Mechanical Properties of Diffusion Bonding Joint of SiC and Al-Sn Alloys at Elevated Temperatures

Houhong Pan*, Isao Itoh and Masaaki Matsubara

Engineering Faculty, Gunma University, Kiryu 376-8515, Japan

Aluminum alloys were selected to bond to SiC by diffusion bonding in the atmosphere for researching their bondability. Diffusion bonding was carried out at 873 K for 3.6 ks and 7.2 ks under bonding pressures of 2 MPa, 4 MPa and 8 MPa. The mechanical properties of SiC/Al-0.5Sn joints and SiC/Al-0.5Sn-1Mg joints at elevated temperatures were examined by shear test, and the fracture surfaces of joints were investigated using SEM and EPMA. The results indicate that (1) pure aluminum cannot be bonded to SiC. Adding 0.5%Sn into aluminum can improve bondability. The compound addition of 0.5%Sn and 1%Mg into aluminum can improve both the shear strength and the elevated temperature properties of joint. (2) In the case of SiC/Al-0.5Sn diffusion bonding, the fracture fully occurs on bonding surfaces. In the case of SiC/Al-0.5Sn-1Mg diffusion bonding, the fracture partly occurs in the side of SiC. (3) The optimum bonding pressure is 4 MPa and 8 MPa for SiC/Al-0.5Sn and SiC/Al-0.5Sn-1Mg diffusion bonding, respectively. In optimum bonding condition, the maximum shear strength of SiC/Al-0.5Sn-1Mg joint is 51.7 MPa.

(Received March 30, 2001; Accepted September 7, 2001)

Keywords: aluminium-tin alloy, SiC, ceramic, diffusion bonding, elevated temperature, shear strength

1. Introduction

Advanced ceramics are great attractive materials for structural and functional applications. This is due to their excellent high temperature mechanical characteristics, good wear and corrosion resistances. However, the fabrication of ceramic components with complex geometry or larger size is very difficult by conventional processes such as machining, casting and forging because of its brittleness and high melting temperature. Bonding of ceramic and metal was recognized as one of the feasible technologies for the practical application of ceramics.

There are many bonding techniques that can be used to bond ceramics to metal.¹⁻⁶⁾ Diffusion bonding is a promising method for practical applications. In diffusion bonding of ceramics and metal, a material is usually inserted as interlayer to make up for the incoherence of ceramics and the inherent difference of heat expansion coefficient between ceramics and metals. It has been reported that aluminum alloys are used as an interlayer for diffusion bonding of ceramics.⁷⁻¹¹⁾ Previous work in our laboratory has also demonstrated that an Al-Sn alloy can be used as a good insert metal in vacuum-free diffusion bonding of metal and ceramics.⁸⁻¹¹⁾

In the present study, the diffusion bonding of SiC to the Al-Sn alloys in the atmosphere along with the mechanical property of these joints at elevated temperatures is researched.

2. Experimental Procedure

2.1 Materials and specimen preparation

The ceramic used in the present work is SC221, a kind of SiC supplied by Kyocera Corporation (Japan). SC221 contains B and C as sintering reagents. According to its nominal composition, SC221 contains 99.5 mass%SiC and total 0.5 mass%B and C. The dimension of SiC specimen is 20 mm in length, 10 mm in width, and 6 mm in thickness.

Table 1 Conditions of diffusion bonding.

Bonding temperature	873 K
Bonding time	7.2 ks
Bonding pressure	2, 4 and 8 MPa
Heating rate	20 K/min
Cooling rate	Air-cooling

And the faying surfaces were polished to the roughness of $Ra = 0.02-0.04 \mu\text{m}$ by manufacturer.

Aluminum, Al-0.5 mass%Sn (Al-0.5Sn) and Al-0.5 mass%Sn-1 mass%X (X=Cu, Mg, Zn, Ti, Si, Bi, Cr, Mn or Ni) (Al-0.5Sn-1X) alloys were prepared by melting at least 99.9% pure metals in a medium frequency induction furnace. During melting, the solution was agitated to avoid segregation. The specimens of Al-Sn alloys were firstly cut into pieces with dimensions of $20 \times 10 \times 10 \text{ mm}^3$, and then the bonded surface was ground with P220-P1000 grit SiC paper, and finally polished with $9 \mu\text{m}$ diamond powder.

To remove any remaining contaminations adhering to the bonding surfaces, both SiC and aluminum alloy pieces were cleaned in acetone with ultrasonic agitation for 5 min prior to bonding.

2.2 Diffusion bonding procedure

After cleaning, the diffusion couples of SiC and aluminum alloys were set into a bonding jig for alignment and heated in an electric furnace. Diffusion bonding was performed in the atmosphere. The conditions of diffusion bonding are shown in Table 1. Bonding temperature and bonding time are decided with reference to diffusion bonding of Al-Sn alloys to alumina, silicon nitride and zirconia.⁸⁻¹¹⁾

2.3 Mechanical testing

The strength of joints was measured by shear test. Bonded specimens were firstly cut into two pieces and then ground with P500 grit SiC paper. Test treatment was carried out at the

*Corresponding author, Graduate Student.

Table 2 The bondability summary of diffusion bonding of SiC to aluminum alloys. ○: Good △: Poor ×: cannot —: not performed.

Bonding conditions	Al	Al-0.5Sn	Al-0.5Sn-1X (X=Cu, Mg, Zn, Si, Ti, Bi, Cr, Mn or Ni)								
			Cu	Mg	Zn	Si	Ti	Bi	Cr	Mn	Ni
873 K-2 MPa-3.6 ks	—	○	—	○	—	—	—	—	—	—	—
873 K-2 MPa-7.2 ks	—	○	—	○	—	—	—	—	—	△	—
873 K-4 MPa-7.2 ks	×	○	○	○	○	○	○	—	○	△	○
873 K-8 MPa-7.2 ks	×	○	○	○	×	○	○	×	○	△	○

temperature ranging from room temperature to 773 K. Heating rate is 5 K/min, while cross-head speed is 0.5 mm/min. After the temperature reached the setting value, the temperature was held for 10 minutes prior to loading. The number of tested specimens was three for every bonding and testing condition, and shear strength was calculated by their average value.

2.4 Observation of fracture surfaces

The fracture surfaces of joints were examined using scanning electron microscopy (SEM). The element distributions on fracture surface were analyzed by means of electron probe micro-analyzer (EPMA). The examination was carried out at an accelerating voltage of 15 kV.

3. Results

3.1 Bondability

Table 2 summarizes the bondability of SiC to aluminum alloys. Pure aluminum cannot be bonded to SiC. Adding 0.5%Sn into aluminum can give effective bonds under various bonding conditions. Compound addition of 0.5%Sn and 1%Mg, Si, Ti, Cr or Ni into aluminum can also give effective bonds. Specially, the compound addition of 0.5%Sn and 1%Mg will obviously enhance bonding strength (Ref. Fig. 3). However, the compound addition of 0.5%Sn and 1%Mn into aluminum only results in poor bonding joint, which tends to break up when cut into two pieces. The compound addition of 0.5%Sn and 1%Zn can spawn bonding joint only under bonding condition of 873 K-2 MPa-7.2 ks. The compound addition of 0.5%Sn and 1%Bi cannot give effective bonding joint.

3.2 Mechanical property at elevated temperature

Both SiC/Al-0.5Sn and SiC/Al-0.5Sn-1Mg couples were selected to examine the mechanical property at elevated temperature, based on the test of bondability of Al-0.5Sn-1Mg alloy to SiC and to other ceramics.⁸⁻¹¹⁾

Figure 1 shows the shear strength of SiC/Al-0.5Sn diffusion joints versus shear test temperature. It can be seen that shear strength increases with the increase of shear test temperature ranging from room temperature to 373 K, and then decreases with the increase of shear test temperature. The relationship between shear strength of aluminum alloy 1100 and test temperature is also illustrated in Fig. 1.¹²⁾ The chemical composition of 1100 aluminum alloy is equivalent to Al-0.5Sn alloy. At the same test temperature, strength of SiC/Al-0.5Sn joints is greatly lower than that of 1100 aluminum alloy.

Fig. 1 Shear strength of SiC to Al-0.5Sn alloy diffusion bonding joint under different bonding pressure as a function of shear test temperature.

Fig. 2 Shear strength of SiC to Al-0.5Sn-1Mg alloy diffusion bonding joint under different bonding pressure as a function of shear test temperature.

The relationships between shear strength of SiC/Al-0.5Sn-1Mg diffusion joints and shear test temperature are shown in Fig. 2. It can be seen that shear strength increases with the increase of shear test temperature at first, and then decreases slightly with the increase of shear test temperature in the range from 373 to 473 K. Thereafter, shear strength decreases with the increase of shear test temperature. The relationship between shear strength of aluminum alloy 5005, which has a chemical composition equivalent to Al-0.5Sn-

Fig. 3 The shear strength of SiC to Al–Sn alloy diffusion bonding joints at shear test temperature of 373 K as a function of bonding pressure.

1Mg alloy,⁸⁾ and test temperature is also shown in Fig. 2.¹³⁾ Over the shear test temperature of 373 K, strength of joints bonded under 8 MPa is higher than that of aluminum alloy 5005.

Figure 3 shows the shear strength of SiC/Al–0.5Sn and SiC/Al–0.5Sn–1Mg joints at shear test temperature of 373 K as a function of bonding pressure. In the case of SiC/Al–0.5Sn joint, the shear strength gets higher with the increase of bonding pressure in the range of 2 MPa to 4 MPa, and then decreases slightly with the increase of bonding pressure. In the case of SiC/Al–0.5Sn–1Mg joint, the shear strength slightly increases with the increase of bonding pressure ranging from 2 MPa to 4 MPa, and then obviously increases with the increase of bonding pressure.

3.3 Microstructure of fracture surface

The fracture position of SiC/Al–0.5Sn joints is different from SiC/Al–0.5Sn–1Mg joints. All SiC/Al–0.5Sn joints get broken across the bonding interface. In the case of SiC/Al–0.5Sn–1Mg joints, the cracks partly occur in the side of SiC and result in the shatter of SiC. In this case, it is considered that the strength of joint is affected by thermal stress. In our study, fracture surfaces are always observed over the bonding interface.

The SEM and characteristic X-ray images on both SiC and Al–0.5Sn alloy sides for SiC/Al–0.5Sn joint, which was bonded under bonding condition of 873 K–8 MPa–7.2 ks, and on Al–0.5Sn alloy surface before bonding are shown in Fig. 4. It can be seen that the distribution of Sn is obviously different after bonding. In the fracture surface, the content of Sn obviously increases.

The SEM and the characteristic X-ray images on both SiC and Al–0.5Sn–1Mg alloy sides for SiC/Al–0.5Sn–1Mg joint, which was bonded at 873 K, under 8 MPa for 7.2 ks, and on Al–0.5Sn–1Mg alloy surface before bonding are illustrated in Fig. 5. It shows that the distribution of Mg is basically identical with the distribution of Sn on the fracture surface.

4. Discussion

For making aluminum alloys, EPMA show that Mg and Bi coexist with Sn on the whole, and Mn and Si partly coexist with Sn.^{8,10,11)}

It is evident that adding 0.5%Sn into aluminum can im-

prove the diffusion bondability of aluminum alloys and SiC. The reason is that, (1) At bonding temperature, Sn in aluminum alloys will remelt into liquid, and the liquid Sn near the bonding interface is squeezed into the bonding interface by bonding pressure. (2) The liquid Sn breaks oxide films on the aluminum alloys surface and protects the aluminum alloys from an attack of air. (3) Sn remaining in the bonding interface after bonding relaxes the thermal stress partly because of its good plasticity. However, it must be pointed out that the excess Sn in the interface is unfavorable to the bonding strength.⁹⁾

The compound addition of 0.5%Sn and 1%Mg can improve the diffusion bonding strength of aluminum alloys and SiC. The phenomenon had been observed in diffusion bonding of Al–Sn alloys to alumina,⁸⁾ nitride¹⁰⁾ and zirconia,¹¹⁾ too. The reason is that Mg is squeezed into the bonding interface along with the liquid Sn, and reduces oxide films, which exists in interface and prevents the couple from bonding.

Diffusion bonding of SiC/Al–1Mg not carried out in this study. However, I. Itoh *et al.*⁸⁾ have reported the diffusion bonding of Al₂O₃/Al–*x*Mg (*x* = 0.52, 0.95, 2.73). The shear strength of Al₂O₃/Al–*x*Mg joints is about half of that of Al₂O₃/Al–0.5Sn–1Mg joints. And the fracture of Al₂O₃/Al–*x*Mg joints occurred in the side of Al₂O₃, and the fracture of Al₂O₃/Al–0.5Sn–1Mg joints occurred in the side of aluminum alloy.⁸⁾ Therefore, only adding Mg into aluminum cannot release thermal stress.

For aluminum, the effect of Bi is about the same with Sn. When the compound adding 1%Bi and 0.5%Sn into aluminum, same as the excess Sn, the bonding strength is seriously weakened and leads to the bonding failure. It also had been observed in diffusion bonding of Al–Sn alloys to zirconia¹¹⁾ and nitride.¹⁰⁾

For the negative effect on the bonding strength, which produced by the compound addition of Sn and Mn or Zn, we cannot yet give a satisfactory explanation, now. It will be considered in the future.

Usually, the shear strength of any joint at room temperature is higher than that of high temperature. However, the measured result shows that the maximum shear strength is achieved at a shear test temperature of 373 K (Fig. 1 and Fig. 2). It could be explained that there is residual stress in joints. It is well known that the post-bonding cooling has greater influence on the residual stress. The greater cooling rate, the greater residual stress. Air-cooling in the present work is conducted at the greater cooling rate, thus leading to the greater residual stress in joints. When shear test is carried out at room temperature, the residual stress leads to the decrease of shear strength. When shear test is performed at 373 K, the residual stress is relieved partly, so the shear strength increases.

A bonding pressure is an important process parameter for diffusion bonding. An appropriate bonding pressure will help relieve the pore among bonded material by means of the plastic deformation of bonded material. And a suitable bonding pressure is usually determined by the hardness and strength of the bonded material. In the case of SiC/Al–0.5Sn diffusion bonding, 4 MPa is the optimum bonding pressure. When the bonding pressure reaches to 8 MPa, the liquid Sn squeezed into the interface will increase. Con-

Fig. 4 SEM micrographs and X-ray images of (a) SiC fracture surface (b) aluminum alloys fracture surface for diffusion bonding of SiC and Al-0.5Sn alloy under bonding pressure of 8 MPa (c) Al-0.5Sn alloy surface before bonding.

Fig. 5 SEM micrographs and X-ray images of (a) SiC fracture surface; (b) aluminum alloys fracture surface for diffusion bonding of SiC and Al-0.5Sn-1Mg alloy under bonding pressure of 8 MPa; (c) Al-0.5Sn-1Mg alloy surface before bonding.

sequently, the bonding strength decreases slightly as shown in Fig. 3. The compound adding of Sn and Mg into aluminum increases the strength and hardness of aluminum alloy, such that SiC/Al-0.5Sn-1Mg diffusion bonding needs 8 MPa bonding pressure.

From the results of fracture surface observed (Fig. 4

and Fig. 5), it follows that the distribution of Sn on fracture surface is different between SiC/Al-0.5Sn joint and SiC/Al-0.5Sn-1Mg joint. In the case of Al-0.5Sn alloy, liquid Sn which has good flowability is scattered in the bonding interface. In the case of Al-0.5Sn-1Mg alloy, the flowability of liquid Sn maybe reduced because of the coexistence of Mg

or the existence of Mg_2Sn metallic-compound (but Mg_2Sn cannot be detected by X-ray diffractometer), so that the distribution of Sn in bonding interface is heterogeneous.

5. Conclusion

The diffusion bondability of aluminum alloys to SiC was investigated. The mechanical properties of SiC/Al–0.5Sn and SiC/Al–0.5Sn–1Mg joints at elevated temperatures were researched. The following results could be obtained:

(1) Pure aluminum cannot be bonded to SiC. Adding 0.5%Sn into aluminum can improve bondability. The compound addition of 0.5%Sn and 1%Mg into aluminum can improve the strength and the elevated temperature properties of joint.

(2) In the case of SiC/Al–0.5Sn diffusion bonding, the fractures fully occur on bonding surfaces. In the case of SiC/Al–0.5Sn–1Mg diffusion bonding, the fractures partly occur in the side of SiC.

(3) The optimum bonding pressures are 4 MPa and 8 MPa for SiC/Al–0.5Sn and SiC/Al–0.5Sn–1Mg diffusion bonding, respectively. In optimum bonding condition, the maximum shear strength of SiC/Al–0.5Sn–1Mg joint is 51.7 MPa.

(4) There are residual stresses in both SiC/Al–0.5Sn and SiC/Al–0.5Sn–1Mg joints. A suitable post-bonding heat treatment is necessary.

(5) The distribution of Sn on fracture surface is different between SiC/Al–0.5Sn and SiC/Al–0.5Sn–1Mg joints. In the case of SiC/Al–0.5Sn–1Mg joints, the distribution of Sn in the bonding interface is heterogeneous.

REFERENCES

- 1) P. Lourdin, D. Juvé and D. Tréheux: J. Euro. Ceram. Soc. **16** (1996) 745–752.
- 2) A. Watannaba, H. Kato and K. Yoshikawa: Mater. Sci. Tech. **9** (1993) 155–160.
- 3) A. H. Elsayy and M. F. Fahmy: J. Mater. Proc. Tech. **77** (1998) 266–272.
- 4) S.-I. Matsuoka: J. Mater. Proc. Tech. **75** (1998) 259–265.
- 5) K. Hokamoto, M. Fujita, H. Shimokawa and H. Okugawa: J. Mater. Proc. Tech. **85** (1999) 175–179.
- 6) P. Yang, B. N. Turman, S. J. Glass, J. A. Halbleib, T. E. Voth, F. P. Gerstle, B. Mckenzie and Jerry R. Clifford: Mater. Chem. Phys. **64** (2000) 137–146.
- 7) S. Maki and M. Nakamura: Light Metal **40** (1990) 75–81.
- 8) I. Itoh, Y. Otoguro, K. Hasegawa, T. Yamagami and H. Matuoka: Light Metal **41** (1991) 245–250.
- 9) I. Itoh, Y. Otoguro and T. Doi: Light Metal **42** (1992) 459–463.
- 10) I. Itoh, Y. Otoguro, T. Doi and S. Kimura: Light Metal **43** (1993) 258–262.
- 11) I. Itoh, Y. Otoguro, T. Doi and K. Ikuta: Light Metal **43** (1993) 134–138.
- 12) *Structure and Property of Aluminum Alloy*, (The Japan Institute of Light Metal, 1991) pp. 416.
- 13) *Structure and Property of Aluminum Alloy*, (The Japan Institute of Light Metal, 1991) pp. 451.