Development of Resistance Welding for Silicon Carbide

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Resistance welding was applied to the bonding of SiC to metals. The welded interface structure was observed by high-resolution transmission electron microscopy to reveal the reaction during welding. The maximum bonding temperature of SiC varied with the rate of welding current rise. At the welded interface, Al_4C_3 , Al and an amorphous phase were formed adjacent to SiC in the SiC/Al system. The SiC/Al interface was flat at the atomic level and the crystallographic orientation relationship between SiC and Al was observed. For the SiC/Ag-Cu-Ti alloy system, the reaction phases TiC and Ti_5Si_3 were formed at the interface. The thickness of the reaction phases varied with the rate of welding current rise, and, under specific welding conditions, Ag formed directly adjacent to SiC without the reaction phases.
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1. Introduction

Silicon carbide has excellent thermal and mechanical properties, and its application is further extended with the development of new bonding techniques. Brazing and diffusion bonding are typical effective methods of bonding SiC and metals, and have been widely used because of their productivity and reliability. However, they require a long bonding time, and during bonding, the atmosphere should be controlled to prevent oxidation. Thus, in this study, we applied resistance welding, which takes only a few seconds for bonding and is mainly used in the field of the metal bonding, for bonding SiC to metals.

The welding systems used were SiC/Al and SiC/Ag-Cu-Ti. The bonding processes of these systems have been widely studied at the atomic level. In the SiC/Al system bonded by solid state bonding, a thin amorphous phase is observed at the interface and the formation of the amorphous phase is discussed on the basis of thermodynamic and kinetic considerations.¹⁾ In contrast, in the SiC/Al system bonded with molten Al, the reaction phase Al_4C_3 is formed.^{2,3)} In previous reports,¹⁻³⁾ the analysis of the interface microstructure has been suggested to be important, because the morphology of the interface varies depending on the bonding process. In the SiC/Ag-Cu-Ti system, in addition to the atomic structure observation of the interface, the reaction between SiC and molten Ag-Cu-Ti alloy is directly clarified *in situ* at the atomic level. Moreover, SiC dissociation and the nucleation and growth of the reaction phase TiC are dynamically observed.⁴⁻⁶⁾ However, the resistance welding processes of the above systems have not been reported so far.

In this study, the welded interface produced by resistance welding was observed using a high-resolution transmission electron microscope (HRTEM) to understand the bonding process of the resistance welding, and was compared with that produced by other bonding methods.

Table 1 Physical properties of the SiC.

Coefficient of thermal expansion ($\times 10^{-6} \text{ K}^{-1}$ (at 1073 K))	Thermal conductivity (W/m·K (at R.T.))	Specific resistance ($\Omega \text{ m} \times 10^{-2}$ (at R.T.))
4	194	0.01

Fig. 1 Schematic illustration of resistance welder of SiC.

2. Experimental

Polycrystalline 3C-SiC were used for resistance welding. The physical properties of this SiC are shown in Table 1. The welded metals were Ag-27.4 mass%-4.9 mass% Ti alloy foil and Al foil. The thicknesses of the Ag-Cu-Ti alloy foil and Al foil were 250 μm and 12 μm , respectively. The SiC were cut into plates (2 mm $\times$ 2 mm $\times$ 1 mm) with a low-speed saw and its surface was cleaned with ethanol. The surfaces of the Ag-Cu-Ti alloy foil and Al foil were ground by buffing before welding. Figure 1 shows a schematic illustration of the resistance welder. The Ag-Cu-Ti alloy foil or Al foil was placed between two SiC plates. An alternating current in the range of 25~50 A was passed through the SiC plates for about 0.3~25 s. The plates were heated to 873~2473 K with Joule heat according to the current variation. The temperature of the SiC was measured using a thermocouple placed on the SiC plate. The bonded specimen was sliced perpendicular to the interface, followed by mechanical polishing and thinning using an Ar^+ -ion beam at an accelerating voltage of 3 keV in preparation for transmission electron microscopy. The microstructure of the bonded specimen was observed using a HRTEM (JEM-2000FX, JEOL, Japan) at an accelerating

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Fig. 2 Relation between welding temperature and the rate of welding current rise of SiC/Ag-Cu-Ti alloy.

voltage of 200 kV. The element distribution around the interface was identified by energy-dispersive X-ray spectroscopy (EDS) equipped with a HRTEM (TECNAI F20, Philips, Netherlands).

3. Results and Discussion

3.1 Thermal behavior of SiC during resistance welding

First, we clarified the relationship between SiC temperature and welding current during resistance welding. In this experiment, welding current was increased from 0 to 30 A at a constant rate, and then turned off immediately upon reaching 30 A. Figure 2 shows the relationship between the temperature variation and the rate of welding current rise up to 30 A. Figure 2 shows that the SiC plate temperature depends on the rate of welding current rise, and that, as the rate of welding current rise increases, the maximum temperature of the SiC plates increases. In the SiC/Ag-Cu-Ti alloy system, a maximum temperature of approximately 2473 K was obtained within 0.3 s. The maximum temperature showed no further increase even when welding current was kept at 30 A for 3~5 s after the constant welding current rise.

In the following experiments, we fixed the welding current but changed the rate of welding current rise to a fixed welding current to obtain various kinds of welded specimen.

3.2 Resistance welding of SiC/Al

Figure 3 shows a bright field image around the welded interface between SiC and Al for a welding current of 50 A. The rate of welding current rise was 100 A/s. Under this welding condition, the maximum welding temperature was approximately 2473 K and the entire welding process took 0.5 s. Among specimens welded under various welding conditions, this specimen had a sufficiently high strength for processing into a thin film for HRTEM observation.

In Fig. 3, black contrast regions are observed adjacent to SiC and the interface between SiC and the regions show step morphology. At the interface, the {111} plane of SiC tends to be parallel to the interface. Figure 4 shows a low magnification lattice image of the region around the interface of SiC/Al. Electron diffraction patterns and lattice images suggested that Al_4C_3 , Al and an amorphous phase formed directly adjacent to SiC. Broken lines in Fig. 4 indicate the interfaces among Al_4C_3 , Al and the amorphous phase determined from the lattice image. White contrasts parallel to the interface is

Fig. 3 (a) Bright field image of the welded interface between Al and SiC. R.P. indicate the reaction phase. (b) Schematic image of SiC/R.P. interface in (a). Several parts of the interface indicated by broken lines tend to parallel to the (111) plane of SiC.

Fig. 4 Magnified image of the SiC/reaction phase interface. Al_4C_3 , Al and amorphous phase was observed at the interface.

Fig. 5 High-resolution image of the SiC/reaction phase interface. Arrows denote the Al_4C_3 /Al/SiC interfaces. Aluminum forms on the (111) plane of the SiC with an orientation relationship of $(111)\text{SiC} \parallel (111)\text{Al}$, $[1\bar{1}0]\text{SiC} \parallel [1\bar{1}0]\text{Al}$.

an optical artifact and do not relate to the interface structure. Figure 5 shows a high-resolution image of the region around the triple point of Al_4C_3 , Al and SiC. The morphology of the

Fig. 6 EDS spectra obtained from the amorphous phase at the SiC/Al interface.

SiC/Al interface is flat at the atomic level. Aluminum forms on the (111) plane of the SiC with an orientation relationship of (111)SiC // (111)Al, $[1\bar{1}0]$ SiC // $[1\bar{1}0]$ Al.

The (111) plane of the SiC parallel to the interface is a polar plane. In the literature, when a molten alloy reacts with the basal plane of 6H-SiC which is the same structure of the (111) plane of the 3C-SiC, 6H-SiC tends to dissociate along the basal plane, which is a polar plane formed by either C or Si atoms.^{4,5)} After the dissociation of SiC, reaction phases form from the molten alloy. Our observations suggest that SiC dissociated along the (111) plane, which is the polar plane of 3C-SiC, and Al formed on the (111) plane with a crystallographic orientation relationship.

An amorphous phase, shown in Fig. 4, occasionally formed at the interface. To clarify amorphous-phase formation, EDS spectra were obtained. Figure 6 shows typical EDS spectra, which indicate that the amorphous phase adjacent to the SiC consists of Al, Si, C and O. This kind of amorphous phase is also observed at the Al/SiC diffusion-bonded interface.¹⁾ Formation of the amorphous phase was explained to be a result of the diffusion of Si, C and Al to amorphous silica, which was present on the SiC surface before bonding. However, at the interface bonded with molten Al, no amorphous phase was observed.^{2,3)} In the present welding technique, the welding time and temperature were extremely short (0.5 s) and high (2473 K), respectively, in contrast to those in the previous experiments. Thus, the freezing of oxygen-containing molten Al alloy which was produced by the dissolution of SiO₂ was considered to be associated with the amorphous phase formation.

The formation of Al₄C₃ and Al phases adjacent to the SiC was explained taking thermodynamics into consideration.^{7,8)} Thermodynamic calculation gives the following reaction equation between SiC and Al.

Here, [Si] represents Si in the Al-Si liquid solution. In this experiment, the short welding time prevented Si diffusion, and the local Si concentration near the interface increased. The high Si concentration is considered to suppress continuous Al₄C₃ layer formation.

At the present stage of our investigation, temperature dependence of the reaction phase formation in the present system was not clarified. The detailed analysis of the formation process of the reaction phase will be done in the future.

Table 2 Thickness of the reaction phases in the SiC/Ag-Cu-Ti alloy.

Specimen	Ratio of current rise (A/s)	Maximum temperature (K)	Reaction layer thickness (nm)
1	1.2	933	222
2	11	1434	187
3	18	1645	14
4	100	2473	407

Fig. 7 Bright field image of the reaction phases produced at the SiC/Ag-Cu-Ti welded interface in specimen 1.

3.3 Resistance welding of SiC/Ag-Cu-Ti alloy

Table 2 shows the welding conditions in the SiC/Ag-Cu-Ti alloy system. The rate of welding current rise to a welding current of 30 A varies from 1.2 A/s to 100 A/s. Under these welding conditions, a maximum welding temperature in the range from 933 K to 2473 K is obtained. Figure 7 shows a bright field image of the region around the interface of the SiC/Ag-Cu-Ti alloy of specimen 1 in Table 2. Two layers of the reaction phases are observed. Electron diffraction patterns indicated that the upper reaction phase was Ti₅Si₃, and the lower one was TiC.

The average thicknesses of the reaction phases differed among specimens 1, 2 and 4, as shown in Table 2, however, the morphologies of these specimens were similar to that of specimen 1 shown in Fig. 7.

Figure 8 shows a bright field image of the interface of the SiC/Ag-Cu-Ti alloy of specimen 3. In contrast to specimens 1, 2, and 4, reaction phases hardly observed. Figure 9 shows the high-resolution image of the region around the interface of specimen 3. At the interface, a thin reaction phase is observed adjacent to the SiC. The lattice image of the reaction phase suggests that the layer consisted of TiC and Ti₅Si₃ nanoparticles. In some regions, Ag directly connects with the SiC. The average thickness of the layer was about 14 nm.

The morphology of the SiC crystal was unchanged after welding for specimens 1–4.

There have been several extensive studies of the kinds of reaction phase in the SiC/Ag-Cu-Ti alloy system.⁹⁾ In SiC/Ag-Cu-Ti alloy brazing, TiC and Ti₅Si₃ are produced as

Fig. 8 Bright field image of the welded interface of SiC/Ag-Cu-Ti in specimen 3.

Fig. 9 High-resolution image of the welded interface of SiC/Ag-Cu-Ti in specimen 3.

reaction phases. HRTEM observation has revealed that the TiC layer initially forms adjacent to the SiC following Ti_5Si_3 formation.¹⁰⁾ This double layer formation consisting of an outer Ti_5Si_3 layer and inner TiC layer was also confirmed by direct *in-situ* HRTEM observation.⁶⁾ The kinds of reaction phase formed in the previous experiments are in accordance with the present results.

The relationship between the thickness of the reaction phases and the rate of welding current rise, shown in Table 2, was discussed as follows. Under certain welding conditions such as those for specimen 3, the thicknesses of the reaction layers were minimum. The thickness variation was considered to be associated with the quantity of heat and maximum

temperature. As the rate of welding current rise increases, the quantity of heat during welding decreases, because of the shorter welding time. In contrast, maximum welding temperature, which affects the growth rate of the reaction phases, increases. These conflicting behaviors regarding the growth of the reaction phases between the quantity of heat and the maximum temperature were considered to determine the welding conditions that lead to the minimum thickness of the reaction layer.

4. Conclusions

Resistance welding was applied to the bonding of SiC to Al or Ag-Cu-Ti alloy. The interface morphology variation dependence on welding conditions was revealed using HRTEM and the following results were obtained.

- (1) Welding temperature depended on the rate of welding current rise. In SiC/Ag-Cu-Ti alloy, a maximum temperature of approximately 2473 K was obtained within 0.3 s.
- (2) In the SiC/Al system, Al_4C_3 , Al and an amorphous phase were formed adjacent to SiC. The SiC/Al interface was flat at the atomic level. Aluminum formed on the (111) plane of SiC with an orientation relationship of $(111)\text{SiC} // (111)\text{Al}$, $[\bar{1}\bar{1}0]\text{SiC} // [\bar{1}\bar{1}0]\text{Al}$.
- (3) In the SiC/Ag-Cu-Ti system, the reaction phases TiC and Ti_5Si_3 were formed at the interface. Depending on the rate of welding current rise, the thickness of the reaction phases varied. Under specific welding conditions, Ag directly formed adjacent to SiC without reaction phases.

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