

Article

Vacuum Brazing of 55 vol.% SiC_p/ZL102 Composites Using Micro-Nano Brazing Filler Metal Fabricated by Melt-Spinning

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Abstract: The joining methods of Aluminum matrix composites reinforced with SiC particles (SiC_p/Al MMCs) are a challenge during the manufacturing process due to the significant differences between SiC particles and base aluminum in terms of both physical and chemical properties. Micro-nano brazing filler metal Al-17.0Cu-8.0Mg fabricated by melt-spinning technology was employed to deal with the joining problem of 55 vol.% SiC_p/ZL102 composites in this work. The result indicated that the foil-like brazing filler metal contained uniformed cellular nano grains, with a size less than 200 nm. The solidus and liquidus temperatures of the foil-like brazing filler metal decreased by 4 °C and 7 °C in comparison with the values of the as-cast brazing filler metal due to the nanometer size effect. The maximum joint shear strength of 98.17 MPa achieved with a brazing temperature of 580 °C and holding time of 30 min was applied in vacuum brazing process. The width of the brazing seam became narrower and narrower with increasing brazing temperature owing to the strong interaction between the micro-nano brazing filler metal and 55 vol.% SiC_p/ZL102 composites. The fracture morphology of the joint made at a brazing temperature of 580 °C was characterized by quasi-cleavage fracture. After brazing, the chemical concentration gradient between the brazing filler metal and base material disappeared.

Keywords: SiC_p/ZL102 composites; micro-nano brazing filler metal; vacuum brazing; microstructure; shear strength

1. Introduction

Aluminum matrix composites reinforced with SiC particles (SiC_p/Al MMCs) have attracted more and more attention from researchers around the world because of their excellent performances such as high specific stiffness and specific strength, low thermal expansion coefficient, good radiation resistance, and so on [1–4]. In recent years, SiC_p/Al MMCs have been widely used in aerospace, weaponry, and electronics industries [5–8]. SiC_p/Al MMCs are also favored in the field of electronic packaging due to their high dimensional stability and thermal conductivity. However, the joining methods of SiC_p/Al MMCs are still a challenge for researchers during the manufacturing process due to the significant differences between SiC particles and base aluminum in terms of both physical and chemical properties, which severely limit the promotion and application of SiC_p/Al MMCs [9–12].

At present, joining methods of SiC_p/Al MMCs mainly focus on fusion welding [13–15], diffusion welding [16,17], and brazing [18–20]. However, it is difficult to obtain high-quality welded

joints by those conventional joining methods. For example, when fusion welding was applied to SiC_p/Al MMCs, the segregation of SiC particles appeared in a molten pool due to the poor liquidity. In addition, a mass of brittle phases such as Al₄C₃ would be generated at the weld seam [21,22]. Wang X.H. [23] et al. conducted TIG welding on 15 vol.% SiC_p/6061Al composites and found that the brittle phase of Al₄C₃ was formed when SiC particles reacted with base Al at high temperature. In order to reduce the heat input, Pichumani S. [24] et al. used pulse current TIG welding during the welding of 8 vol.% SiC_p/Al composites. However, the Al₄C₃ phase was still produced during the welding, which significantly affected the performance of the welded joint. When diffusion welding was used to weld high-volume fraction SiC_p/Al MMCs, the aluminum oxide film produced during the welding process was difficult to remove, which damaged the continuity of the SiC particle-reinforced phase. More importantly, diffusion welding requires a stricter welding sample size and shape. As a consequence, it is hard to employ diffusion welding to satisfy the complex engineering applications of SiC_p/Al MMCs [25,26]. Brazing has the characteristics of a low welding temperature, uniform heating of the welding sample, and less thermal deformation. Therefore, it is considered to be one of the most effective joining methods for welding high-volume fraction SiC_p/Al MMCs. To braze SiC_p/Al composites, Wu M. [27] et al. reduced the melting point of brazing filler metal by adding elements Ni and Cu into Al-Si eutectic brazing filler metal, which made the brazing temperature lower and increased the joint performance. Wang P. [28] et al. used active brazing filler metal Al-12Si-1.5Mg-4Ti to braze nickel-plated SiC_p/Al MMCs and found that the active brazing filler metal had strong wettability to SiC_p/Al MMCs. Bangash, M.K. [29] et al. used Al-Cu-Mg and Al-Si-Mg-Ti two aluminum-based brazing filler metals to braze Al-6016 aluminum alloy plates and aluminum alloy foams. It was found that the Al-Cu-Mg amorphous brazing filler metal had higher diffusion into the alloy than the Al-Si-Mg-Ti amorphous bonding alloy. Gao Z. [30] et al. added Ni to Al-Cu-Mg brazing filler metal for brazing SiC_p/Al MMCs. A brazed joint with better performance, better wettability, and fluidity was obtained. It is very important to improve the wettability between the brazing filler metal and SiC_p/Al MMCs by selecting the appropriate alloying elements.

It is well known that SiC_p/Al MMCs oxidize easily in the atmosphere environment due the strong affinity between aluminum and oxygen; the resulting oxide film limits the wetting and spreading of the brazing filler metal, which makes it difficult to form high-quality brazed joints. In view of this, a self-developed micro-nano foil-like brazing filler metal was utilized in this research to braze 55 vol.% SiC_p/ZL102 composites in a vacuum environment. The thermodynamic properties, microstructural characteristics and phase composition of the brazing filler metal produced by melt-spinning technology were studied primarily. Different brazing temperatures were applied in this research to evaluate the influence of a micro-nano sized brazing filler metal on the microstructure evolution, element distribution, and mechanical property of the joints. The fracture morphology of the brazed joint at the optimal brazing temperature was investigated as well. This research provides a new possible means for the joining of high-volume fraction SiC_p/Al MMCs.

2. Materials and Methods

In this experiment, 55 vol.% SiC_p/ZL102 composites made by pressureless infiltration technology were used as brazing specimen. The microstructure is shown in Figure 1 and was composed of SiC particles with 55% volume and a ZL102 aluminum alloy matrix. The chemical composition of the ZL102 aluminum alloy is shown in Table 1. Brazing specimens with the size of 20 mm × 10 mm × 2 mm were cut by a wire cut electric discharge machine (DK7745, Suzhou Baojun CNC Equipment Co., Ltd., Suzhou, China). To prepare the micro-nano brazing filler metal, pure Al and Cu, as well as an Al50-Mg master alloy with a purity of 99.99% were melted in a vacuum induction furnace and cast in an iron mold three times to remove impurities in the raw materials. After smelting, the as-cast brazing filler metal alloy with the chemical composition of Al-17.0Cu-8.0Mg was obtained. The metallographic structure of the as-cast brazing filler metal is shown in Figure 2. Then, the as-cast brazing filler metal alloy was moved into the quartz glass tube in a melt-spinning machine. The melt-spinning was also

carried out in a vacuum environment with a vacuum degree of 2.0×10^{-2} Pa. In order to obtain defect-free and micro-nano sized foil-like brazing filler metal, the rotational speed of the copper roller was set to 1400 r/min, and the argon injection pressure in the quartz glass tube was set to 0.02 MPa. The prepared foil-like brazing filler metal with thickness of 70 μm and width of 10 mm is shown in Figure 3.



Figure 1. Microstructure of 55 vol.% SiC_p/ZL102 composites.

Table 1. Chemical composition of ZL102 (in wt.%).

Element	Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
wt. %	10.0–13.0	0.0–0.7	≤0.30	≤0.50	≤0.10	≤0.10	≤0.20	Balance



Figure 2. Metallographic structure of the as-cast brazing filler metal.



Figure 3. Foil-like brazing material fabricated by melt-spinning technology.

The 55 vol.% SiC_p/ZL102 composites should be pretreated before vacuum brazing due to the presence of oxidation film and oil stains on the surface of composites. The process was as follows: first of all, the joining surfaces of the specimen were polished by 800# sandpaper. Secondly, the polished specimens were put into a bath filled with a 1:1 mixture of alcohol-acetone and then the specimens were cleaned ultrasonically for 10 min. Subsequently, the cleaned brazing specimens were corroded in 7% NaOH solution for 30 s, and then placed in 5% HNO₃ solution for 60 s. Finally, the brazing specimens were washed with ultrasonic water for 10 min. After pretreatment, the assembled overlap joints with the brazing filler metal were joined in a vacuum furnace (ZHS-60, China Electronics

Technology Group Corporation, Taiyuan, China). Figure 4 shows the schematic diagram of the brazing joint. During the brazing, a pressure of 0.01 MPa was applied to the sandwich specimen. Based on thermodynamic properties of the brazing filler metal and characteristic of SiC_p/ZL102 composites, the brazing temperature was set to be within the range of 560 °C to 600 °C, the brazing time was set to 30 min, and the heating rate was 10 °C/min. Heating started when the vacuum was lower than 5×10^{-3} Pa, and cooling started after brazing. The cooling rate was 3 °C/min, and the sandwich specimen was taken out when cooled to below 180 °C.

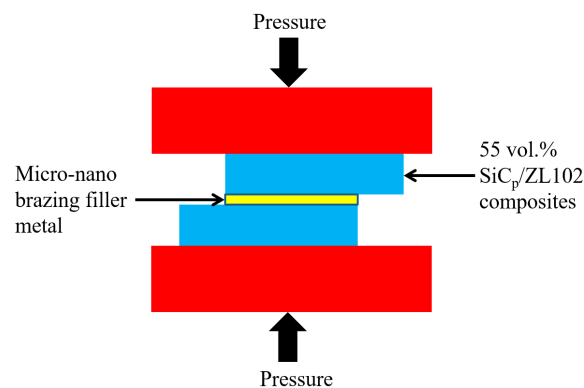


Figure 4. Schematic diagram of the brazing joint.

Before the vacuum brazing, thermodynamic properties of the as-cast and foil-like brazing filler metal were analyzed by differential scanning calorimetry (DSC) used a thermal analyzer (Setaram Evolution 2400, Global (Hong Kong) Technology Co., Ltd., Hong Kong, China). The temperature was raised to 600 °C at a rate of 10 °C/min. The phase composition of the foil-like brazing filler metal was analyzed by using a D8 ADVANCE X-ray diffractometer (Bruker, Karlsruhe, Baden-Wurttemberg, Germany). During XRD measurements, Cu-K α radiation was utilized with the following test conditions: tube voltage of 40 kV, tube current of 150 mA, scanning angle of 10–90°, step size of 0.02°, and scanning speed of 10°/min. After the brazing process, the joints were polished by 400–1000# sandpaper. The metallographic structure of the brazed joint was observed by an optical microscope (OLYMPUS-CK40M, Shanghai Baji Industrial Co., Ltd., Shanghai, China). The shear strength of the brazed joint was tested on a universal electronic testing machine (CMT5205, MTS Systems (China) Co., Ltd., Shenzhen, China), and the shear rate was set to 0.1 mm/min. Observations of the microstructure and fracture morphology of brazed joints were carried out by a scanning electron microscope (Carl Zeiss NTS GmbH, Merlin Compact, Jena, Thuringia, Germany), secondary electron imaging (SEM) and the composition and diffusion of the elements in brazed joints were analyzed by energy-dispersive X-ray spectroscopy (EDS).

3. Results and Discussion

3.1. Thermodynamic Property and Microstructural Characteristics of the Brazing Filler Metal

The DSC curve of the brazing filler metal before and after the melt-spinning process is shown in Figure 5. Figure 5a is a DSC curve of the as-cast brazing filler metal made by the high-frequency induction melting furnace, and Figure 5b shows the DSC curve of the foil-like brazing filler metal made by melt-spinning technique characterized with an extremely rapid cooling rate. It can be found from Figure 5 that the solidus and liquidus temperatures of the foil-like brazing filler metal decreased by 4 °C and 7 °C in comparison with the values of the as-cast brazing filler metal. The corresponding molten temperature region decreased by 3 °C. The decrease of the thermodynamic temperature was related to the grain size. The melt-spinning technique can refine the grain size significantly due to the rapid cooling rate.

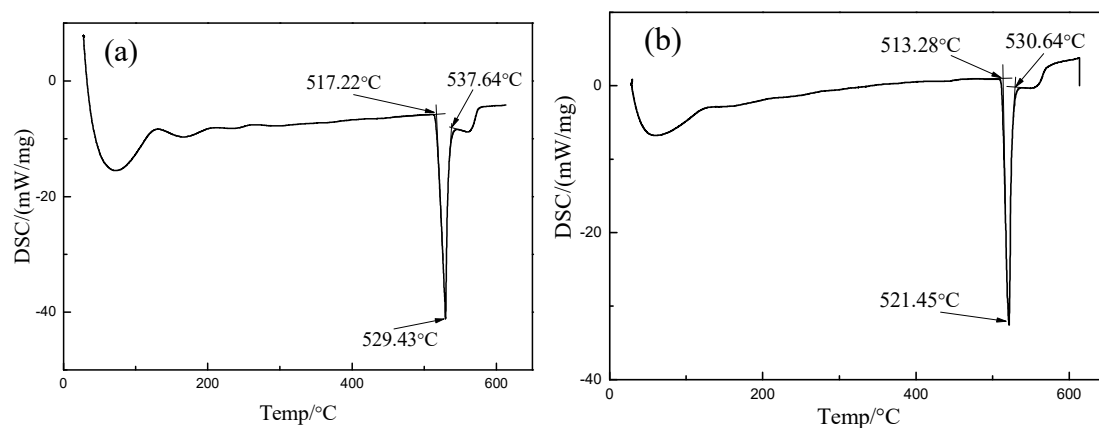


Figure 5. DSC curve of the brazing filler metal alloy: (a) as-cast brazing filler metal; (b) foil-like brazing filler metal.

Figure 6 shows the microstructure of the traditional as-cast brazing filler metal viewed under a scanning electron microscope. It can be seen that there were many cell crystals and dendrites in the as-cast brazing filler metal, and some areas had defects such as pores, and the grain size in the as-cast brazing filler metal was large. The melt-spinning technology can produce the microstructures which can vary greatly from those formed in traditional slow-cooled bulk material. Figure 7 shows the microstructure of the foil-like brazing filler metal made by the melt-spinning technique. The side of the foil-like brazing filler metal contacting the copper roller was called the near-roller surface while the other side was called the free surface. Figure 7a displays the microstructure foil-like brazing filler metal at the free surface; the average grain size is about 159.09 nm, and Figure 7b displays the microstructure at the near-roller surface; the average grain size is about 129.63 nm. Figure 7 indicated that there was no microdefect such as micro-voids and element segregation in the foil-like brazing filler metal. It can be known from the microstructure that foil-like brazing filler metal mainly contained uniform cellular nano grains, and the sizes of the cellular grains were less than 200 nm, which had the characteristics of nanomaterials. As shown in Figure 7, the grain size at the near-roller surface was smaller than that at the free surface due to the faster cooling rate. The results showed that owing to its small size and high surface free energy, the chemical potential of the foil-like brazing filler metal containing micro-nano grains was much higher than that of the bulk material. As a result, the melting point of the micro-nano sized brazing filler metal was depressed in comparison to that of the bulk crystals. Compared with the brazing filler metal prepared by conventional methods, there was a lower melting point and better diffusibility. High-quality brazing joints can be obtained when micro-nano sized brazing filler metal was utilized in experiment.

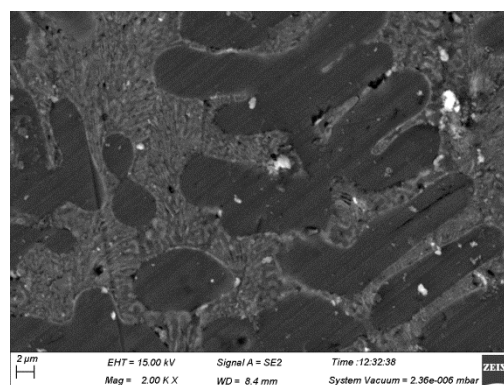


Figure 6. Microstructure of the as-cast brazing filler metal.

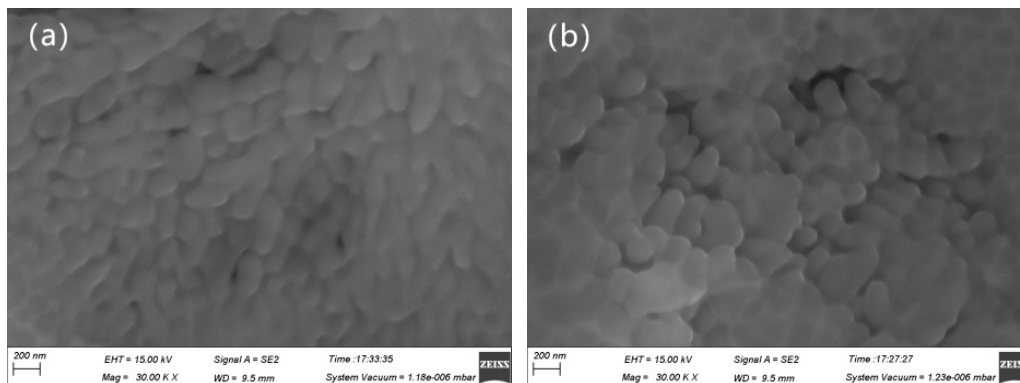


Figure 7. Microstructure of the foil-like brazing filler metal: (a) microstructure of the free surface; (b) microstructure of the near-roller surface.

Figure 8 is the X-ray diffraction analysis (XRD) curve of the foil-like brazing filler metal, which indicates that there are mainly five kinds of phases: α -Al, Al_2MgCu , AlCu , AlCu_3 and Cu_2Mg , and the content of the Al_2MgCu phase is relatively high. Due to the high chemical activity at elevated temperature, alloying elements Mg and Cu in filler metal were mainly in the form of intermetallic compounds. Combined with the analysis in Figure 7, we can infer that the sizes of intermetallic compounds were limited to the nanoscale. Those intermetallic compounds distributed in α -Al were very uniform due to the rapid cooling rate during manufacturing.

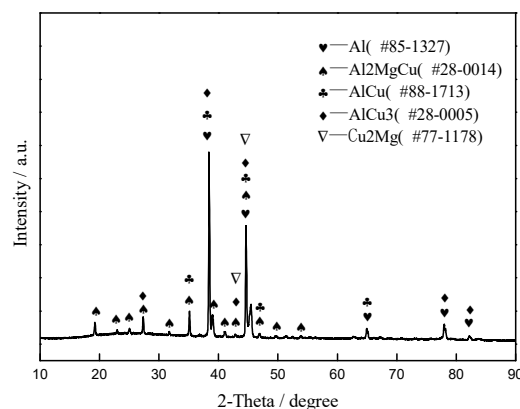


Figure 8. X-ray diffraction analysis curve of the foil-like brazing filler metal.

3.2. Microstructure and Element Distribution Analysis of Brazed Joints

Figure 9 shows the optical microstructure evolution of 55 vol.% $\text{SiC}_p/\text{ZL102}$ composites joints made in a brazed temperature range of 560 °C to 600 °C by using micro-nano foil-like brazing filler metal Al-17.0Cu-8.0Mg. As shown in Figure 9a, some small defects such as an unwetted area and micro-void between the filler metal and SiC particle existed at the interface, which had significant effect on the joint mechanical property. The reason for that was the wettability and interaction between the filler metal and composites was very weak at a lower brazing temperature of 560 °C on account of the lower atomic activity. Figure 9 indicated that brazed joints were continuous and tightly bonded, without physical defects such as micro-voids and cracks when the brazing temperature exceeded 570 °C. The interaction between the filler metal and composites was enhanced under the condition of a relatively high brazing temperature. It can be seen in Figure 9b–e that a gray needle-like or massive eutectic Si structure appeared in the center of the brazing seam. As shown in Figure 9e, the quantity of eutectic Si in the brazing seam was almost as much as in composites. This was due to the large number of Si elements in the base material, which diffused into the brazing joint during the brazing process and formed the eutectic structure with Al elements in the brazing joint [31]. This indicated that a strong

interaction between the micro-nano brazing filler metal and 55 vol.% SiC_p/ZL102 composites occurred. Consequently, the width of the brazing seam became narrower and narrower with the increase in the brazing temperature.

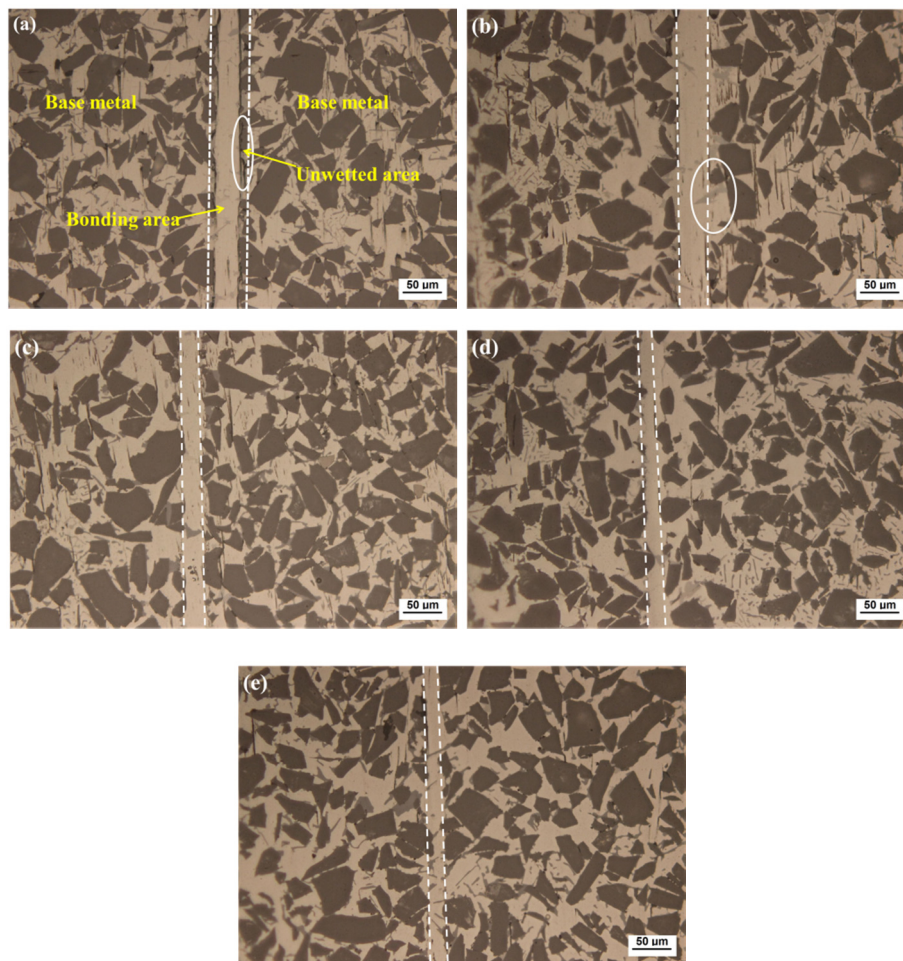


Figure 9. Optical microstructure of joints brazed at different temperatures: (a) 560 °C; (b) 570 °C; (c) 580 °C; (d) 590 °C; (e) 600 °C.

SEM image of a typical region at the interface of the 55 vol.% SiC_p/ZL102 composite joint made at 580 °C and corresponding energy dispersive X-ray analysis are presented in Figure 10. Figure 10 was taken in secondary electron mode. It can be clearly observed that there were two kinds of interfaces: the interface between the brazing filler metal and aluminum matrix, as well as the other interface between the brazing filler metal and SiC particle. Figure 10a indicated that the combination of the two type of interfaces was quite compact. The chemical composition of the joint was analyzed using EDS, as shown in Figure 10a. Some white block phases appeared near the brazing seam. Testing points A and B were located at the center of these white block phases. At point A, the chemical composition was measured as 48.4Al-50.6Cu-0.9Si-0.1Mg (wt.%). At point B, the chemical composition was measured as 29.8Al-37.4Cu-21.0C-8.7Si-3.0Mg (wt.%). Elements of Al and Cu were the primary composites in these white regions. At point B, a small amount of Mg was included which may form the AlMgCu intermetallic. Moreover, these white block phases were mainly distributed around the SiC particle, which meant that the interface between the SiC particle and aluminum was the main diffusion path for Cu. The white block phase can be found at the top left corner in Figure 10a. This suggested that the diffusion distance of element Cu exceeded at least 100 μm under the brazing temperature of 580 °C, which can reduce the effects of brittle intermetallic compounds such as Al₂Cu and AlCu in the brazing seam. At point C, the chemical composition was measured as 95.1Al-4.0Cu-0.9Mg (wt.%). Al was

the primary composite in the brazing seam. The content of Cu and Mg in this area was much lower than that in the original brazing filler metal (Al-17.0Cu-8.0Mg). Figure 10b–e display the individual elemental line scanning profile of Al, Mg, Cu, and Si, respectively. As can be seen, the distributions of elements Al, Mg, Cu, and Si were quite homogeneous except the areas of the white block phase and SiC particle. After brazing, the chemical concentration gradient between the brazing filler metal and base material disappeared. The line scanning profile also indicated that the inter-diffusion phenomenon between the brazing filler metal and 55 vol.% SiC_p/ZL102 composites occurred intensively.

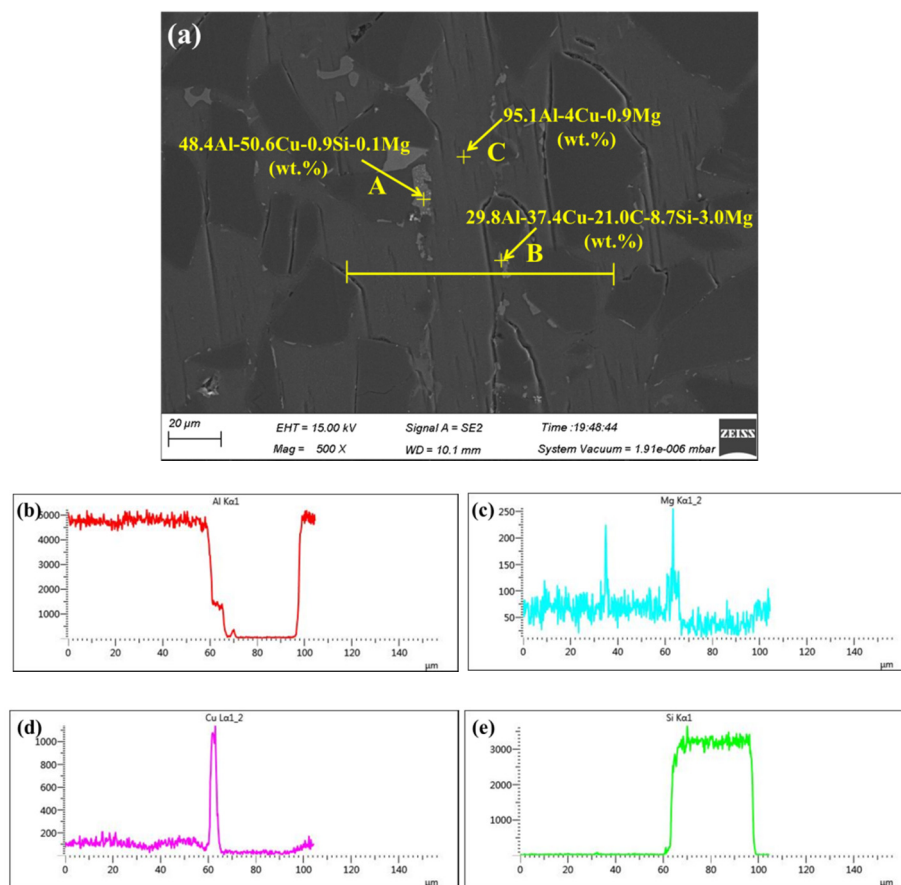


Figure 10. SEM image of a typical region at the interface of the 55 vol.% SiC_p/ZL102 composite joint made at 580 °C and corresponding energy dispersive X-ray analysis: (a) SEM image; (b–e) individual elemental line scanning profile of Al, Mg, Cu, and Si, respectively.

Under the condition of high temperature, Mg was more active than Al, which made it have the possibility to react with alumina on the surface of SiC_p/Al MMCs [32], as shown in Equation (1).



That reaction can eliminate some part of dense alumina, which will improve the wettability of the brazing filler metal. Through the energy spectrum analysis in Figure 10a, it can be seen that the content of Mg in the joint was much lower than that in the original brazing filler metal. As is known, Mg has a quite high saturated vapor pressure compared to the other elements, such as Al, Cu, Fe, etc. During the course of vacuum brazing, the volatile Mg was gradually vaporized and accumulated. A part of the accumulated Mg vapor broke the aluminum oxide film covering on the surface of SiC_p/Al MMCs and then was discharged. As a consequence, the liquid brazing filler metal could diffuse into the base material along the broken location of the aluminum oxide film. Therefore, the chemical composition balance between the brazing seam and base material was achieved.

3.3. Mechanical Properties of Brazed Joints

To find out the optimal process parameters, the effect of brazing temperature on the mechanical property of the joint was investigated, as displayed in Figure 11. Five specimens were tested for each brazing condition to obtain the average shearing data. The joint shear strength increased with the increasing in brazing temperature from 560 °C to 580 °C. At a brazing temperature of 560 °C, the joint shear strength was only 57.43 MPa due to the insufficient diffusion between the brazing filler metal and the matrix, shown from the analysis in Figure 9a. The maximum shear strength of the joint was 98.17 MPa at the brazing temperature of 580 °C. For vacuum brazing, mutual diffusion has to abide by the Arrhenius equation expressed in Equation (2), which is the diffusion coefficient of the filler materials. As can be seen, the diffusion coefficient $D(T)$ is a function of temperature (T), which is a process parameter and can be controlled during the experiment.

$$D(T) = D_0 \exp\left(-\frac{Q}{RT}\right) \quad (2)$$

where T is the diffusion brazing temperature, Q the activation energy, R the gas constant, and D_0 the diffusion constant.

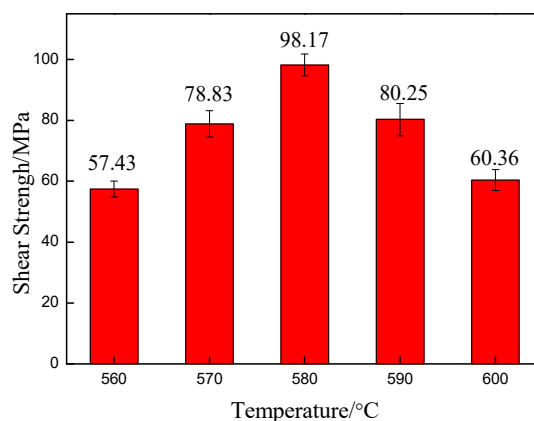


Figure 11. Shear strength of brazed joints at different temperatures.

With the temperature increase, the diffusion coefficient of elements in the brazing system will increase significantly. However, a further increase in the brazing temperature to 590 °C and 600 °C caused a decrease of shear strength to 80.25 MPa and 60.36 MPa, respectively. The change in shear strength at that high temperature was due to the excessive interaction of elements in the joint and matrix, which caused the generation and growth of brittle intermetallics such as Al_2Cu and AlCu having a remarkable influence on the shear strength. On the other hand, a small part of liquid aluminum effused from the 55 vol.% $\text{SiC}_p/\text{ZL102}$ composites during the course of vacuum brazing when the brazing temperature of 600 °C was utilized. This phenomenon had a considerable negative effect on the joint shear strength and mechanical property of 55 vol.% $\text{SiC}_p/\text{ZL102}$ composites.

3.4. Fracture Analysis of Brazed Joints

Figure 12 displays the typical scanning fracture morphology and EDS analysis of the joint made using micro-nano brazing filler metal Al-17.0Cu-8.0Mg at a temperature of 580 °C and holding time of 30 min after room temperature shear testing. As can be seen in Figure 12, both sides of the joint fracture were characterized by the quasi-cleavage fracture. No SiC particles can be found in fracture surface, which meant that the fracture occurred in the brazing seam rather than the interface between the brazing filler metal and 55 vol.% $\text{SiC}_p/\text{ZL102}$ composites. Using EDS analysis, the chemical composition of point A was measured to be 97.5Al-2.5Cu (wt.%). It indicated that the scratching area in the fracture was mainly composed of aluminum solid solution, having good plasticity. The chemical

composition in the cleavage fracture area, such as point B, C, and D was composed of elements of Al, Si, Cu, and Mg, which were 65.2Al-32.2Si-2.1Cu-0.4Mg (wt.%), 29.7Al-27.6Si-22.2Mg-17.4Cu-3.1O (wt.%), and 37.8Al-22.7Si-21.8Mg-16.5Cu-1.3O (wt.%), respectively. The only source of element Si was 55 vol.% SiC_p/ZL102 composites. As can be seen in Figure 12, the Si content at points B, C, and D exceeded 22.7 wt.%, which signified that interdiffusion between the micro-nano brazing filler metal and 55 vol.% SiC_p/ZL102 composites took place sufficiently during the course of vacuum brazing. The intermetallic compound phases (IMC) such as Mg₂Si, Al₂Cu, and Cu₂Mg would be formed due to the high activity of the micro-nano brazing filler metal at high temperature. During vacuum brazing, the formation of brittle IMC would cause stress concentration around the IMC interface. In the following shearing test, the joint was easily cracked in this area of stress concentration. However, the fracture appearance demonstrated that there was no large blocked IMC in the joint, and this would be very beneficial in terms of increasing the joint mechanical property. To better analyze the fracture mechanism of brazed joints, Figure 13 shows the shear curve with temperature of 580 °C and holding time of 30 min. The orce-displacement curve was relatively smooth and there was no yield phenomenon. Therefore, the brazing joint is a brittle fracture.

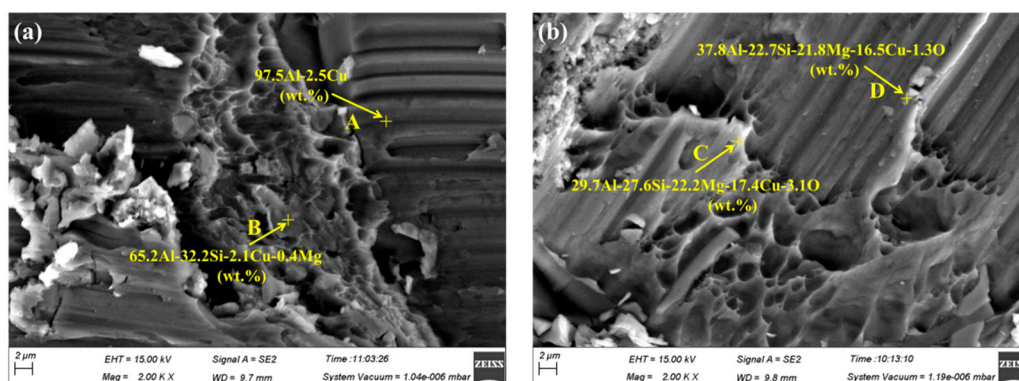


Figure 12. Scanning fracture morphology and EDS analysis of the joint made using micro-nano brazing filler metal Al-17.0Cu-8.0Mg at a temperature of 580 °C and holding time of 30 min: (a) one side of the fracture; (b) the other side of the fracture.

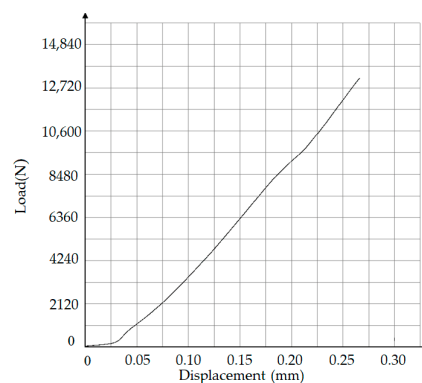


Figure 13. Shear curve at a temperature of 580 °C and holding time of 30 min.

4. Conclusions

In this work, 55 vol.% SiC_p/ZL102 composites were successfully bonded through the brazing process under a vacuum condition. Micro-nano brazing filler metal Al-17.0Cu-8.0Mg fabricated by melt-spinning technology was utilized for brazing in a temperature range of 560–600 °C, with a holding time of 30 min. This new micro-nano brazing filler metal and corresponding brazing process can provide a technical reference and theoretical value for dealing with the joining problem of SiC_p/Al MMCs. The main conclusions can be summarized as following:

- (1) Using melt-spinning technology, the foil-like brazing filler metal Al-17.0Cu-8.0Mg was obtained. The microstructure analysis indicated that the foil-like brazing filler metal mainly contained uniformed cellular nano grains, with a size less than 200 nm. The solidus and liquidus temperatures of the foil-like brazing filler metal decreased by 4 °C and 7 °C in comparison with the values of the as-cast brazing filler metal due to the nanometer size effect. Compared with the brazing filler metal prepared by conventional methods, the micro-nano brazing filler metal had higher toughness, lower melting point, and better diffusibility, which were more conducive to the wetting and spreading behavior between the brazing filler metal and base material.
- (2) The microstructure observation indicated that brazed joints were continuous and tightly bonded, without physical defects such as micro-voids and cracks when the brazing temperature exceeded 570 °C. Moreover, the width of the brazing seam became narrower and narrower with increasing brazing temperature owing to the strong interaction between the micro-nano brazing filler metal and 55 vol.% SiCp/ZL102 composites. Some white block phases mainly containing elements Al and Cu appeared near the brazing seam. The main diffusion path for Cu was the interface between the SiC particle and aluminum. After brazing, the chemical concentration gradient between the brazing filler metal and base material disappeared.
- (3) The maximum joint shear strength was achieved at 98.17 MPa at the brazing temperature of 580 °C. The joint shear strength increased in the temperature range of 560 °C to 580 °C. However, a further increase in the brazing temperature to 590 °C and 600 °C caused a decrease in shear strength to 80.25 MPa and 60.36 MPa, respectively. The excessive interaction in the joint and matrix caused the generation and growth of brittle intermetallics such as Al₂Cu and AlCu having a remarkable influence on the shear strength.
- (4) The fracture morphology of the joint made at a brazing temperature of 580 °C was characterized by quasi-cleavage fracture. Fractures occurred in the brazing seam rather than the interface between the brazing filler metal and 55 vol.% SiCp/ZL102 composites since no SiC particles could be found in the fracture surface. There was no large blocked intermetallic compound in the joint, and this would be very beneficial in terms of increasing the joint mechanical properties.

Author Contributions: Investigation, D.Q., Z.G., and X.B.; resources, Z.W.; supervision, J.N.; writing—original draft preparation, D.Q.; writing—review and editing, Z.G. and J.N. All authors have read and agreed to the published version of the manuscript.

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