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Joining 6061 aluminum alloy with Al–Si–Cu filler metals

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ABSTRACT

In this study, brazing of 6061 aluminum alloy was carried out with Al–10.8Si–10Cu and Al–9.6Si–20Cu filler metals at 560 °C. The addition of 10 wt.% copper into the Al–12Si filler metal lowered the solidus temperature from 586 °C to 522 °C, and the liquidus temperature from 592 °C to 570 °C. With the addition of 20 wt.% copper into the Al–12Si filler metal, the liquidus temperature of the filler metals decreased from 592 °C to 535 °C. The main microstructures of the two Al–Si–Cu filler metals in the study consisted of Al solid solution, fine silicon particles, and Al_2Cu intermetallic compounds. The shear strengths of the 6061 alloy brazed with Al–12Si at 600 °C decreased as brazing time increased. The average shear strengths fell from 39 MPa for 10 min to 23 MPa for 60 min of brazing. Joint strengths of the 6061 alloy brazed with Al–10.8Si–10Cu filler metal increased as brazing time increased and reached about 67 MPa at the brazing time of 60 min. Shear strengths of about 40 MPa for the 6061 aluminum joint with Al–9.6Si–20Cu filler metal were obtained irrespective of the brazing periods. The high hardness value of the 6061 aluminum alloy subtract near the butt joint interface after brazing with Al–Si–Cu filler metal could be attributed to the fact that the copper penetrated and formed Al_2Cu intermetallic compounds.

1. Introduction

6061 aluminum alloy is one of the most extensively used of the 6000 series aluminum alloys. It offers a range of good mechanical properties, good surface finish, excellent corrosion resistance, and good workability. Therefore, 6061 aluminum alloy has been widely used in ship building, aircraft and aerospace components, electrical fittings and connectors, and automobile industries. The joining process of aluminum alloys is a very important fabrication technique. Due to the low melting temperature of aluminum alloy and high affinity of aluminum to oxygen, brazing of aluminum alloys is considered to be difficult. Among the variety of joining techniques, brazing with Al–Si alloys has been adopted as a reliable and economical method for the bonding of aluminum alloys [1,2]. Al–Si alloys such as commercial aluminum brazes BAlSi-3 and BAlSi-4, with silicon contents between 7% and 13%, have proven successful in joining some aluminum alloys in the strength and corrosion-chemical aspects [3,4]. Since these aluminum brazes have melting temperatures in the range of 575–610 °C, the working temperature of these aluminum brazing alloys must be above 590 °C. This brazing temperature is too high relative to the melting point of 6061 aluminum alloy, which has a solidus temperature of 592 °C. Thus, the development of low-melting-point filler metals is an important goal of the aluminum industry [5]. In the past few years, there have been reports of low-melting-point filler metals for brazing aluminum alloys developed by adding copper into Al–Si alloys [6,7]. Tsao et al. [8] used Al–9.6Si–20Cu filler metal to braze 3003 aluminum alloy at 550 °C and obtained a bonding strength of 77 ± 14 MPa. This study employs two Al–Si–Cu filler metals to join 6061 aluminum alloy. The effects of copper contents and brazing duration on the joint reliability were investigated by measuring the joint shear strengths as well as characterizing the interfacial microstructures and microhardness.

2. Experimental

The Al–Si–Cu filler metals were prepared from Al–12Si alloy (supplied by Degussa AG, Germany) and copper in a vacuum arc furnace under a high-purity argon atmosphere. Copper of 99.99% purity in the shape of slugs was mixed with Al–12Si slugs in the amounts of 10 wt.% and 20 wt.% of the total weight 100 g, respectively. In order to get a homogenous composition within the filler metals, the alloys were remelted at least 3 times. The chemical compositions of the filler metals in the study, as measured by electron probe microanalyzer (EPMA, JEOL TXA-8600SX), are shown in Table 1. After the filler metal was solidified in a water-cooled copper mold, the cast ingots were rolled into 0.3 mm thick foil. The microstructural observations of the filler metals were carried out with a field-emission scanning electron microscope (FE-SEM, Philips XL40). The chemical distribution of the elements was analyzed with an electron probe microanalyzer (EPMA, JEOL TXA-8600SX). Differential thermal analysis (DTA, TA Instruments SDT-2960) was used to determine the melting temperature of the filler metals, which were heated from room temperature to 700 °C under argon atmosphere at a heating rate of 10 °C/min. Table 2 shows the chemical compositions of the 6061 aluminum alloy used for joining. The solidus and

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Table 1
Chemical compositions of the filler metals in this study.

Alloy	Chemical composition (wt.%)		
	Si	Cu	Al
Al–12Si	11.8	0	Bal.
Al–10.8Si–10Cu	10.85	10.3	Bal.
Al–9.6Si–20Cu	9.64	20.3	Bal.

Table 2
Chemical compositions of the 6061 aluminum alloy.

Alloy	Chemical composition (wt.%)					
	Mg	Si	Cu	Cr	Mn	Al
6061	1.10	0.61	0.25	0.12	0.01	Bal.

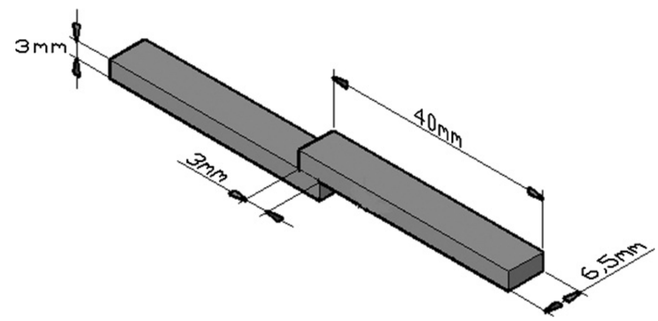

Fig. 1. Schematic representation of the brazed specimens for shear testing in this study.

liquidus temperatures of the 6061 aluminum alloy used in this study were 592 °C and 654 °C, respectively.

The materials supplied for brazing were processed into plates with a size of 40 mm × 6.5 mm × 3 mm. For the evaluation of bonding strength, 6061 aluminum specimens were overlapped with an overlap length of 3 mm. Fig. 1 shows the geometry and dimensions of the brazing specimens subjected to shear testing. Prior to brazing, the bonding surfaces of 6061 aluminum specimens and the surfaces of filler metals were ground with SiC paper down to grade 1200. The 200 μm thick foils of the filler metals were then placed between the 6061 aluminum plate specimens. The brazing process was conducted in a vacuum furnace under a high-purity argon atmosphere at 560 °C. After various brazing periods, the bonding strengths were measured by shear testing. The shear test was carried out using a tensile testing machine (Hung Ta Instrument HT-2402). Fractured surfaces were characterized by a field-emission scanning electron microscope (FE-SEM, Philips XL40) coupled to an energy dispersion X-ray (EDX). A set of the brazed specimens was cross-sectioned and analyzed with an electron probe microanalyzer (EPMA, JEOL TXA-8600SX).

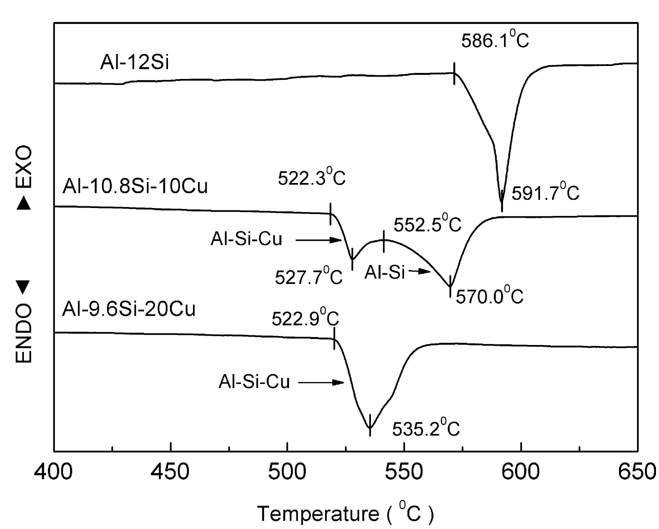

Fig. 2. DSC analysis of the Al–12Si, Al–10.8Si–10Cu and Al–9.6Si–20Cu filler metals.

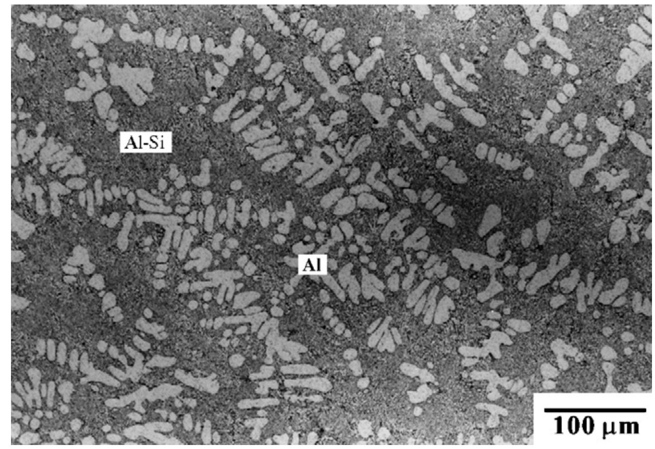

Fig. 3. Microstructure of the Al–12Si filler metal.

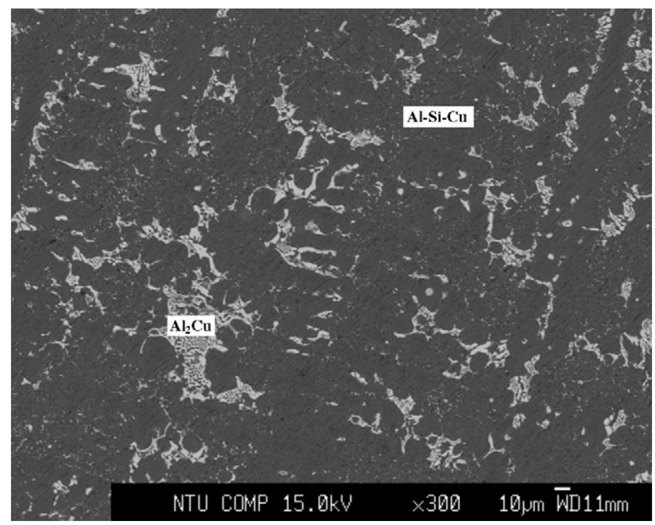

Fig. 4. Microstructure of the Al–10.8Si–10Cu filler metal.

Phase identification was conducted by a Siemens D5000 X-ray diffractometer with Mo Kα radiation, scanning at a speed of 0.023° and a step time of 2 s. The microhardness of the brazing interface was measured with a Shimadzu type microsclerometer (Shimadzu HMV-2), using Vickers diamond-pyramid indenters, a 50 g load, and a load time of 10 s. Average hardness values obtained from 5 indentations were realized.

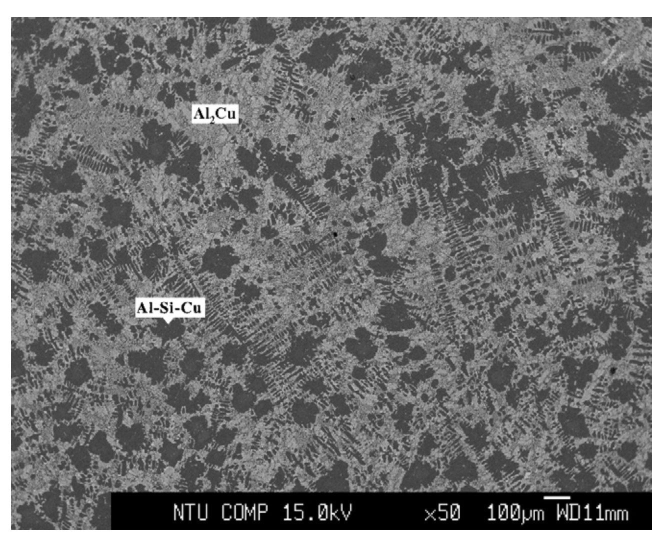

Fig. 5. Microstructure of the Al–9.6Si–20Cu filler metal.

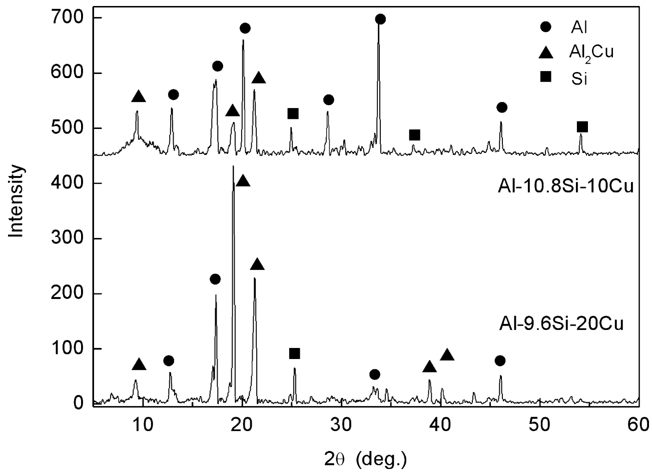

Fig. 6. XRD analysis for the Al–10.8Si–10Cu and Al–9.6Si–20Cu filler metals.

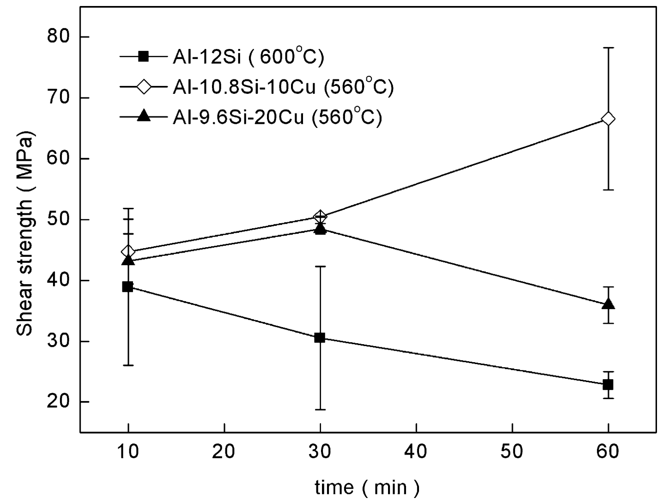

Fig. 7. Shear strengths of 6061 aluminum alloy joints after brazing with Al–12Si, Al–10.8Si–10Cu, Al–9.6Si–20Cu filler metals.

3. Results and discussion

Fig. 2 shows the DTA curves of the Al–12Si, Al–10.8Si–10Cu and Al–9.6Si–20Cu filler metals. The melting temperature range of Al–12Si alloy was from 586 °C to 592 °C. The microstructure of the Al–12Si filler metal consisted of an Al–Si eutectic phase (gray) and an Al-rich phase (white), as shown in Fig. 3. Two endothermic peaks were found in the DTA curve of the Al–10.8Si–10Cu alloy, which corresponds to the Al–Si–Cu ternary eutectic point and

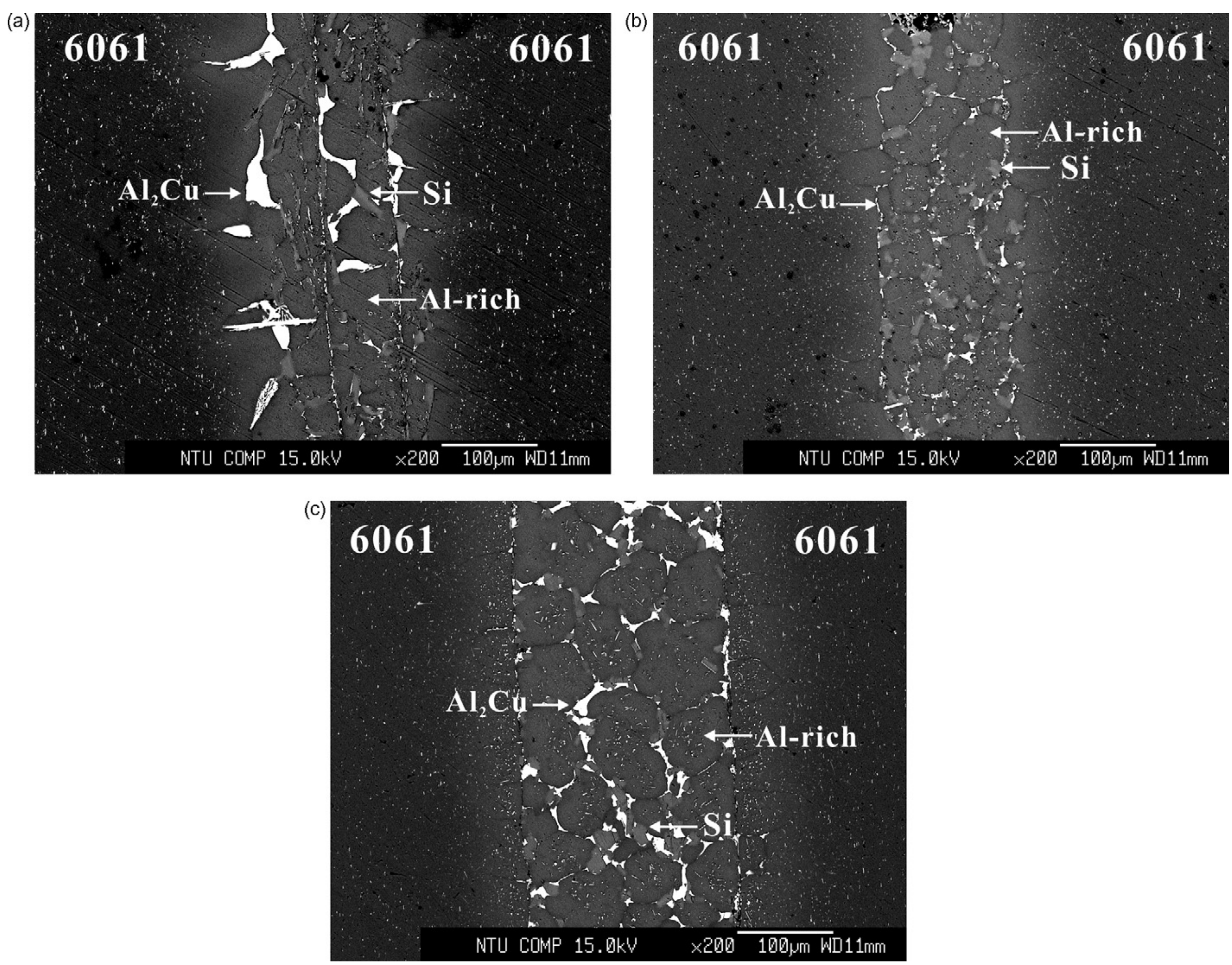

Fig. 8. Micrographs of the 6061 aluminum alloy joints after brazing with the Al–10.8Si–10Cu filler metal at 560 °C for (a) 10 min, (b) 30 min, and (c) 60 min.

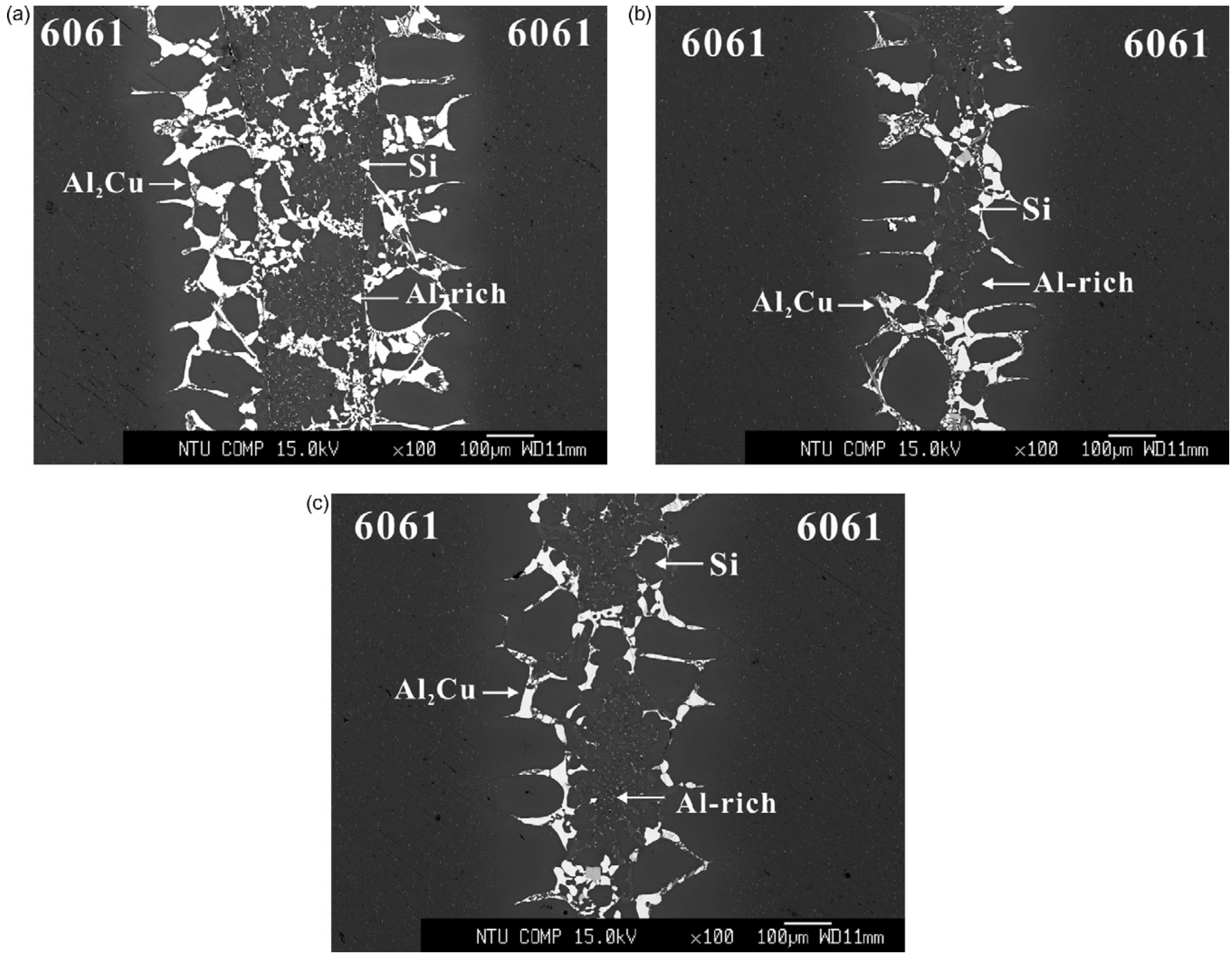

Fig. 9. Micrographs of the 6061 aluminum alloy joints after brazing with the Al–9.6Si–20Cu filler metal at 560 °C for (a) 10 min, (b) 30 min, and (c) 60 min.

Al–Si liquidus temperature near the Al–Si binary eutectic, according to the Al–Si–Cu ternary and Al–Si binary diagrams, respectively [9,10]. The addition of 10 wt.% copper into the Al–12Si filler metal resulted in decreases of the solidus and liquidus temperatures of about 64 °C and 22 °C, respectively. Fig. 4 shows the microstructure of the Al–10.8Si–10Cu filler metal, which contained the Al-rich phase (gray), fine silicon particles in the dark region and the Al_2Cu intermetallic compound (white).

When the copper content of the Al–Si filler metals was increased from 10% to 20%, the liquidus temperature decreased from 570 °C to 535 °C, as shown in Fig. 2. The solidus temperature remained almost constant, at 522.5 °C. Only one endothermic reaction was found in the DTA curve of Al–9.6Si–20Cu filler metal, and the melting point was near the Al–Si–Cu ternary eutectic point 525 °C [10]. The microstructure of the Al–9.6Si–20Cu filler metal consisted of an Al-rich phase (gray), Al_2Cu intermetallic compounds, and some fine silicon particles in the dark region, as shown in Fig. 5. Fig. 6 shows the XRD analysis of Al–10.8Si–10Cu and Al–9.6Si–20Cu filler metals. The results of the XRD analyses confirmed the phases observed in the microstructure of the Al–10.8Si–10Cu and Al–9.6Si–20Cu filler metals, which contained an α-Al solid solution, fine silicon particles, and Al_2Cu intermetallic compounds.

Fig. 7 shows the shear strengths of the 6061 aluminum alloy brazed with Al–12Si, Al–10.8Si–10Cu and Al–9.6Si–20Cu filler metals for various periods. The joint possessed an average shear strength of about 39 MPa after 10 min of brazing, and one of about 23 MPa after 60 min of brazing with Al–12Si filler metal at 600 °C. It is clear that joint strength decreased as brazing time increased. Joint strengths of the 6061 aluminum alloy brazed with Al–10.8Si–10Cu filler metal at 560 °C increased as brazing time increased, reaching about 67 MPa at the brazing time of 60 min. Shear strengths of about 40 MPa were obtained in the 6061 aluminum alloy joint

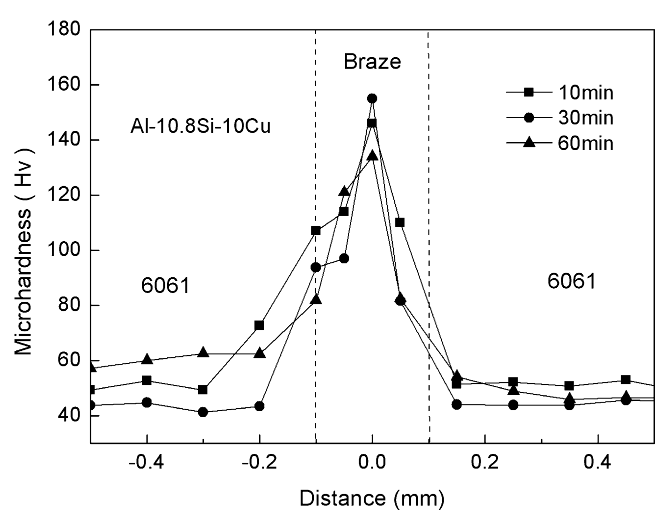

Fig. 10. Microhardness for the brazing interface of 6061 aluminum alloy joints with Al–10.8Si–10Cu filler metal at 560 °C.

with Al–9.6Si–20Cu filler metal at 560 °C, irrespective of the brazing periods.

Fig. 8a–c shows the back scattered electron images of the interface of the 6061 aluminum alloy joints with Al–10.8Si–10Cu filler metal after brazing at 560 °C for various periods. A large number of coarse clusters of Al_2Cu and some Si particles can be seen embedded in the filler metal. After 60 min of brazing, the Al_2Cu tends to segregate at the grain boundary of the filler metal. Fig. 9a–c shows the microstructure of the interface of 6061 aluminum alloy joints brazed with Al–9.6Si–20Cu at 560 °C for various periods. The butt joint region extends to a width of about 300 μm, where the Al_2Cu penetrated intergranularly into the 6061 aluminum alloy joint.

For the 6061 aluminum alloy joints with Al–10.8Si–10Cu and Al–9.6Si–20Cu filler metals, after brazing at 560 °C, a large number of coarse clusters Al_2Cu and some Si particles were found to be embedded in the filler metals. Thus, the average hardness values, obtained from 5 indentations, of the filler metals were higher than that of the 6061 aluminum substrate. Fig. 10 shows the line profile microhardness values of 6061 aluminum alloy joints brazed with Al–10.8Si–10Cu filler metal for various brazing periods. The average hardness value of the 6061 aluminum alloy was about 40–50 Hv. When the filler metal contained Al_2Cu intermetallics, the hardness values in the filler metal were in the range 80–150 Hv, higher than that of the 6061 aluminum substrate. The microhardness inside the Al–9.6Si–20Cu filler metal in the 6061 aluminum joints was much higher due to the large amount of Al_2Cu intermetallics, as shown in Fig. 11. The high hardness value of the 6061 aluminum alloy subtract, with a width of about 300 μm near the butt joint interface, could be attributed to the fact that the copper penetrated and formed Al_2Cu intermetallics.

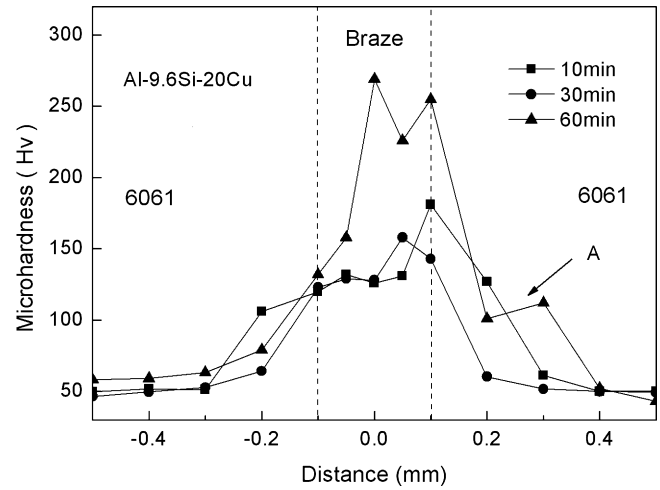

Fig. 11. Microhardness for the brazing interface of 6061 aluminum alloy joints with Al–9.6Si–20Cu filler metal at 560 °C.

Fig. 12a–c shows the SEM fractographs of the 6061 aluminum alloy surfaces brazed with Al–10.8Si–10Cu for various periods, after shear tests. The fractured surface of the sample brazed for 10 min reveals a large area of planar unbonded regions, as shown in Fig. 12a. As the brazing period increased, the amount of planar unbonded area decreased. Thus, the lower shear strength of the

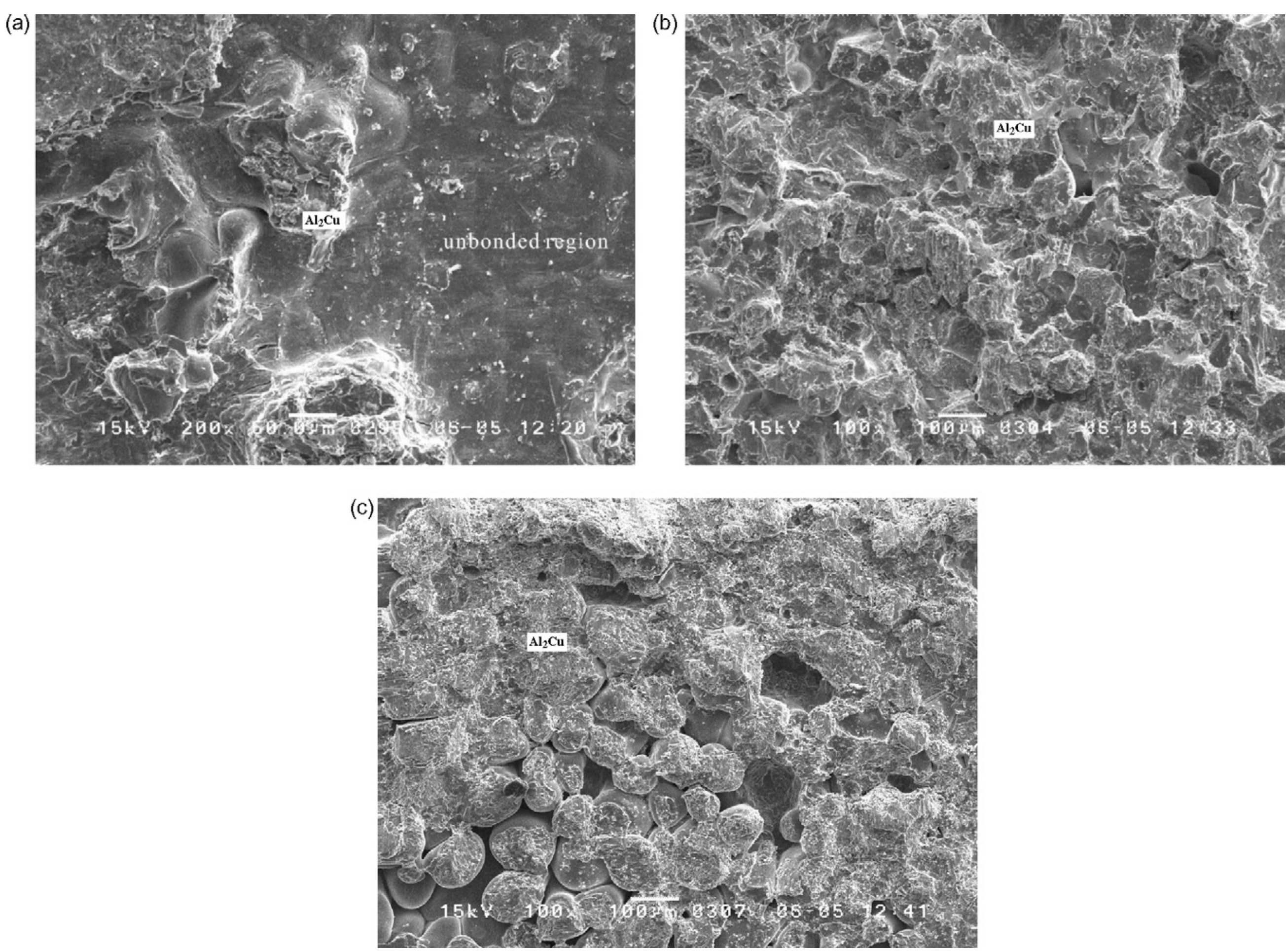

Fig. 12. Fractographs of the 6061 aluminum alloy joints bonded with Al–10.8Si–10Cu filler metal at 560 °C for (a) 10 min, (b) 30 min, and (c) 60 min.

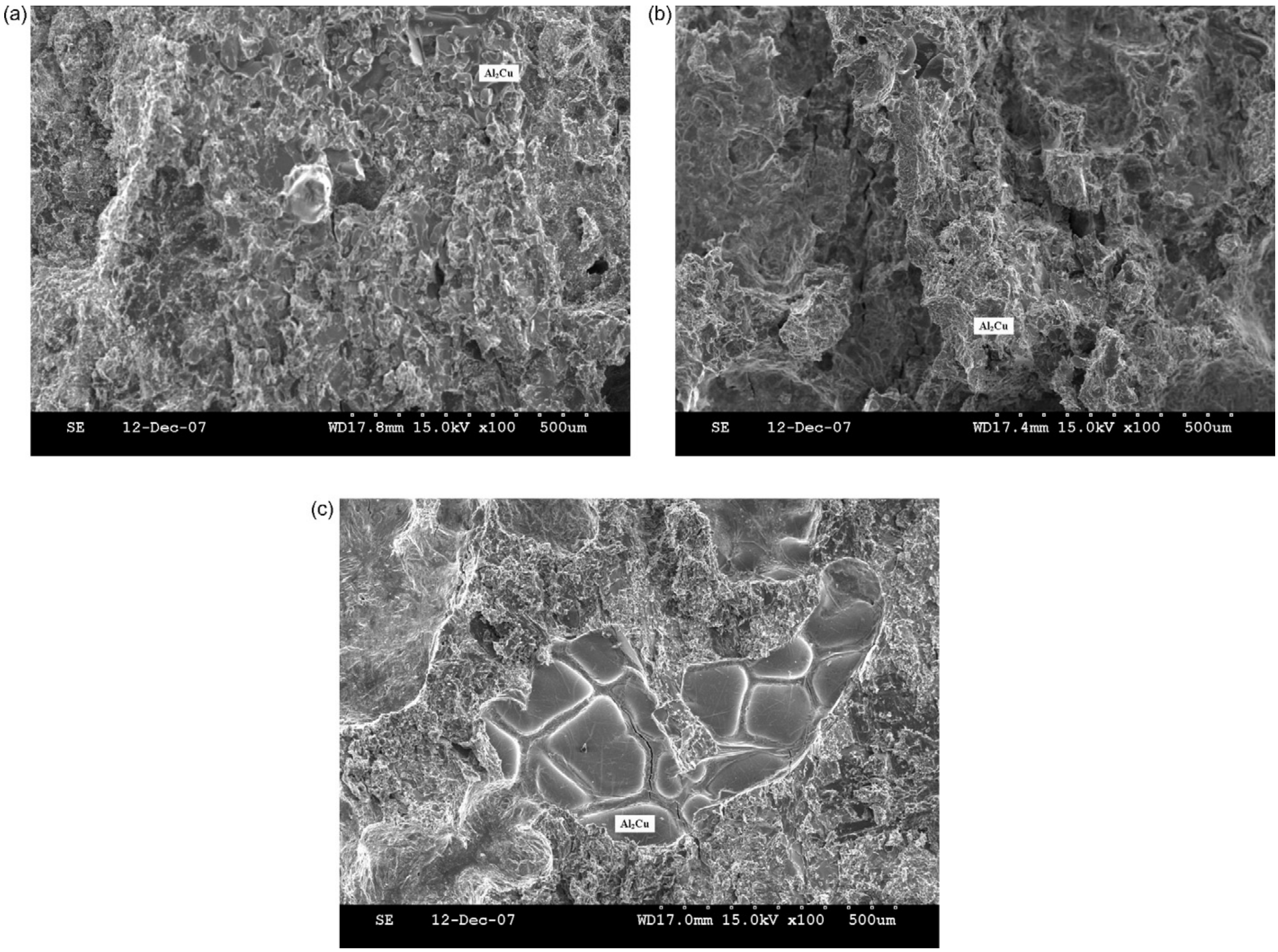

Fig. 13. Fractographs of the 6061 aluminum alloy joints bonded with Al–9.6Si–20Cu filler metal at 560 °C for (a) 10 min, (b) 30 min, and (c) 60 min.

6061 aluminum alloy joints brazed for 10 min could be attributed to the larger unbonded regions, as compared with the joints brazed for 30 min and 60 min. Fig. 13a–c shows the fractographs of the 6061 aluminum alloy surfaces brazed with Al–9.6Si–20Cu for various periods, after shear tests. Fractography of the specimens reveals the brazed 6061 aluminum alloy joint fractures inside the filler metal. For the specimen brazed for 60 min, large Al_2Cu coarse particles are observed in the fracture surface.

4. Conclusion

The liquidus temperature of Al–12Si alloy was reduced from 592 °C to 570 °C and 535 °C by adding 10 wt.% and 20 wt.% copper, respectively. The main microstructures of the Al–Si–Cu filler metals consisted of the Al–Si eutectic structure, the α-Al solid solution and fine silicon particles, and Al_2Cu intermetallic compounds. The average bonding shear strengths of the 6061 aluminum alloy brazed with Al–10.8Si–10Cu filler metal at 560 °C for 10 min and 60 min were 45 MPa and 67 MPa, respectively. When the Al–9.6Si–20Cu filler metal was employed to braze the 6061 alloy, the average bonding shear strengths were 43 and 36 MPa after 10 min and 60 min of brazing, respectively. The average bonding strengths were 39 MPa and 23 MPa with the conventional Al–12Si filler metal after 10 min and 60 min of brazing, respectively. Brazing with filler alloys Al–9.6Si–10Cu and Al–8.4Si–20Cu, the shear strengths of the brazed joints of 6061 aluminum alloy were higher than the joints with conventional Al–12Si filler metal. While both the Al–10.8Si–10Cu and the Al–9.6Si–20Cu filler metals contained large numbers of coarse clusters of Al_2Cu intermetallic and Si particles, the hardness values in the filler metals were much higher than that of the 6061 aluminum substrate. The high hardness value of the 6061 aluminum alloy subtract, near the butt joint interface, could be attributed to the fact that the copper penetrated and formed Al_2Cu intermetallics during brazing. Brazing with the Al–8.4Si–20Cu filler metal which contained more copper, made the joints brittle, and the shear strength of the joints for 60 min brazing decreased.

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