

## Strengthening mechanism of ceramic particle reinforced bonds by ultrasonic brazing of AlMMCs

LENG Xue-song<sup>1</sup>, WANG Chang-wen<sup>1</sup>, ZHANG Yang<sup>2</sup>, CHEN Xiao-guang<sup>1</sup>, YAN Jiu-chun<sup>1</sup>

1. State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China;
2. School of Materials Science and Engineering, Shijiazhuang Tiedao University, Shijiazhuang 050043, China

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**Abstract:** Composite materials (55% (volume fraction) SiC<sub>p</sub>/A356) were brazed with the assisted ultrasonic wave by filling with a Zn-based alloy solder. With different bonding temperatures, two kinds of bonds, which contained 7% and 35% SiC particles, respectively, were fabricated. The results show that the two kinds of bonds have not only different microstructure properties, but also different crack propagation behaviors, which will bring on wide difference in mechanical properties. The shear strength of the bond containing 35% SiC particles is above 244 MPa, which is 84.7% higher than that of the bond containing 7% SiC particles. The reason is that the SiC particles in the composite bonds can effectively suppress the fracture. And the fracture is also effectively delayed by the Al-based solid solution in the composite bonds. Therefore, with appropriate bonding parameters, ultrasonic brazing can make the SiC particles and Al contents increase in the bond, and this distribution will contribute to the enhanced strength of the brazed bonds.

**Key words:** aluminum metal matrix composites; brazing with assisted ultrasonic wave; fracture behavior

### 1 Introduction

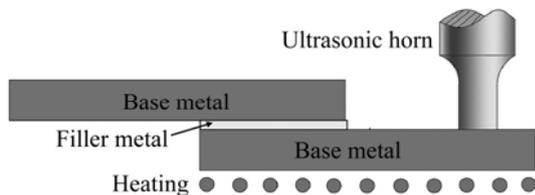
Aluminum metal matrix composites (Al-MMCs) with the reinforcement of SiC particles are perfect materials for the application on the electronic packaging and aerospace industry field. But this material is difficult to join because of the bad weldability. For fusion welding, due to the high viscosity and poor flowability in the liquid weld pool, the undesired reactions between the Al matrix and ceramic particles result in a poor appearance and a weak mechanical property of the joints [1–2]. For the non-fusion joining approaches, such as diffusion bonding [3–4], transient liquid phase bonding [5–6] and brazing [7–8], Al-MMCs are used to be joined with low volume fraction reinforcement. The reason is that with high volume fraction reinforcement, these approaches are greatly limited because of microsegregation or inhomogeneous distribution of the reinforcements in the weld as a result of rejections of SiC particulates by the solidification front. Then the mechanical properties of the welded joint are decreased.

Therefore, new methods are needed to treat these obstacles. WIELAGE et al [9] directly reinforced the conventional Sn-based solders by ceramic particles and obtained a composite bond with 100% increase in strength. HUANG et al [10] used an Al–Si–SiC–Ti mixed powder interlayer to obtain an improved composite bond of 50 MPa during the joining of 6063–SiC<sub>p</sub> composites by reactive diffusion bonding. These approaches improve the strength with limits.

In this study, an effective method was put forward. The Al-MMCs with 55% SiC<sub>p</sub>/A356 composite materials were ultrasonic brazed by filling with a Zn-based alloy solder. Based on the particle reinforced mechanism for composite materials [11–12], the particle reinforced composite bond is expected to improve the strength of joints. At different bonding temperatures, the composite bonds containing different volume fractions of SiC particles were fabricated. The crack initiation and propagation behavior in the composite bonds were examined using in situ SEM. The effects of SiC particles and Al-based solid solution on the strength and fracture behavior of the composite bonds were studied.

## 2 Experimental

The SiC<sub>p</sub>/A356 composites used in this study were fabricated by pressureless infiltration processing and contained 55% (in volume fraction) SiC particles with an average diameter of 50 μm. The chemical composition (in mass fraction) of the matrix metal was (6.5%–7.5%) Si, (0.25%–0.45%) Mg, (0.08%–0.20%) Ti, Al of the rest. The solder was a Zn–Al alloy with the composition of 89.3% Zn, 4.20% Al and 3.22% Cu. Its melting point was 383–399 °C. The shear strength of the Zn–Al alloy was 131 MPa. The dimension of the samples was 40 mm×10 mm×20 mm and the overlapping length was 10 mm. The Zn–Al filler with a dimension of 10 mm×10 mm×0.3 mm was located between the two parts to be joined. Surfaces to be bonded were mechanically polished to a 500-grit finish and then ultrasonically degreased in acetone. The actual brazing procedure was conducted by applying ultrasonic waves. The samples were heated to a preset temperature (420 or 475 °C) in air. An ultrasonic wave, maintaining 20 s, with the amplitude of 10–15 μm and a frequency of (20±0.5) kHz was then applied to the rear part of the samples, shown as Fig. 1.

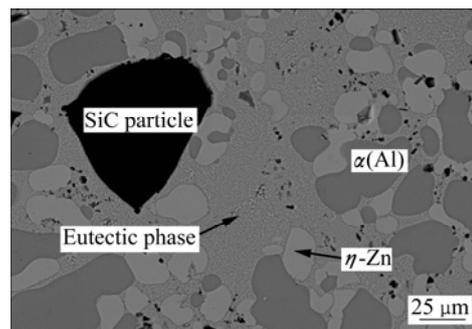


**Fig. 1** Schematic diagram of bonding process with ultrasonic wave

A shear test was used to determine the bond strength. The overlapping dimension used for testing was 5 mm×10 mm, which was cut from the original joints. The shear strength of the brazed bonds was evaluated by a specially designed fixture in an electron tension testing machine (INSTRON–5569). For each bonding condition, three samples were tested to assess the reproducibility of the process. Microstructural observations of the specimens were carried out using a scanning electron microscope (SEM, S–570) equipped with an energy dispersive X-ray spectrometer (EDS, TN5500). The specimens in the in-situ tensile tests were taken from the composite bonds by an electric discharge machine. A U-type notch of 0.2 mm in width was set as a crack source to control the crack initiation site. In situ SEM observations were made by a manually controlled loading device. Monotonic loading was controlled with a straining rate of 0.001 s<sup>-1</sup>.

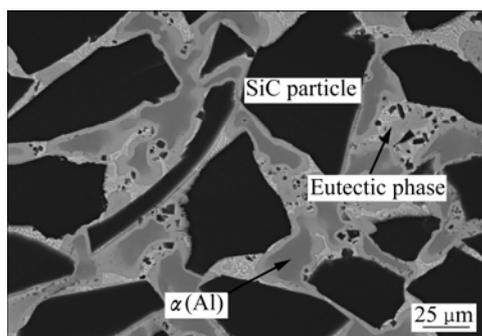
## 3 Result and discussion

Figure 2 shows the structural features of the SiC<sub>p</sub>/A356 joint brazed at 420 °C. The bond has a width of 350 μm, and it is broadened because of base material dissolution. The SiC particles of 7% in volume fraction from the base materials were scattered over it. The bond metal matrix is a Zn-based alloy. It is basically comprised of a mixture of three phases, namely α, η and eutectic phases. The α phase is an Al-based solid solution with a composition (in mass fraction) of 70.65% Zn, 26.65% Al and 2.70% Cu. The η phase is a Zn-based solid solution with a composition of 93.36% Zn, 1.79% Al and 4.85% Cu. The chemical composition of the eutectic phase is 86.97% Zn, 8.05% Al and 4.98% Cu. The grain size of α phase is significantly larger than that of the η phase, and they are embedded in the eutectic phase. The shear strength of the reinforced bonds can reach 153 MPa.



**Fig. 2** Microstructure of SiC<sub>p</sub>/A356 joints brazed at 420 °C

Figure 3 shows the structural features of the SiC<sub>p</sub>/A356 joint brazed at 475 °C. The bond zone was broadened to 850 μm because of the base material dissolution and the particles with a volume fraction of 35% from the base materials well-distributed in the bond zone. There is a mixture of mainly two phases, namely α phase and eutectic phase. The primary α phase shows a typical dendritic structure. And its microsegregation was measured by EDS microanalysis and BSE images. The chemical composition of the dendrite centre is 42.17% Zn, 56.11% Al and 1.72% Cu and the dendrite edge is 70.59% Zn, 26.65% Al and 2.79% Cu. With the increase of SiC particle volume fraction from 7% to 35%, the Al content (mass fraction) in the bond zone increases from 10.28% to 31.92%. This also causes α phase increase and the eutectic phase reduce. This phenomenon indicates that with the increase of SiC particle, the mass transfer between the filler metal and the composite increases and the quantity of Al in the bond zone also increases. The shear strength of the reinforced bonds can be increased to 244 MPa, which is 84.7% higher than that at 420 °C.

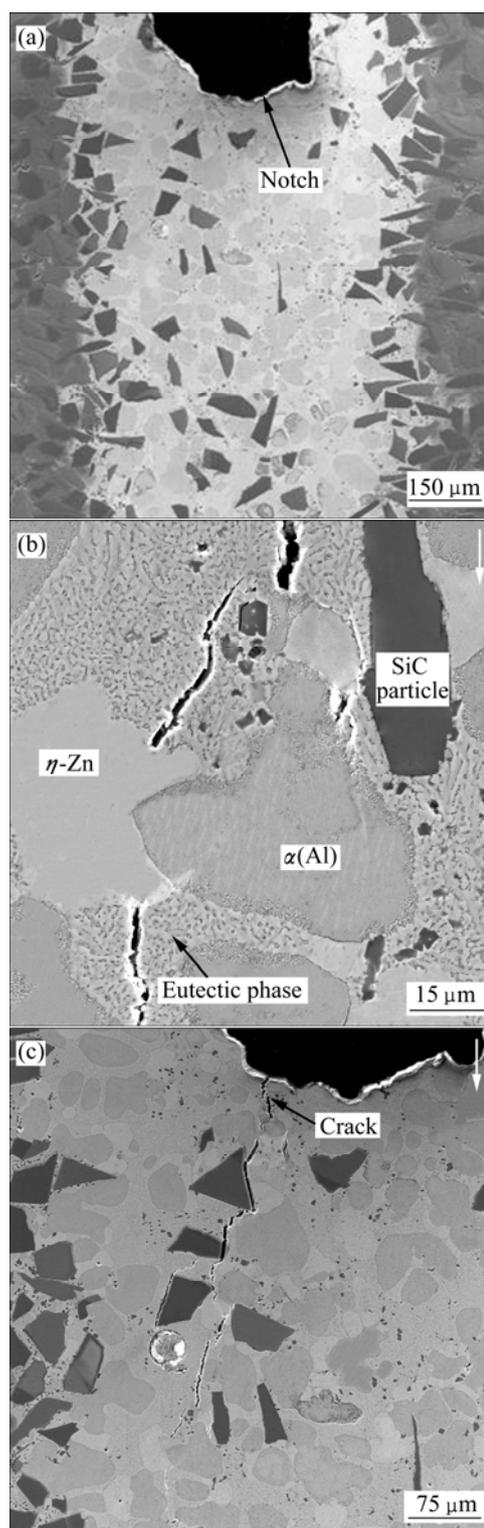


**Fig. 3** Microstructures of SiC<sub>p</sub>/A356 joints brazed at 475 °C

In situ SEM observations were usually used to study the fracture behavior of Al-MMCs [13–16]. This method was also used to assess composite bonds in this work. It is defined *L* and *H* bonds representing the 7% and 35% SiC particles reinforced composite bonds. Figs. 4 and 5 show in situ SEM photographs of *L* and *H* bonds during the tensile loading process, in which the direction of crack propagation is set with the arrow at the top right corner of each figure. In general, for two kinds of composite bonds, all of cracks nucleated in the eutectic phase. For *H* bonds the microcracks initiated in the eutectic phase at a strain of only 0.08% (Fig. 5(a)). But for *L* bonds, the microcracks could not nucleate in any position of the composite bonds with the same strain (Fig. 4(a)), and initiated in the eutectic phases until a strain of 0.36% was reached (Fig. 4(b)). However, the stress in *L* bonds was much less than that in *H* bonds. This indicates that the elastic modulus increases with the increase of SiC particles in the composite bonds.

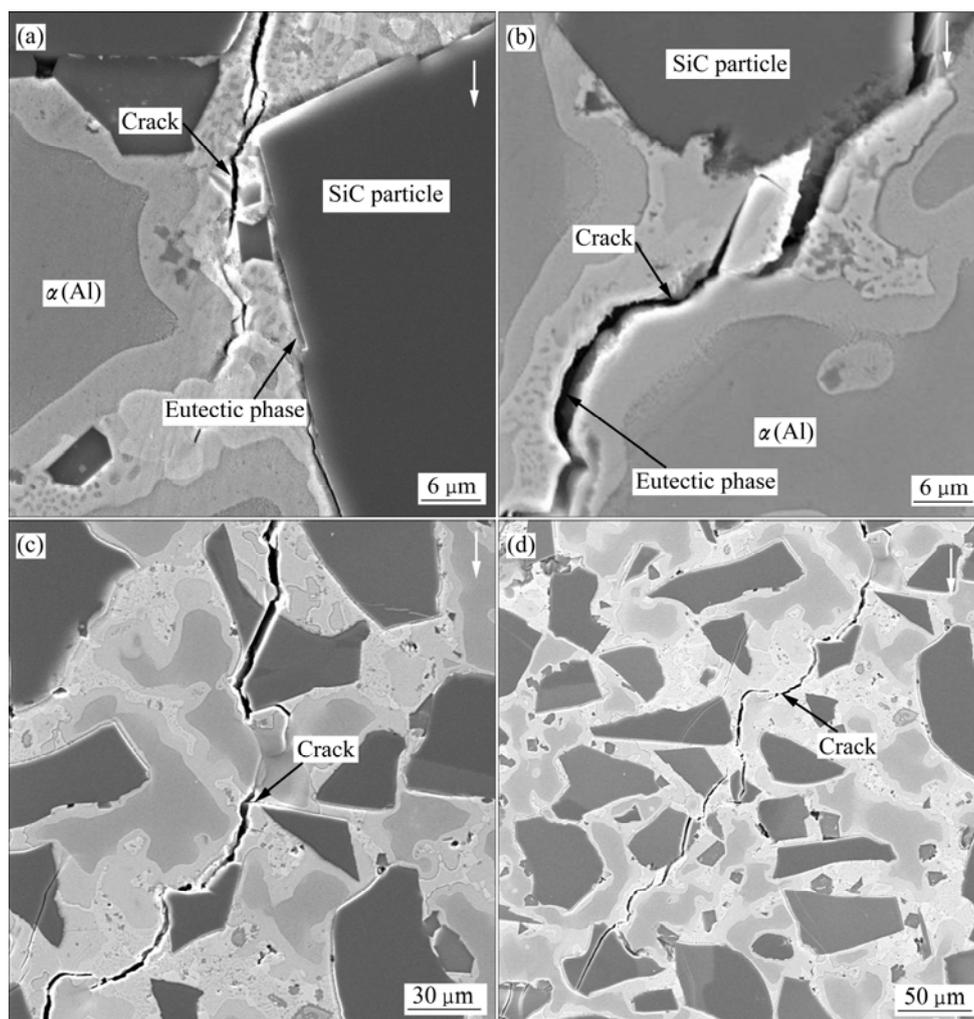
As shown in Fig. 4, when a crack met  $\alpha$  crystalline region, the  $\alpha$  phase might deflect the crack original path (Fig. 5(b)) or temporarily delay the propagation (Fig. 5(c)). When a crack met a SiC particle, the particle was usually broken (Fig. 5(c)) and the crack continued to propagate. But on occasion, some particles were not broken. They induced the crack propagating along the interface between SiC particles and Zn–Al matrix (Figs. 4(c) and 5(c)). For *H* bonds, as the strain reached a critical value (0.33%), the fracture occurred. The crack had a tortuous path and a relatively long propagation process (Fig. 5(d)). However, the crack in *L* bonds initiated at a strain of 0.36%, then linked with other cracks in the neighboring eutectic phases and quickly grew. At a strain of 0.39%, the fracture occurred, the crack line formed a straight path and leading to the final fracture (Fig. 4(c)).

From the above photographs, it can be concluded that the mechanical strength is in close connection with SiC particles and Al-based solid solution. The reason is for the special characteristics of them. For the SiC particle, it will cause an increase in the number of



**Fig. 4** In situ SEM photographs of SiC<sub>p</sub>/A356 brazed bonds with SiC particles of 7% under different strain: (a) 0.08%; (b) 0.36%; (c) 0.39%

dislocations because of the coefficient of thermal expansion mismatch between the matrix and the reinforcement. Because the distribution of dislocations in the Zn–Al matrix is usually not uniform, the microcracks are not easy to nucleate. On the contrary, the dislocations



**Fig. 5** In situ SEM photographs of SiC<sub>p</sub>/A356 brazed bonds with SiC particles of 35% under different strain: (a) 0.08%; (b) 0.17%; (c) 0.21%; (d) 0.33%

will prevent or delay the propagation of microcracks. Besides the effect of dislocation, the SiC particle itself would hinder the microcracks propagation by inducing large differences in the elastic behavior between the matrix and the particle. With the increase of the SiC particle in the bonds, the  $\eta$ -Zn rich phase was replaced by  $\alpha$ (Al) rich dendrites and the volume fraction of the Al-rich phase increased. Because  $\alpha$  phase can undergo serious plastic deformation, these may deflect the crack path or temporarily delay the propagation at the eutectic/ $\alpha$  phase interface, which depend on the locative relations between crack and  $\alpha$  crystalline. So at higher bonding temperature, the more SiC particles and Al content could be made well-distribution in joint, then the increase of strength can also be attributed to the increase of Al content.

#### 4 Conclusions

1) At the bonding temperature of 420 °C and 475 °C,

the composite bonds separately containing about 7% and 35% (in volume fraction) SiC particles were produced. The shear strength of the bond containing 35% SiC particles is up to 244 MPa, which is 84.7% higher than that of the bond containing 7% SiC particles.

2) This result is attributed to the different volume fractions of SiC particles and Al content in the composite bonds. On the basis of in situ SEM observations, the microcracks initiated in the eutectic phases for both of bonds. For the bond containing 7% SiC particles, the microcracks propagated in eutectic phases. For the bond containing 35% SiC particles, the microcracks propagated in both the eutectic phases and SiC particles.

3) Fracture is better suppressed in the composite bond containing 35% SiC particles than in the composite bond containing 7%. The reason is that the SiC particles and Al-based solid solution can hinder or delay the propagation of microcracks. The more stress would be loaded to make the bond containing higher volume fraction of SiC particles fracture.

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# 铝基复合材料超声波钎焊陶瓷颗粒增强接头强度机理

冷雪松<sup>1</sup>, 王长文<sup>1</sup>, 张洋<sup>2</sup>, 陈晓光<sup>1</sup>, 闫久春<sup>1</sup>

1. 哈尔滨工业大学 先进焊接与连接国家重点实验室, 哈尔滨 150001;
2. 石家庄铁道大学 材料科学与工程学院, 石家庄 050043

**摘要:** 对含有 55%SiC 高体积分数的铝基复合材料以 Zn 基合金作为钎料层进行超声波辅助钎焊。在 420 °C 和 475 °C 钎焊温度下, 形成分别含有 7% 和 35%SiC 体积分数的连接接头。两种接头的微观拉伸原位分析结果显示, 它们不但具有不同的微观结构, 而且具有不同的裂纹生长传播机制, 从而具有不同的力学性能。含有 35%SiC 的接头剪切强度达到 244 MPa, 比含有 7%SiC 的高出 84.7%。其原因是接头中 SiC 颗粒可以抑制裂纹的产生及传播, Al 基固溶体也可抑制裂纹生长。因此, 在合适的超声波钎焊温度下, SiC 颗粒和 Al 元素更多地扩散至接头区, 使得接头剪切强度增高。

**关键词:** 铝基复合材料; 超声波辅助钎焊; 断裂行为

(Edited by HE Xue-feng)