Ag-5Al braze. However, the dissolution of Cu substrate into the molten braze is much more prominent than that of Ti substrate. The dissolution of Cu substrate is very prominent for all testing temperatures, so the molten braze demonstrates excellent wettability on the Cu substrate. In contrast, the dissolution of Ti substrate into the molten braze is significantly decreased as the testing temperature decreases from 900 °C to 800 °C.[13] The solubility of Ti in Ag-Cu-Ti liquid at 800 °C is as low as 5 wt pct, as shown in Figure 6(b). Apparently, the decrease of Ti substrate dissolved into the molten braze may result in poor wettability of the braze alloy tested below 850 °C (Figure 2).

In addition to dissolution of the substrate into the molten braze during the wetting angle test, the types of interfacial reaction layers also play an important role in wetting behavior of the 95Ag-5Al braze on the Ti substrate. The formation of the AlCu$_2$Ti interfacial reaction layer at 850 °C or 830 °C greatly deteriorates the wettability of the molten braze on the Ti substrate. In contrast, the presence of the interfacial CuTi and Cu$_4$Ti$_3$ reaction layers is beneficial for the wettability

Table II. The Shear Strength of Infrared-Brazed Cu/95Ag-5Al/Ti Specimens

Brazing Temperature	Brazing Time	Shear Strength	Average Shear Strength
830 °C	60 s	164 MPa	163.5 MPa
	60 s	163 MPa	
830 °C	300 s	186 MPa	190.5 MPa
	300 s	195 MPa	
850 °C	60 s	197 MPa	198.5 MPa
	60 s	200 MPa	
850 °C	300 s	141 MPa	160.0 MPa
	300 s	180 MPa	

of the molten 95Ag-5Al braze on the Ti substrate, as illustrated in Figure 2.

D. *Mechanical Evaluation of the Infrared-Brazed Specimen*

Because there are cracks observed for the infrared-brazed specimen at 900 °C, as shown in Figures 4(e) and (f), it is advised that the infrared brazing temperature should be below 900 °C in order to avoid the formation of brittle phase(s) in the joint. Shear tests were performed for specimens infrared brazed at 830 °C and 850 °C, respectively. Table II shows the shear strength of infrared-brazed Cu/95Ag-5Al/Ti specimens. The shear strengths of infrared-brazed Cu/95Ag-5Al/Ti specimens are between approximately 141 and 200 MPa. In addition, an SEM failure analysis was performed in order to reveal the fracture mechanism of the infrared-brazed specimen in the shear test, with the following results.

Cross sections of the aforefractured specimens were mounted in epoxy and examined by SEM.[7] Figure 11 shows the cross section of the Ti/95Ag-5Al/Cu joint after shear test infrared brazing for various brazing conditions. The BSE images are chosen for the SEM failure analysis. Distortion of the infrared-brazed joint is observed due to high flow stress in the shear test, as shown in Figure 11(c) by an arrow. All infrared-brazed specimens were fractured along the interfacial reaction layer between Ti and the braze alloy. Additionally, the aforementioned EPMA chemical analyses demonstrate that the AlCu$_2$Ti phase dominates the interfacial reaction between the braze and Ti substrate. The hardness of the AlCu$_2$Ti phase is as high as Hv 700.[15] It is reasonable to infer that the interfacial AlCu$_2$Ti is brittle and detrimental to its bonding strength. Figure 12 shows fractographs after shear test for specimens infrared brazed at various brazing conditions. The fractured surface is primarily composed of cleavage instead of ductile dimple fracture. It is thus reasonable to conclude that the interfacial AlCu$_2$Ti reaction layer is brittle, and its formation undermines the shear strength of the infrared-brazed joint.

The X-ray structural analyses of the fractured surfaces after shear test for specimens infrared brazed at various conditions are also performed. The experimental results demonstrate that the characteristic reflections of silver, copper, and Ti are widely observed in the X-ray data, which is agreement with the previous EPMA chemical analysis results. In addition, the X-ray reflections of interfacial Ti$_2$Cu are weak because of its low thickness. Unfortunately, the X-ray analysis of the AlCu$_2$Ti phase cannot be accurately identified due to insufficient structural data available in the JCPDS data bank.
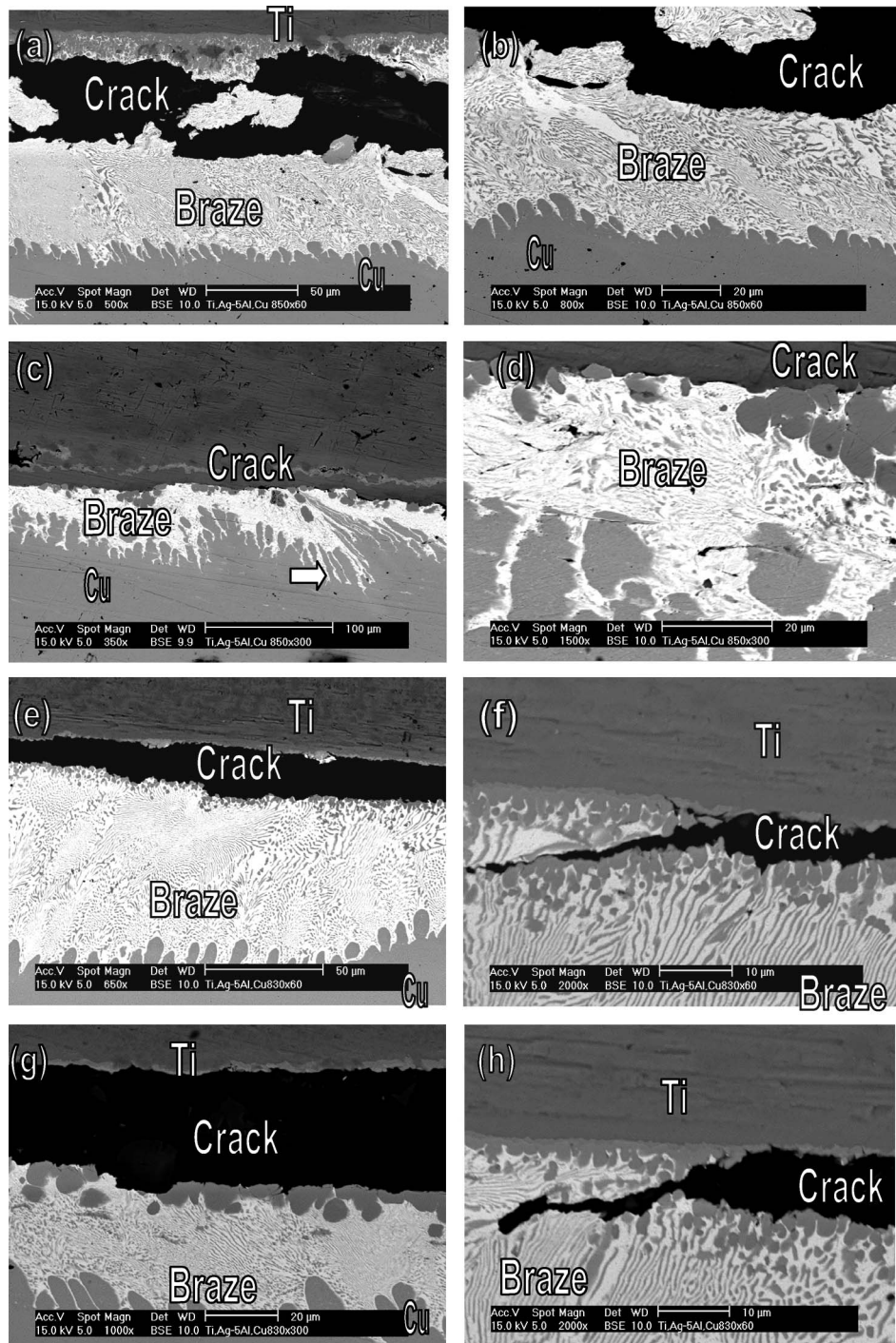
Fig. 11—Cross section of the Ti/95Ag-5Al/Cu joint after shear test infrared brazed at (*a*) and (*b*) 850 °C, 60 s; (*c*) and (*d*) 850 °C, 300 s; (*e*) and (*f*) 830 °C, 60 s; and (*g*) and (*h*) 830 °C, 300 s.

IV. CONCLUSIONS

The microstructural evolution and bonding strength of the infrared-brazed Cu/95Ag-5Al/Ti joint were experimentally assessed. The primary conclusions are summarized as follows.

1. The wetting angle of the molten braze on the Ti substrate tested at 830 °C is as high as 100 deg, and the wetting angle rapidly decreases with increasing brazing temperature. The molten 95Ag-5Al braze can completely wet the Ti substrate at 900 °C after 65 seconds. In contrast, the molten braze demonstrates excellent wettability on Cu substrate for all testing temperatures.

2. For specimens infrared brazed at 900 °C, the molten braze tends to separate into two liquids, an Ag-rich liquid and a liquid rich in Cu and Ti. The Ag-rich liquid flows out of the joint, so only the liquid rich in Ti and Cu is left in the joint after brazing. The infrared-brazed joint consists mainly of Cu_2Ti and Cu_4Ti. Additionally, both CuTi and Cu_4Ti_3 are observed at the interface between the braze and Ti substrate.
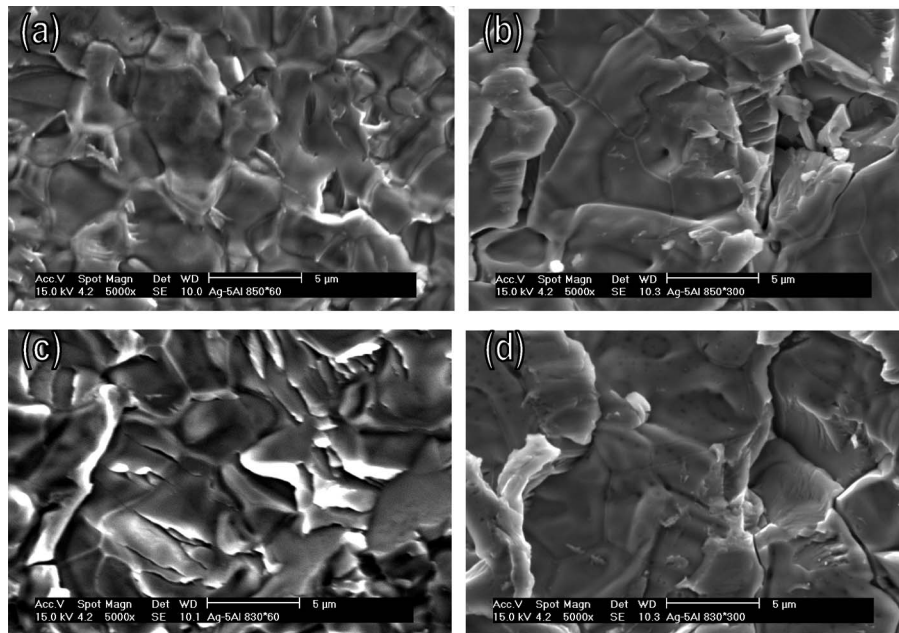
Fig. 12—Fractographs after shear test for specimens infrared brazed at (*a*) 850 °C, 60 s; (*b*) 850 °C, 300 s; (*c*) 830 °C, 60 s; and (*d*) 830 °C, 300 s.

3. The microstructures of specimens infrared brazed at 830 °C and 850 °C are very different from that of the specimen infrared brazed at 900 °C. The dissolution of Ti substrate significantly decreases as the brazing temperature is decreased from 900 °C into 850 °C (or 830°C). Specimens infrared brazed at 830 °C and 850 °C are primarily comprised of Cu-rich phase and Ag-Cu eutectic. In addition, both Ti_2Cu and $AlCu_2Ti$ phases are observed at the interface between the braze and Ti substrate.

4. Although the use of infrared brazing cannot completely prohibit the formation of interfacial reaction layer(s), infrared brazing provides an effective way to inhibit the growth of reaction layer(s) at the interface between braze alloy and substrate.

5. It is advisable that the infrared brazing temperature be kept below 900 °C in order to avoid the formation of brittle phase(s) in the joint. The shear strengths of infrared-brazed specimens at 830 °C and 850 °C are between 160 and 198.5 MPa. All infrared-brazed specimens fracture along the interfacial $AlCu_2Ti$ reaction layer between Ti and the braze alloy, and extensive cleavage fracture dominates the fractured surface. Thus, the interfacial $AlCu_2Ti$ reaction layer is detrimental to the shear strength of the infrared-brazed joint.

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