

Brazeability of a 3003 Aluminum Alloy With Al-Si-Cu-Based Filler Metals

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Al-Si-Cu-based filler metals have been used successfully for brazing 6061 aluminum alloy as reported in the authors' previous studies. For application in heat exchangers during manufacturing, the brazeability of 3003 aluminum alloy with these filler metals is herein further evaluated. Experimental results show that even at such a low temperature as 550 °C, the 3003 alloys can be brazed with the Al-Si-Cu fillers and display bonding strengths that are higher than 77 MPa as well. An optimized 3003 joint is attained in the brazements with the innovative Al-7Si-20Cu-2Sn-1Mg filler metal at 575 °C for 30 min, which reveals a bonding strength capping the 3003 Al matrix.

Keywords Al-Si-Cu fillers, 3003 aluminum alloy, brazeability

1. Introduction

3003 aluminum alloy possesses the advantages of high thermal conductivity, good workability, low cost, and superior corrosion resistance. Therefore, it has played a major role in the manufacturing of heat exchangers, where brazing is an essential process in the production of aluminum heat exchangers. Commercially available filler metals for this purpose are usually targeted at the Al-12Si alloy, which has a eutectic point at about 577 °C. However, brazing with the traditional filler metal at such a high melting temperature requires the process to be performed at a relatively high temperature (i.e., above 600 °C). As a result, the aluminum workpieces can be partially molten in the industrial furnace during the brazing process.

In the past few years, tremendous efforts have been made for the development of a low-melting-point filler metal to braze with aluminum alloys that would have satisfactory bonding strength. Suzuki et al.[1] had introduced a eutectic Al-4.2Si-40Zn filler metal with a 535 °C melting point, but its disadvantage would lie in the very high vapor pressure of zinc, which could constitute quite an impediment to the vacuum brazing process. Kayamoto et al.[2] reported on a series of Al-Ge-Si-Mg filler metals, among which the three alloys with higher germanium contents (25, 35, and 45 wt.%) possessed quite low melting temperature ranges (solidus to liquidus, 435-480 °C, 448-510 °C, and 466-539 °C, respectively). When these filler metals were applied to the brazing of a 6061 aluminum alloy at 575 °C, the brazed joints provided sufficient joint strengths above 200 MPa. However, for brazing a 5052 aluminum alloy, the bonding strength decreased to values lower than 100 MPa. In addition, germanium is approximately 400 times the price of aluminum, making the alloy excessively expensive for most applications. Humpston et al.[3] and Jacobson et al.[6] further developed an Al-5Si-20Cu-2Ni filler metal with a melting range between 518 °C and 538 °C. When this filler metal was used for brazing a 3001 aluminum alloy, a shear strength over 75 MPa was obtained.

In the previous studies of the authors, the brazeability of a 6061-T6 aluminum alloy using a series of Al-Si-20Cu-based filler metals was evaluated.[4,5] For application in the manufacturing of heat exchangers, the brazeability of a 3003 aluminum alloy with these filler metals was further investigated. The results are compared with those using the traditional Al-12Si filler metal.

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2. Experimental

The preparations of various filler metals (Al-9.6Si-20Cu, Al-7Si-20Cu-2Sn, and Al-7Si-20Cu-2Sn-1Mg) were the same as those reported in a previous study.[1] The microstructures of the filler metals were observed by optical microscopy (OM) after etching in a 10 vol.% H_3PO_4 solution at 50 °C for 60 s.

Table 1 Chemical Composition, Solidus and Liquidus, and the Ultimate Tensile Strength of the 3003 Aluminum Alloy (a)

	Chemical Composition								
Alloy	Mn	Si	Cu	Zn	Fe	Al	T_S, °C	T_L, °C	σ_{UTS}, MPa
3003-O	1.07	0.28	0.12	0.01	0.48	Bal.	592	654	112

(a) T_S: solidus; T_L: liquidus; σ_{UTS}: ultimate tensile strength; 3003-O: annealing heat treatment.

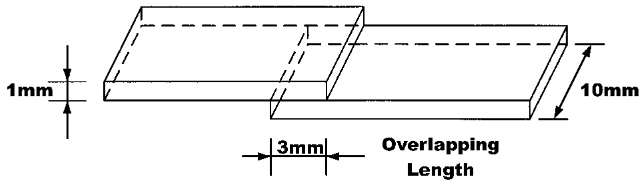

Fig. 1 Geometry and dimensions of the brazed specimens for tensile testing

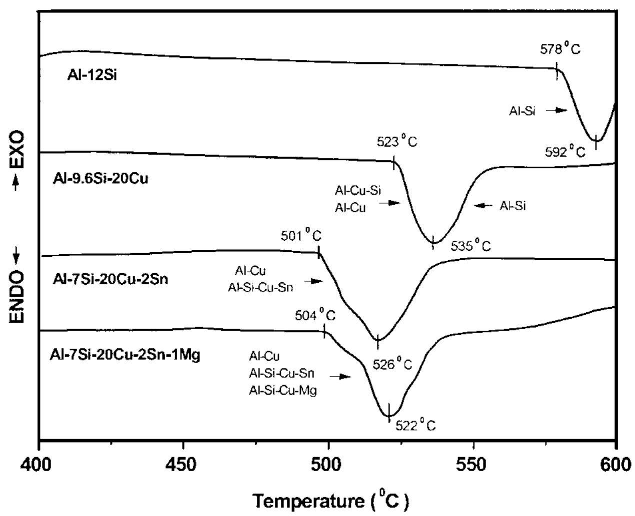

Fig. 2 DTA curves of the filler metals in this study

Table 2 Solidus, Liquidus, and Melting Range of Filler Metals in This Study

Filler Metals	T_S, °C	T_L, °C	ΔT, °C
Al-12Si	579	593	14
Al-9.6Si-20Cu	524	543	19
Al-7Si-20Cu-2Sn	504	526	22
Al-7Si-20Cu-2Sn-1Mg	501	522	21

(a) T_S: solidus; T_L: liquidus; ΔT: melting range.

The chemical composition, solidus, liquidus, and the ultimate strength of the as-annealed 3003 aluminum alloy (3003-O) are shown in Table 1. For the evaluation of bonding strengths using these filler metals, 3003 aluminum plate specimens (1 mm in thickness, 25 mm in length, and 10 mm in width) were lapped for an overlap length of 3 mm with a clearance of 0.2 mm, as shown in Fig. 1. The brazing process was conducted in a vacuum furnace at a pressure setting of 5×10^{-5} torr. The brazing time was held constant for 30 min. The cross-sections of the brazed joints were analyzed by an electron microanalyzer (EMPA).

3. Results and Discussion

The melting temperatures (solidus and liquidus) of the filler metals in this study, as determined from the differential thermal analysis (DTA) curves in Fig. 2, are summarized in Table 2. It can be seen that both the solidus and liquidus of Al-9.6Si-20Cu are about 50 °C lower than those of the Al-12Si filler metal. A further addition of 2% Sn to the ternary Al-Si-Cu alloy causes its melting temperature to drop about 20 °C. The final Al-7Si-20Cu-2Sn-1Mg alloy carries its solidus and liquidus at 501 °C and 522 °C, respectively, which are much lower levels than those of the traditional Al-12Si filler metal.

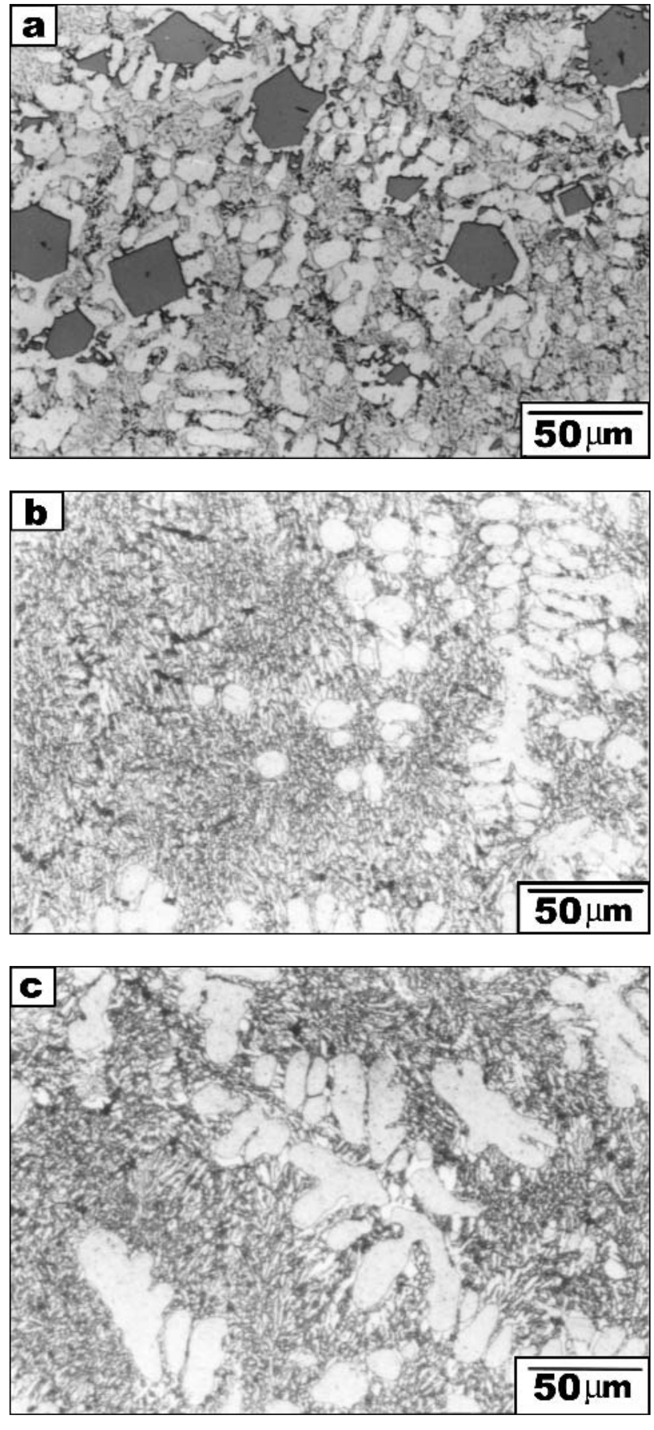

Fig. 3 Microstructures of (**a**) Al-9.6Si-20Cu, (**b**) Al-7Si-20Cu-2Sn, and (**c**) Al-7Si-20Cu-2Sn-1Mg filler metals

The microstructure of the Al-9.6Si-20Cu alloy, as shown in Fig. 3(a), is composed of Al-Cu and Al-Cu-Si eutectic phases, the $CuAl_2$ (θ) intermetallic compound, and pure Si particles. The Si particles disappear in the Al-7Si-20Cu-2Sn and Al-7Si-20Cu-2Sn-1Mg alloys, as shown in Fig. 3(b) and (c). Their microstructures contain a dendrite α-Al solid solution and various eutectic phases.

The bonding strengths of the 3003 joints brazed with various filler metals at various temperatures are demonstrated in Table 3. Since the traditional Al-12Si filler metal possesses a eutectic point at about 577 °C (DTA-analyzed melting range, 579-593 °C), any brazing process for this filler metal that is carried out at around this temperature is destined for failure. Not until the brazing temperature is raised to 600 °C can the 3003 aluminum alloy then be bonded with this filler metal. The bonding strength in this case is higher than the ultimate strength of the 3003 aluminum alloy (112 MPa), and, consequently, the tensile specimens will fracture in the 3003 aluminum alloy matrix. When the Al-9.6Si-20Cu filler metals are used to braze the 3003 aluminum alloy at 550 °C, the bonding strength is 77 ± 14 MPa. However, while the Al-7Si-20Cu-2Sn and Al-7Si-20Cu-2Sn-1Mg filler metals are applied to brazing at 550 °C, the bonding strengths are improved to 83 ± 15 MPa and 95 ± 12 MPa, respectively.

As the brazing temperature is raised to 575 °C using the Al-7Si-20Cu-2Sn-1 Mg filler metal, a sound joint with a bonding strength higher than the ultimate strength of the 3003 aluminum alloy is achieved (Table 3). Figure 4(a) shows the microstructure of the joint for such an optimized case in which a 3003 aluminum alloy is brazed with Al-7Si-20Cu-2Sn-1Mg at 575 °C for 30 min. The lap joint width is about 200 μm, which is much narrower than that of a 6061 aluminum brazement using the same filler metal and under the same brazing conditions (Fig. 4b). It can be attributed to the much higher solidus of the 3003 aluminum alloy (648 °C) vs that of the 6061 aluminum alloy (592 °C), resulting in a larger temperature difference between the solidus of the Al-matrix and the brazing temperature (575 °C) for the 3003 aluminum alloy.

Table 3 Brazing Temperatures and Bonding Strengths of the 3003 Aluminum Brazements in This Study

Filler Metals	Bonding Temperature, °C	Bonding Strength, MPa	Fracture Location
Al-12Si	575	Failed	Lap joint
Al-12Si	600	>112 (a)	Matrix
Al-9.6Si-20Cu	550	77 ± 14	Lap joint
Al-7Si-20Cu-2Sn	550	83 ± 15	Lap joint
Al-7Si-20Cu-2Sn-1Mg	550	95 ± 12	Lap joint
Al-7Si-20Cu-2Sn-1Mg	575	>112 (a)	Matrix

(a) The ultimate tensile strength of the 3003 aluminum alloy.

The EPMA element mapping in Fig. 5 reveals that the Al content in the lap joint decreases distinctly after brazing. The depletion of Al is countered by the enrichment of the Si and Cu elements (Fig. 5c and d). However, the locations of the Si-rich and Cu-rich phases are separate. It also has been found that the Sn and Mg elements have vanished in the lap joint (Fig. 5e and f), which implies that both elements have dissolved into the 3003 Al-matrix. In contrast with the microstructure shown in Fig. 3(c), the EPMA results indicate that the composition of the filler metal greatly changed during the brazing reaction with the 3003 aluminum alloy.

4. Conclusions

In summary, it can be concluded that sound joints can be obtained for the brazing of the 3003 aluminum alloy using the developed Al-Si-Cu-based filler metals at lower temperatures than those that the traditional Al-12Si filler metal has adopted in the brazing process. When the Al-7Si-20Cu-2Sn-1Mg filler metal is applied to brazing at 575 °C for 30 min, the bonding strength is higher than the ultimate strength of the 3003 aluminum alloy. Under this condition, the brazing process is destined to failure using the traditional Al-12Si filler metal. It was also found that the 3003 aluminum joint possesses a much narrower reaction zone compared to that of a 6061 aluminum joint brazed with the same filler under the same brazing conditions (i.e., 575 °C for 30 min).

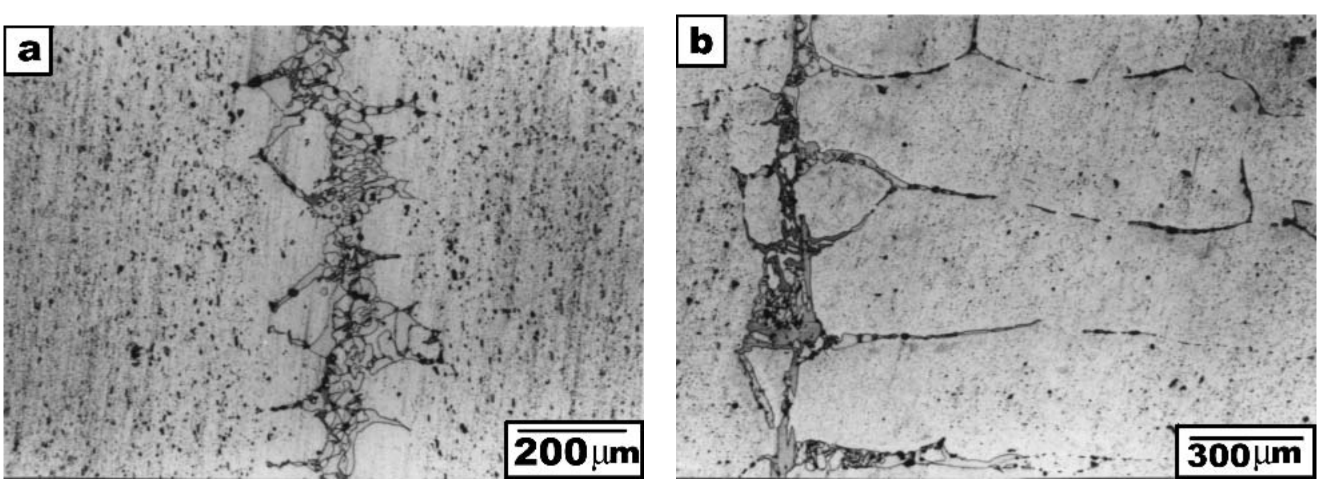

Fig. 4 Microstructure of the 3003 aluminum joint (**a**) in comparison with that of the 6061 aluminum joint and (**b**) after brazing with the Al-7Si-20Cu-2Sn-1Mg filler metal at 575 °C for 30 min

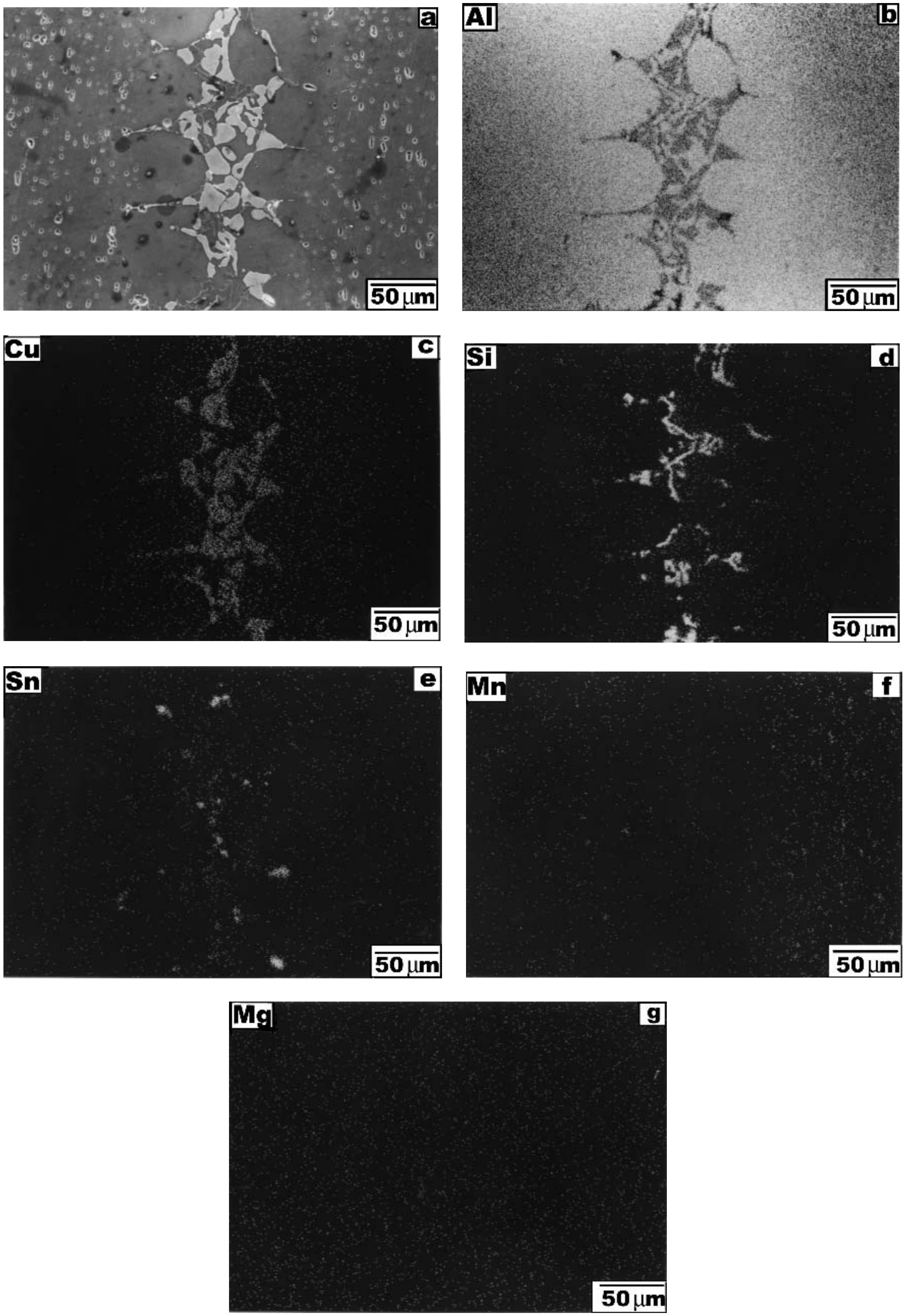

Fig. 5 EMPA element mapping of the 3003 aluminum butt joint brazed with the Al-7Si-20Cu-2Sn-1Mg filler metal at 575 °C for 30 min

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