Development of a Low-Melting-Point Filler Metal for Brazing Aluminum Alloys

T.H. CHUANG, M.S. YEH, L.C. TSAO, T.C. TSAI, and C.S. WU

The study is concerned with developing low-melting-point filler metals for brazing aluminum alloys. For this purpose, thermal analyses of a series of Al-Si-Cu-Sn filler metals have been conducted and corresponding microstructures observed. The results showed that the liquidus temperature of Al-Si-Cu filler metals dropped from 593 °C to 534 °C, when the amount of copper was increased from 0 to 30 pct. As the copper content reached further to 40 pct, the liquidus temperature would rise to 572 °C. By adding 2 pct tin into the Al-Si-20Cu alloys, the liquidus and solidus temperature would fall from 543 °C to 526 °C and from 524 °C to 504 °C, respectively. The main microstructures of Al-Si-Cu alloys consist of the α-Al solid solution, silicon particles, the $CuAl_2$ (θ) intermetallic, and the eutectic structures of Al-Si, Al-Cu, and Al-Si-Cu. For further improvement of the brazability of this filler metal, magnesium was added as a wetting agent, which would remove the residual oxygen and moisture from the brazed aluminum surface and reduce the oxide film. Based on results gleaned from the thermal analyses, a new filler metal with the composition Al-7Si-20Cu-2Sn-1Mg is proposed, which possesses a melting temperature range of 501 °C to 522 °C and a microstructure that includes an Al-Si solid solution, silicon particles, a tin-rich phase, and $CuAl_2$, $CuMgAl_2$, and Mg_2Si intermetallic compounds. When this filler metal was used to braze the 6061-T6 aluminum alloy, an optimized bonding strength of 196 ± 19 MPa was achieved.

I. INTRODUCTION

OWING to their high specific strength, low cost, and superior corrosion resistance, aluminum alloys have been widely used in aerospace, automobile, and construction industries. Also, by virtue of good thermal conductivity, they are often employed in heat exchanger manufacturing. In industrial application, the bonding problem with these aluminum alloys has always been a serious consideration. Among a variety of techniques, brazing has been adopted as a reliable method for the bonding of aluminum components,[1] wherein a eutectic Al-12Si (wt pct) alloy is recognized as the most popular filler metal.[2,3] Although a sound joint can be obtained with this traditional filler metal, its brazing temperature is high relative to the melting point of pure aluminum due to the high eutectic point of the Al-12Si alloy at about 577 °C, which can bring about degradation of mechanical properties or even localized melting in some engineering aluminum alloys when brazed. Therefore, the development of a low-melting-point filler metal with a satisfactory bonding strength is an important task for the aluminum industry. For this purpose, a series of efforts have been made in the past few years. Humpston *et al.*[4] and Jacobson *et al.*[5] had developed an Al-20Cu-2Ni-5Si filler metal with a melting temperature range between 518 °C and 538 °C. For the brazing of a 3003 Al alloy with this filler metal, a shear strength over 75 MPa was obtained. Suzuki *et al.*[6] reported on a eutectic Al-4.2Si-40Zn filler metal with a melting point of 535 °C. The disadvantage of that filler metal lies in the fact that the vapor pressure of zinc is very high and thus unsuitable for the vacuum brazing process. Kayamoto *et al.*[7] found a low-melting-point Al-Ge-Si-Mg filler metal. When that filler metal was applied to braze a 6061 aluminum alloy at 575 °C for 60 minutes, the brazed joints provided sufficient joint strength equal to that of the base alloy. However, germanium is approximately 400 times the price of aluminum, making the alloy excessively expensive for most applications.

In this present study, an Al-7Si-20Cu-2Sn-1Mg filler metal with a low melting temperature range of 501 °C to 522 °C has been developed. When applied to braze the 6061-T6 aluminum alloy, this filler metal displayed excellent wettability and a high bonding strength of 196 ± 19 MPa.

II. EXPERIMENTAL

In order to develop a low-melting-point and high strength filler metal for the brazing of aluminum alloys, a series of Al-Si-Cu alloys with the compositions shown in Table I were prepared by melting in alumina crucibles equipped with an air furnace. The Al-Si alloys were molten first at 700 °C, and then the temperature was raised to 1000 °C when various amounts of copper (99.9 wt pct, 2-mm-diameter slug) were added into the molten aluminum alloy. Then, the mixture was stirred for 30 minutes for homogenization. Some Al-Si-Cu master alloys were further added with tin and magnesium elements. They were then cast in a stainless steel mold.

The thermal analyses for various filler metals (20 mg) were conducted with a DU PONT* model 2000 differential thermal analyzer (DTA). The specimens were heated from

*DU PONT is a trademark of E.I. Du Pont de Nemours & Co., Inc., Wilmington, DE.

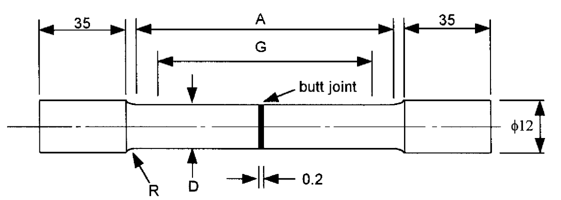
T.H. CHUANG, Professor, L.C. TSAO, Doctoral Candidate, and T.C. TSAI, Postdoctor, are with the Institute of Materials Science and Engineering, National Taiwan University, Taipei 106, Taiwan, Republic of China. M.S. YEH, Associate Professor, is with the Department of Mechanical Engineering, Chung-Hua University, Hsin-Chu 300, Taiwan, Republic of China. C.S. WU, Engineer, is with the Metal Industries Research and Development Center, Kaohsiung 811, Taiwan, Republic of China.

Manuscript submitted November 18, 1999.

Table I. Chemical Compositions and Thermal Properties of Al-Si-(Cu, Sn, Mg) Filler Metals in This Study

Sample	Chemical Compositions (Wt Pct) Si	Cu	Sn	Al	T_S* (°C)	T_L* (°C)	ΔT* (°C)
1	12.0	0	0	bal	579	593	14
2	11.4	5	0	bal	523	579	56
3	10.8	10	0	bal	522	565	43
4	10.2	15	0	bal	523	548	25
5	7.0	15	3	bal	504	545	41
6	9.6	20	0	bal	524	543	19
7	9.0	25	0	bal	523	537	14
8	8.4	30	0	bal	523	534	11
9	7.8	35	0	bal	522	558	36
10	7.2	40	0	bal	523	572	49
11	7.0	20	2	bal	504	526	22
12	7.0	20	2Sn-1Mg	bal	501	522	21
13	7.0	20	3	bal	504	526	22
14	9.0	20	5	bal	504	523	19
15	8.4	20	10	bal	504	520	16

*T_S indicates the solidus temperatures of the filler metals. T_L indicates the liquidus temperatures of the filler metals. $\Delta T = T_L - T_S$.



G: Gage length	50.00 ± 0.06 mm
D: Diameter	10.00 ± 0.02 mm
R: Radius of fillet, min	4 mm
A: Length of reduced section, min	60 mm

Fig. 1—Geometry and dimensions of the butt joint specimen for tensile testing.

room temperature to 600 °C at a heating rate of 10 °C/min under argon atmosphere. The microstructure was observed by means of optical microscopy and scanning electron microscopy after metallographic preparation and etching in 10 vol pct H_3PO_4 at 50 °C for 60 seconds. The phases as observed in the microstructure were identified with an X-ray diffractometer (XRD), an energy dispersive X-ray spectroscope, and an electron probe microanalyzer (EPMA). Finally, 6061-T6 aluminum alloy rods with a diameter of l2 mm were brazed in a vacuum furnace with the developed filler metal. For comparison, the conventional Al-12Si filler metal was also used. The brazing process was carried through in a vacuum of 5×10^{-5} torr for various specimens, respectively, at 550 °C, 575 °C, and 600 °C for 30 or 60 minutes. Some specimens after brazing were treated in a T6 temper condition: solution treated at 520 °C for 1.5 hours, water quenched, and then aged at 175 °C for 8 hours. The bonding strength at the butt joint was measured *via* tensile testing at a constant crosshead speed of 10^{-4} ms^{-1} at room temperature. The specimens for tensile testing were prepared from brazed samples, and their geometry and dimensions are given in Figure 1. In order to ascertain reproducibility, at least three specimens were tested for each brazing condition.

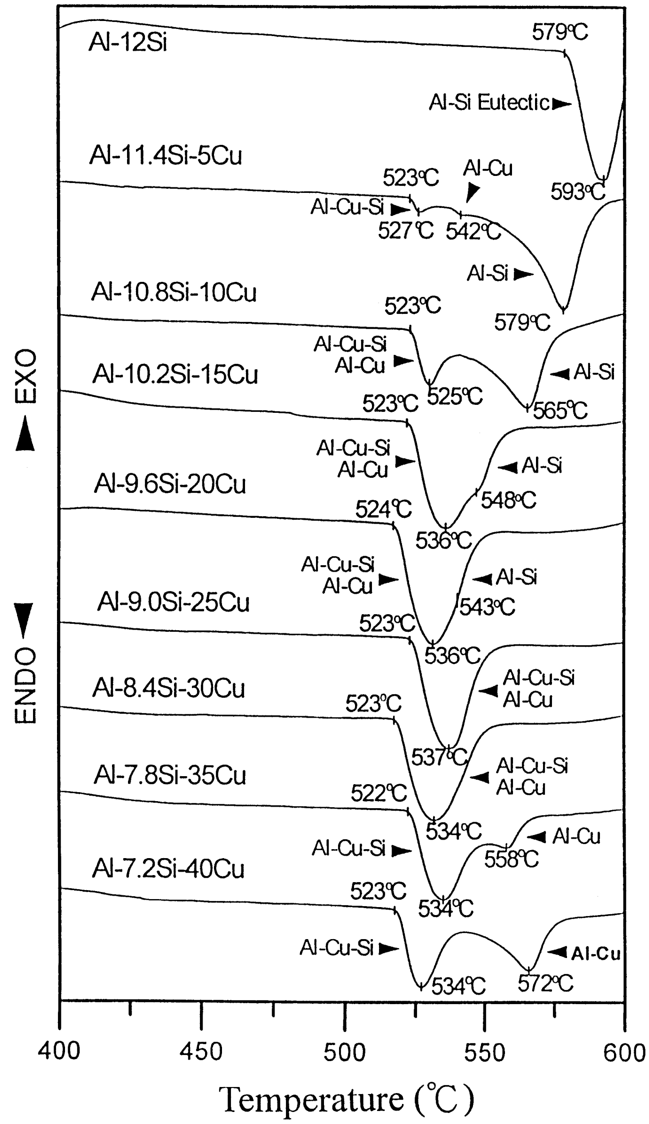


Fig. 2—DTA curves of the Al-12Si alloy and Al-Si-Cu filler metals.

III. RESULTS AND DISCUSSION

Figure 2 shows the DTA curves of various filler metals used in this study. The melting temperatures (solidus and liquidus) were taken from the DTA curves listed in Table I. Since the heating process in the DTA analysis was in a nonequilibrium condition, the eutectic Al-12Si alloy showed a melting temperature range from 579 °C to 593 °C, rather than the equilibrium eutectic point at 577 °C. Figure 3 showed two distinct structures as observed in the Al-12Si alloy: a lamellar Al-Si eutectic structure and an α-Al dendrite solid solution (shown as large white areas).

Adding 5 pct copper to the Al-12Si alloy would cause the solidus temperature to drop drastically from 579 °C to 523 °C. As the copper content increased further to 40 pct, the solidus temperature still remained constant. However, the liquidus temperatures of these Al-Si-Cu ternary alloys decreased from 593 °C to 534 °C when copper was added up to 30 pct, and then it would go up with the further increasing of the copper content. The result was consistent with the Al-Si-Cu ternary phase diagram,[8] which showed

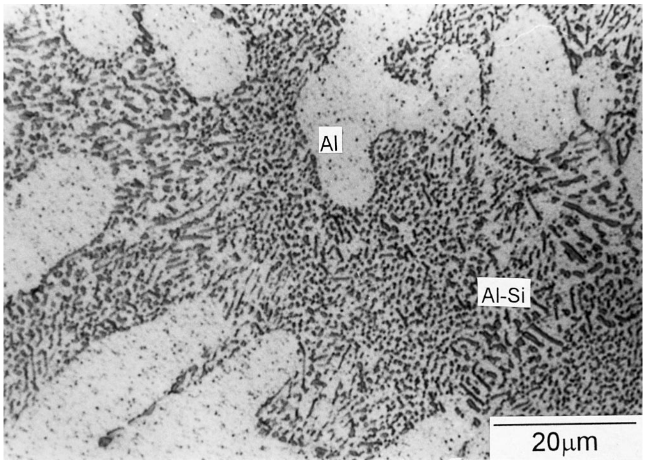


Fig. 3—Microstucture of the Al-12Si eutectic alloy, in casting condition.

a ternary eutectic point at 525 °C with the Al-5.2Si-26.7Cu composition.

Two endothermic peaks were found in the DTA curve of the Al-11.4Si-5Cu ternary alloy (shown in Figure 2), which corresponded to the Al-Cu-Si ternary eutectic point and Al-Cu binary eutectic point at 527 °C and 542 °C, respectively. Increasing the copper content up to 25 pct caused the endothermic peaks to approach each other. For the Al-9Si-25Cu alloy, which was near the Al-5.2Si-26.7Cu ternary eutectic composition, only one endothermic reaction was found in its DTA curve. When the copper addition went higher than 35 pct, two separated endothermic peaks in the DTA curve appeared again. For the development of a low-melting-point Al-Si-Cu alloy, the copper content was therefore suggested to range between 20 to 30 pct.

The microstructure of the Al-11.4Si-5Cu ternary alloy was composed of an Al-Si eutectic phase, a dendrite α-Al solid solution, and the $CuAl_2$ (θ) intermetallic compound (Figure 4(a)). When the copper content in Al-Si-Cu alloys was higher than 10 pct, some silicon particles (average size about 25 μm) with an Al-Si eutectic phase around them could be detected (Figure 4(b)). The scale of the Al-Si eutectic phase was reduced along with further increasing of the copper content. For the microstructure of the Al-9Si-25Cu alloy displayed in Figure 4(c), the Al-Si eutectic phase and the dendrite α-Al solid solution disappeared, replaced by the Al-Cu eutectic structure, the Al-Cu-Si ternary eutectic structure, and the $CuAl_2$ intermetallic compound. The $CuAl_2$ intermetallic compound increased along with the increasing of the copper content, which caused the alloy to become brittle and thus downgraded its corrosion resistance. For this reason, the concentration of copper in the developed filler metal should be fixed at about 20 pct.

In order to further depress the melting point of the filler

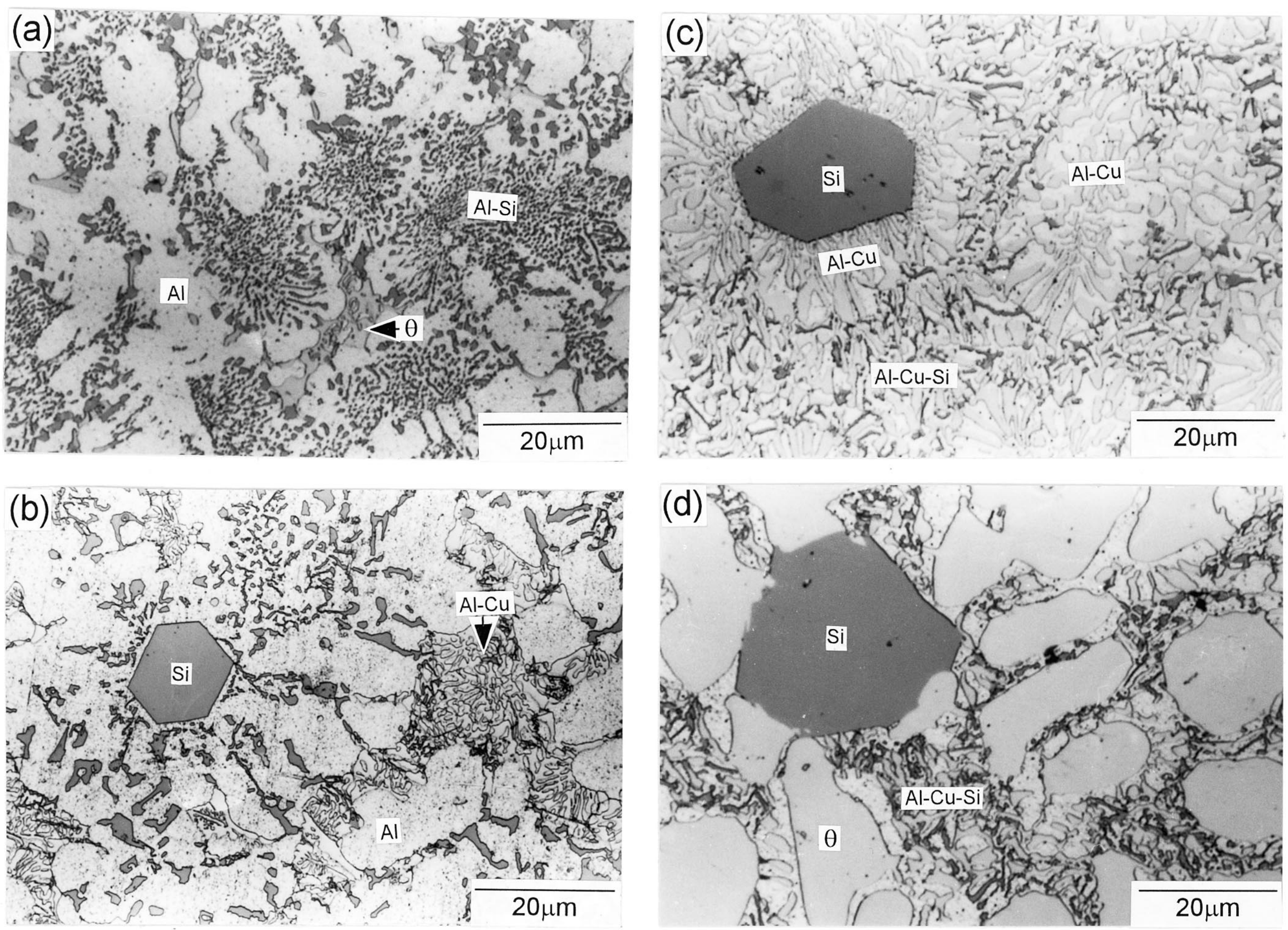


Fig. 4—Microstuctures of Al-Si-Cu filler metals, in casting condition: (*a*) Al-11.4Si-5Cu, (*b*) Al-10.8Si-10Cu, (*c*) Al-9.0Si-25Cu, and (*d*) Al-7.8Si-35Cu.

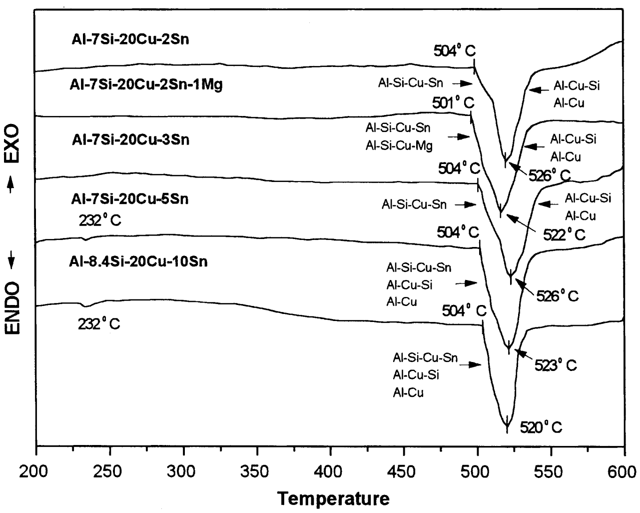


Fig. 5—DTA curves of Al-Si-Cu-Sn-(Mg) filler metals.

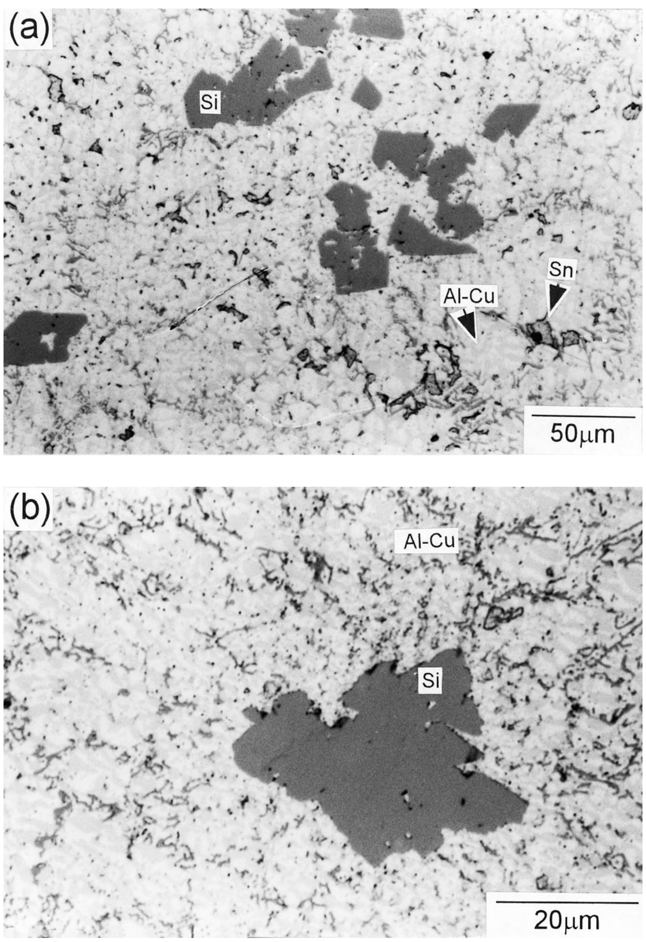


Fig. 6—Microstructures of Al-Si-Cu-Sn filler metals, in casting condition: (*a*) Al-9Si-20Cu-5Sn and (*b*) Al-8.4Si-20Cu-10Sn.

metal, various quantities of tin were added into the Al-Si-20Cu alloy. Figure 5 showed the DTA curves of these Al-Si-Cu-Sn quaternary alloys. An endothermic peak appeared at 232 °C in the DTA curves of Al-Si-Cu-Sn alloys with the tin content higher than 3 pct, which corresponded to the melting point of tin. It implied that the pure tin phase

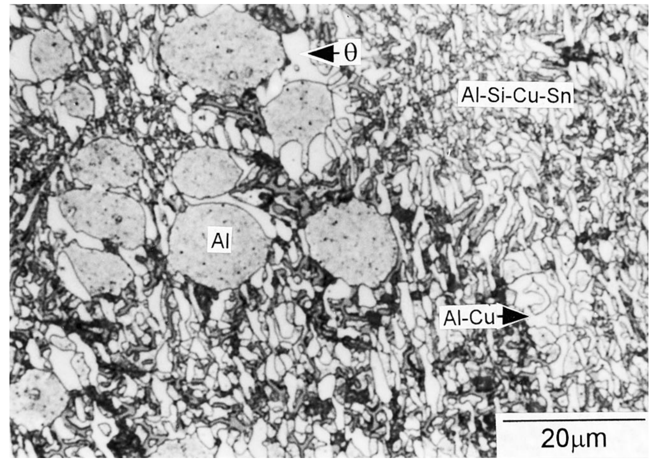


Fig. 7—Microstructure of the Al-7Si-20Cu-2Sn filler metals, in casting condition.

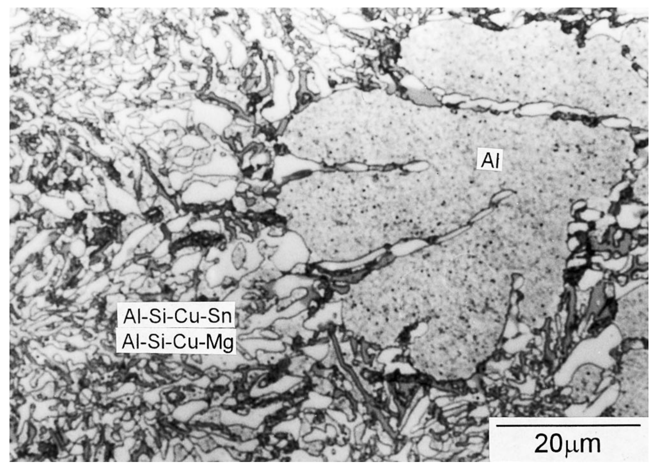


Fig. 8—Microstructure of the Al-7Si-20Cu-2Sn-1Mg filler metal, in casting condition.

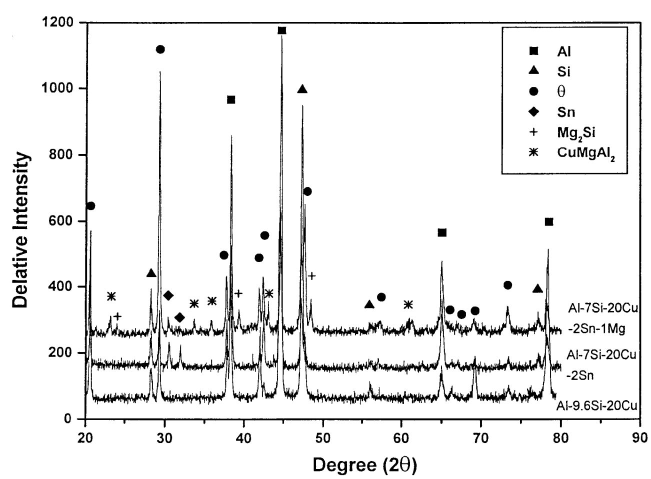


Fig. 9—XRD peaks for the Al-Si-Cu-(Sn,Mg) filler metals in this study.

was retained in these alloys. Another endothermic peak appeared at about 504 °C, which could be attributed to the Al-Cu(-Si-Sn) eutectic reaction. Microstructural observations in Figures 6(a) and (b) confirmed these results, displaying the

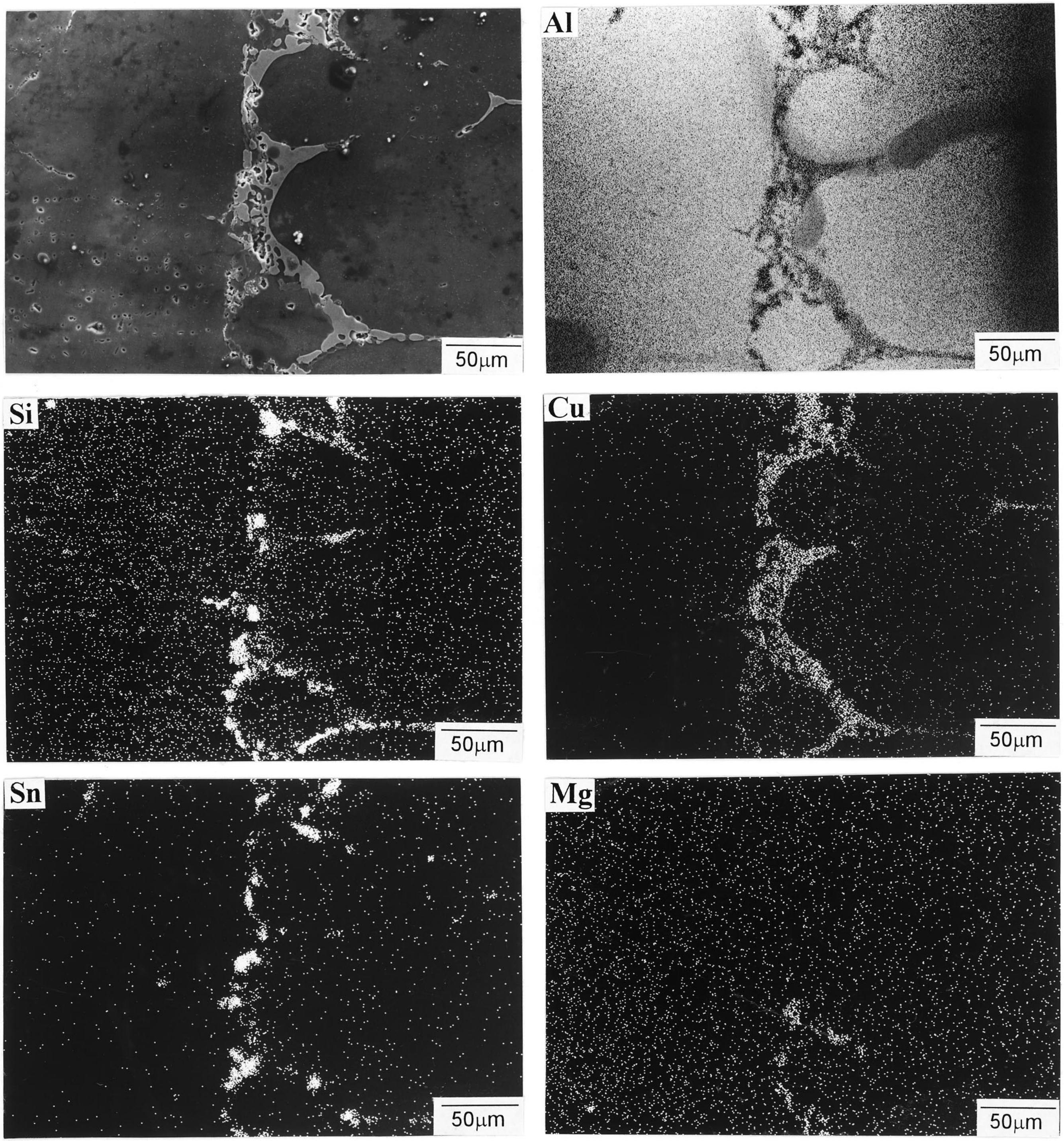


Fig. 10—EPMA element mapping of the 6061-T6 butt joint brazed with Al-7Si-20Cu-2Sn-1Mg filler metal at 550 °C for 30 min.

matrix of a pure tin phase, a $CuAl_2$ phase, silicon particles, and eutectic Al-Cu, Al-Si-Cu, and Al-Si-Cu-Sn phases. The solidus and liquidus temperatures obtained from the DTA curves in Figure 5 are also presented in Table I. As clearly shown, the solidus temperature drastically decreased by about 20 °C with the addition of 2 pct tin. However, a further increase of the tin content at above 2 pct did not depress the melting point any further. Instead, the pure tin phase and silicon particles appearing in these high-tin-content alloys appeared to weaken the brazeability.[9] The optimized amount of tin addition should be about 2 pct and a filler metal with the composition of Al-7Si-20Cu-2Sn was therefore proposed. Figure 7 showed the microstructure of this alloy, which contained none of the pure tin phase and silicon particles. Consistent with the microstructural observation, the endothermic peak at 232 °C disappeared in the DTA curve of this alloy.

For further improvement of the brazability of this filler metal, 1 pct magnesium was added into the Al-7Si-20Cu-2Sn alloy. In this case, magnesium acted as a wetting agent

Table II. Bonding Strengths of the 6061-T6 Butt Joints Brazed with Al-12Si and Al-7Si-20Cu-2Sn-1Mg Filler Metals

Filler Metals	Bonding Conditions	Heat Treatment after Brazing*	Bonding Strength (MPa)	Fracture Location
Al-12Si	600 °C, 30 min	—	59 ± 18	butt joint
Al-12Si	600 °C, 60 min	T6	67 ± 7	butt joint
Al-7Si-20Cu-2Sn-1Mg	550 °C, 30 min	—	74 ± 10	butt joint
Al-7Si-20Cu-2Sn-1Mg	575 °C, 30 min	—	83 ± 7	butt joint
Al-7Si-20Cu-2Sn-1Mg	600 °C, 30 min	—	95 ± 9	butt joint
Al-7Si-20Cu-2Sn-1Mg	550 °C, 60 min	T6	147 ± 12	butt joint
Al-7Si-20Cu-2Sn-1Mg	600 °C, 60 min	—	109 ± 15	butt joint
Al-7Si-20Cu-2Sn-1Mg	600 °C, 60 min	T6	196 ± 19	butt joint

*T6 temper condition: solution treated at 520 °C for 1.5 h, water quenched, and then aged at 175 °C for 8 h.
**The ultimate tensile strength of the 6061-T6 Al alloy for brazing tests was 331 MPa.

by removing the residual oxygen and moisture on the brazed aluminum surface and thus reducing the oxide film. The final composition of the developed filler metal was Al-7Si-20Cu-2Sn-1Mg, which possessed a melting range of 501 °C to 522 °C (shown in Figure 5). The microstructure of this alloy as shown in Figure 8 contained an α-Al solid solution, fine silicon particles, a pure tin phase, and $CuAl_2$, $CuMgAl_2$, and Mg_2Si intermetallic compounds. The XRD peaks as shown in Figure 9 confirmed the phases as observed in the microstructure of this Al-7Si-20Cu-2Sn-1Mg filler metal. In Figure 9, XRD analyses for Al-9.6Si-20Cu and Al-7Si-20Cu-2Sn filler metals were also included, which were also consistent with the DTA results and microstructural observations for both alloys.

Figure 10 showed the microstructure of the joint where a 6061-T6 aluminum alloy was brazed with Al-7Si-20Cu-2Sn-1Mg at 550 °C for 30 minutes. The butt joint region extended to a width of about 400 μm, where the filler metal penetrated intergranularly into the 6061-T6 butt joint. The EPMA mapping in Figure 10 revealed that the aluminum content in the butt joint decreased ostensibly after brazing. The depletion of aluminum was replaced by the enrichment of copper elements. The Si and Sn elements appeared as clusters of intermetallic compounds containing Al and Mg. When compared with the XRD analysis in Figure 9, this implied that the composition of this Al-7Si-20Cu-2Sn-1Mg filler metal had greatly changed during the brazing reaction with the 6061-T6 alloy. Table II showed the bonding strengths of the 6061-T6 alloy brazed with Al-12Si and Al-7Si-20Cu-2Sn-1Mg filler metals at various temperatures. Since the 6061-T6 aluminum alloy possessed a high ultimate strength of 331 MPa, the brazed specimens in all cases fractured along the butt joint after tensile tests as indicated in Table II. Furthermore, as Table II evidently showed, when the 6061-T6 alloy was brazed with the conventional Al-12Si filler metal at 600 °C for 60 minutes, and the brazements were henceforth subjected to a T6 treatment, the bonding strength could reach only to about 67 MPa. However, the bonding strength could go up to 147 MPa for the same 6061-T6 alloy when brazed with the Al-7Si-20Cu-2Sn-1Mg filler metal even at a lower temperature of 550 °C for 60 minutes and then subjected to a T6 treatment. When the bonding temperature was increased to 600 °C under the same bonding conditions, the bonding strength of the Al-7Si-20Cu-2Sn-1Mg/6061-T6 brazement went up dramatically to 196 MPa. Figure 11 showed that in this optimized case the fractography

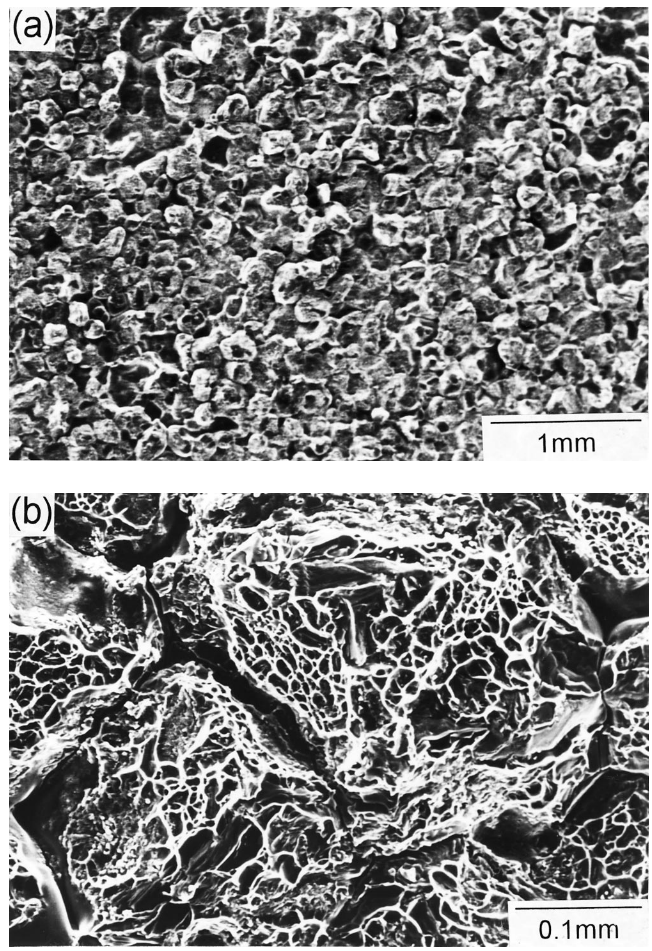


Fig. 11—(*a*) and (*b*) Fractographs of the tensile tested 6061-T6 butt joint brazed with Al-7Si-20Cu-2Sn-1Mg filler metal at 600 °C for 60 min followed with a T6 post-treatment.

of brazement after tensile tests revealed dimple characteristics, which implied that the brazement possessed a ductile fracture mode. The sound joining result was attributed to the much lower liquidus of the Al-7Si-20Cu-2Sn-1Mg filler metal than the brazing temperature and the addition of magnesium to the filler metal that had enabled the molten filler metal to break through the aluminum oxide layer on the bonded surface. Such a bonding condition would be ideal for this filler metal Al-7Si-20Cu-2Sn-1Mg to exercise its good wettability and flowability in the clearance of aluminum assemblies.

IV. CONCLUSIONS

1. The solidus temperatures of the Al-Si-Cu ternary alloys in this study decreased with increasing amount of copper administered. However, their liquidus temperatures fell from 593 °C to 534 °C with the addition of copper from 0 to 30 pct and then climbed up with further increasing of the copper content.
2. The microstructure of Al-Si-Cu alloys consisted of the Al-Si eutectic structure, the α-Al dendrite solid solution, and the $CuAl_2$ (θ) phase. For Al-Si-Cu-Sn quaternary alloys, the microstructure contained a pure tin phase, a $CuAl_2$ phase, silicon particles, and eutectic Al-Cu, Al-Si-Cu, and Al-Si-Cu-Sn phases.
3. The melting temperatures of the Al-Si-Cu alloys decreased further by about 20 °C with the addition of 2 pct tin.
4. When the newly developed Al-7Si-20Cu-2Sn-1Mg filler metal was employed to braze a 6061-T6 alloy at 600 °C for 60 minutes, and then subjected to a T6 treatment, the bonding strength was 196 ± 19 MPa. However, the bonding strength was only 67 ± 7 MPa for the 6061-T6 alloy when brazed with the conventional Al-12Si filler metal under the same bonding conditions.

REFERENCES

1. Y. Sugiyama: *Weld. Int.*, 1989, No. 8, pp. 700-10.
2. H. Kawase, T. Takemoto, M. Asano, I. Kawakatsu, and K. Liu: *Weld. J.*, 1989, vol. 68, pp. 396s-403s.
3. T. Hattori, S. Sakai, A, Sakamoto, and C. Fujiwara: *Weld. J.*, 1994, vol. 73, pp. 233s-240s.
4. G. Humpston, S.P.S. Sangha, and D.M. Jacobson: *Mater. Sci. Technol.*, 1995, vol. 11, pp. 1161-67.
5. D.M. Jacobson, G. Humpston, and S.P.S. Sangha: *Weld. J.*, 1996, vol. 75, pp. 243s-250s.
6. K. Suzuki, M. Kagayama, and Y. Takeuchi: *J. Jpn. Inst. Light Met.*, 1993, vol. 43 (10), pp. 533-38.
7. T. Kayamoto, J.H. Kim, S. Saito, and T. Onzawa: *Proc. Workshop. J. Weld. Soc.*, 1994, vol. 12, pp. 495-501.
8. L.F. Mondolfo: *Aluminum Alloys—Structure and Properties*, Butterworth and Co., London, 1976, pp. 513-15.
9. T. Osawa: *Weld. J.*, 1995, vol. 74, pp. 206s-212s.