Dissimilar joint characteristics of SiC and WC-Co alloy by laser brazing

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Abstract. SiC and WC-Co alloys were joined by laser brazing with an active braze metal. The braze metal based on eutectic Ag-Cu alloy with additional Ti as an active element ranging from 0 to 2.8 mass% was sandwiched by the SiC block and WC-Co alloy plate. The brazing was carried out by selective laser beam irradiation on the WC-Co alloy plate. The content of Ti in the braze metal was required to exceed 0.6 mass% in order to form a brazed joint with a measurable shear strength. The shear strength increased with increasing Ti content up to 2.3 mass%Ti and decreased with a higher content.

1. Introduction
Brazing is suitable for joining dissimilar materials, particularly those that cannot be easily joined by fusion welding, such as ceramics and metals [1-12]. Regarding ceramic materials, silicon carbide (SiC) has several functional characteristics, such as a low thermal expansion coefficient, high thermal conductivity, good high-temperature mechanical properties, superior wear, corrosion, heat, and oxidation resistance, and semiconducting properties [10-15]. However, it is difficult to braze SiC to other materials without the use of an active braze metal or some kind of surface treatment because the wettability of the SiC and the molten braze metal plays a crucial role in the brazing of these materials [7-11, 16, 17]. The technique for the dissimilar brazing of SiC using an active braze metal is applicable to construction materials, cutting tools, ceramic heat exchangers, optical devices, and power devices [10, 11, 14, 18]. Much research on the dissimilar brazing of SiC to other materials has been carried out in recent studies, such as the brazing of SiC to Ni alloy [12, 19, 20], Nb, W [15], TiAl [21], Fe alloy [20], and graphite [2] and the brazing of carbon fiber reinforced SiC to Ti alloy [3, 22]. The behavior of an active element and a molten braze metal in the conventional furnace heating process is well known [13, 16-18, 20, 23-26].

The active element (e.g., Ti, Zr, or Cr) in the braze metal improves the wettability of the SiC and molten braze metal and reacts with the Si and C of the SiC to form stable compounds [13, 16, 18, 20]. The wettability improves with increasing active element content in the braze metal, and the increased wettability in turn increases the joint strength [5, 8, 18, 24]. However, several problems have remained
in conventional brazing, such as material deterioration and thermal stress and strain in the joint [2-11, 15, 18, 22-24, 27]. Especially, depending on the brazing temperature and time, an increase in the active element content can cause a decrease in the joint strength regardless of the improvement in the wettability. This decrease in joint strength occurs because of the high thermal expansion coefficient mismatch between the SiC and the thick reaction layer [4-6, 10, 17, 18, 23]. These problems arise because conventional furnace brazing requires a long treatment time in order to ensure heating and cooling of the whole component.

Such problems can potentially be avoided in laser brazing, which is a novel brazing technique, as the heating and cooling times in this technique are short, and only the selected part of the component needs to be heated [7, 8, 11]. In addition, it contributes to a decrease in the energy consumption of the brazing process. The behaviors of the active element and molten braze metal during laser brazing differ from those during conventional brazing because of the short processing time and smaller selected heating area [7, 8]. In particular, the short processing time affects the diffusion and interfacial reaction processes at the interface of the SiC and the braze metal [3, 10]. However, little information has been reported regarding the effect of active element contents in the dissimilar laser brazing of ceramics and metals [7, 8]. Based on this background, the objective of this study was to determine the effect of Ti as an active element in the braze metal of a dissimilar laser-brazed joint of SiC to WC-Co alloy on the joint strength and the interface structure of the joint; WC-Co alloy was selected as a counter material owing to its low thermal coefficient and relatively high heat resistance.

2. Material and methods

Experiments were carried out using SiC blocks, WC-Co alloy plates, and nine types of Ag-Cu-Ti braze metal sheets with different Ti contents. The SiC block was classified as recrystallized silicon carbide (>99% SiC, porosity: 17%, NGK INSULATORS, LTD.) and had dimensions of 5 × 5 × 3.5 mm. The WC-Co alloy plate (ISO K10 grade, Mitsubishi Materials Corporation) was used as the substrate plate and had dimensions of 10 × 10 × 2 mm. Table 1 lists the chemical compositions of the braze metals. The braze metals were eutectic-type Ag-Cu alloy containing additional Ti as an active element, with the Ti content ranging from 0 to 2.8 mass%. The thickness of the braze metal was 0.1 mm, and its dimensions were fixed at 3 × 3 mm to ensure that it does not flow out of the joint interface. Before brazing, all materials were degreased by ultrasonic agitation in acetone for 10 min and dried in air.

| No. | Ag     | Cu    | Ti    |
|-----|--------|-------|-------|
| 1   | 72.0   | 28.0  | 0     |
| 2   | 71.5   | 28.2  | 0.3   |
| 3   | 71.5   | 28.1  | 0.4   |
| 4   | 71.3   | 28.1  | 0.6   |
| 5   | 71.2   | 27.9  | 0.9   |
| 6   | 70.9   | 27.8  | 1.3   |
| 7   | 70.2   | 28.1  | 1.7   |
| 8   | 70.2   | 27.5  | 2.3   |
| 9   | 69.6   | 27.6  | 2.8   |

Figure 1 shows a schematic illustration of the laser brazing apparatus. The specimen was shaped like a “top hat.” A braze metal sheet was sandwiched between the SiC block (above it) and the WC-Co alloy plate (below it) and placed in a vacuum chamber. The top of the specimen was covered with a transparent quartz glass plate, which not only acted as a window of the vacuum chamber for laser beam irradiation but also fixed the specimen in place. The vacuum chamber was evacuated to less than 10⁻¹ Pa, and then, Ar gas of 99.999% purity was pumped in to atmospheric pressure. This evacuation and substitution cycle was performed five times prior to brazing. During brazing, Ar gas continued to
flow at a rate of 5 L/min. The YAG and LD lasers were coaxially transferred via optical fibers to the laser head unit and irradiated through the transparent quartz glass plate to the top side of the WC-Co alloy plate at an irradiation angle of 85°. Table 2 lists the laser brazing conditions, which were set according to JIS Z3261 BA-8 and previous studies [7, 8]. The WC-Co alloy plate around the SiC was subjected to laser irradiation for 36 s. During laser heating, the temperature of the WC-Co alloy plate was monitored by an R-type thermocouple inserted into a hole beneath the joint on the lower surface of the plate.

After brazing, a shear strength test of the joint was carried out using a precision universal tester operated at a cross-head speed of 0.5 mm/min. Five joints were tested for each of the nine types of braze metals shown in Table 1. Figure 2 shows a schematic illustration of the shear strength test. The WC-Co alloy plate was clamped, and the SiC was loaded by the steel jig. The shear strength was calculated as the maximum load divided by the joining area, which was estimated from the fractured surface. The brazing joint specimens were cross-sectioned and mounted in epoxy resin before being ground with #220 SiC paper and polished with diamond paste. Observations of the macrostructure and microstructure of the brazed interface and its elemental analysis were then performed using a scanning electron microscope (SEM), a transmission electron microscope (TEM), and an energy dispersive X-ray analyzer.

**Figure 1.** Schematic illustration of the laser brazing apparatus.

**Table 2.** Laser brazing conditions.

| Pulsed YAG average output (W) | Pulsed YAG wave length (nm) | CW LD output (W) | CW LD wave length (nm) | Pulse frequency (Hz) | Scanning time (s) | Atmosphere |
|-------------------------------|-----------------------------|------------------|------------------------|----------------------|------------------|-------------|
| 134                            | 1064                        | 20               | 808                    | 100                  | 36               | Ar flow (5L/min) |

**Figure 2.** Schematic illustration of shear strength test.
3. Results and discussion

3.1. Strength of the brazed joint

Figure 3 shows a typical temperature profile of the WC-Co plate during laser brazing. The highest brazing temperature was 1102 K, which is above the melting temperature of the braze metal (approximately 1073 K). Macro cracking could not be observed in any of the brazed joints.

Figure 4 shows the effect of the Ti content on the shear strength of the brazed joint. The content of Ti in the braze metal was required to exceed 0.6 mass% in order to form a brazed joint with a measurable shear strength. Using the braze metal containing 0.4 mass% Ti, the SiC block and WC-Co alloy plate were joined; however, the shear strength was too low to measure. The shear strength increased as the Ti content increased up to 2.3 mass%. Figures 5 (a) and (b) show the fractured surface of the joint on the WC-Co alloy plate after the shear strength test using the braze metals containing 0.6 and 2.3 mass% Ti, respectively. The fracture occurred at the SiC block near the interface of the SiC block and the braze metal with 0.6 mass% Ti and almost at the SiC block with 2.3 mass% Ti. Fracture between the WC-Co alloy plate and the braze metal was not observed in any case. Figure 6 shows the effect of the Ti content on the area fraction of the fractured surface of the SiC block on the braze metal. The area fraction increased with increasing Ti content in the braze metal in a similar tendency as observed in Figure 4 for the range from 0.6 to 2.3 mass% Ti. Figure 7 shows the relationship between the area fraction of the fractured surface of the SiC block on the braze metal and the shear strength. This result indicates that the shear strength increases with increasing the area fraction. These mean that Ti as an active element increased the joint strength of the interface between the SiC block and the braze metal. The increase in shear strength with increasing Ti content in the braze metal is possibly a result of the improvement in the wettability of the SiC and molten braze metal and the formation of stable intermetallic compounds when the Ti reacts with the Si and C in the SiC [13, 16, 18, 20]. The shear strength decreased from 2.3 to 2.8 mass% Ti, the reason for which is discussed later in Section 3.2: Microstructure of the brazed joint. The wide distribution of the shear strength of the joints can be explained by the wide distribution of the strength of the SiC block itself. The fracture strength of the SiC block was determined by the dimension of the pores and cracks in the sintered compact because SiC is a porous ceramic.
Figure 5. Fractured surface of the joint on the WC-Co alloy plate after shear strength test using the braze metals containing 0.6 and 2.3 mass% Ti.

Figure 6. Effect of the Ti content on the area fraction of the fractured surface of the SiC block on the braze metal.

Figure 7. Relationship between the area fraction of the fractured surface of the SiC block on the braze metal and shear strength.

3.2. Microstructure of the brazed joint
Figures 8 (a) and (b) show the cross-sectional macrostructure of the joints using the braze metals containing 0.4 and 2.3 mass% Ti, respectively. Using the 2.3 mass% Ti braze metal, it was observed that the braze metal infiltrated into the void of the SiC blocks; however, this was not the case for the 0.4 mass% Ti. This showed that a sufficient amount of Ti as an active element in the braze metal improved the wettability of the braze metal. Figure 9 shows the cross-sectional microstructure and the element distributions of Si, Ti, Cu, and Ag at the brazed joints of SiC and the braze metal containing 0.4, 2.3, and 2.8 mass% Ti. Carbon could not be identified using the energy dispersive X-ray analyzer. An obvious concentration of Ti was observed at the interface between the SiC and each braze metal. This suggests that the Ti as an active element diffused from the braze metal to the interface so as to decrease the interfacial energy and reacted with the SiC during laser heating. The formation of Ti
concentrated layers at the interface became more obvious with increasing Ti content in the braze metal, which resulted in an increase in the thickness and area of the Ti concentrated layer.

Figure 10 shows the TEM bright field image and element distributions of Si, Ti, Cu, and Ag at the interface between the SiC block and the braze metal containing 2.3 mass%Ti. The microstructure at the interface was divided into five areas depending on the dominant constitutional elements at each position, which are marked in the bright field image as follows: Si at position 1 (in SiC), Ti at position 2, Ti and Si at position 3, Ti and Cu at position 4, and Ag at position 5 in the braze metal. Figures 11 (a)-(d) show the selected area diffraction patterns of the areas corresponding to positions 2, 3, 4, and 5, respectively. These results reveal that the precipitated intermetallic compounds at the interface between the SiC and the braze metal were identified as TiC at position 2, Ti5Si3 at position 3, and Cu4Ti at position 4. Ag was found to be the braze metal at position 5. These results indicated that the Ti concentrated layer formed at the interface consisted of multiple thin layers of TiC, Ti5Si3, and Cu4Ti. The Ti in the braze metal has a high affinity for C and Si in SiC, and it would thus diffuse to the interface and form thin intermetallic compound layers. In addition, Cu as the major alloying element of the braze metal also has a high affinity for Ti, and thus, a Cu4Ti compound was formed following the formation of TiC and Ti5Si3.

![Figure 8](image1.png)

**Figure 8.** Cross-sectional macrostructure of joints using the braze metals containing 0.4 and 2.3 mass%Ti.

![Figure 9](image2.png)

**Figure 9.** Cross-sectional microstructure and the element distributions of Si, Ti, Cu, and Ag at the brazed joints of SiC and the braze metals containing 0.4, 2.3, and 2.8 mass%Ti.
Figures 12 (a)-(c) show the TEM bright field image at the joint interface between the SiC block and the braze metals containing 0.4, 2.3, and 2.8 mass%Ti, respectively. TiC, Ti₅Si₃, and Cu₄Ti were observed using the braze metals containing 0.4, 2.3, and 2.8 mass%Ti. The thickness of the compound layers increased with increasing Ti content in the braze metal. Table 3 lists the coefficients of thermal expansion of SiC, WC-Co alloy, and the reaction compounds [27, 28]. The coefficient of thermal expansion of SiC is similar to that of WC-Co alloy and different from that of the reaction compounds (TiC and Ti₅Si₃). Residual stresses in the SiC and reaction layers would occur in all of the joints [4-6, 10, 17, 18, 23]. Thus, it is considered that the decrease in the shear strength of the joint using the braze metal containing 2.8 mass%Ti would be caused by the high residual stress because of the formation of the thick reaction layers.

Figure 10. TEM bright field image and element distribution at the joint interface between the SiC block and the braze metal containing 2.3 mass%Ti.

Figure 11. Selected area diffraction patterns at (a) position 2, (b) position 3, (c) position 4, and (d) position 5 in the TEM bright field image in Figure 10.

Figure 12. TEM bright field image at the joint interface between the SiC block and the braze metals containing 0.4, 2.3, and 2.8 mass%Ti.
Table 3. Coefficient of thermal expansion (CTE) of SiC, WC-Co alloy, and reaction compounds.

| Material         | Coefficient of thermal expansion ($\times 10^{-6}$ K$^{-1}$) |
|------------------|----------------------------------------------------------|
| SiC              | 4.7                                                      |
| WC-Co alloy      | 5.4                                                      |
| TiC              | 7.4-8.6                                                  |
| $\text{Ti}_5\text{Si}_3$ | 11.0                                                    |

4. Conclusions
The effects of Ti as an active element in the Ag-Cu-Ti braze metal of a dissimilar laser-brazed joint of SiC to WC-Co alloy on the joint strength and the interface structure of the joint were investigated. The following conclusions were drawn about the shear strength and the interface structure of the joint:

1. Ti serving as an active element in the Ag-Cu braze metal enabled the joining of SiC to WC-Co alloy by heating for a short time using laser brazing. The content of Ti in the braze metal was required to exceed 0.6 mass% in order to form a brazed joint with a measurable shear strength.

2. The shear strength of the laser-brazed joint increased with increasing Ti content in the range of 0.4 to 2.3 mass% in proportion to the area fraction of the fractured surface in the SiC, and a higher Ti content decreased the shear strength of the joint.

3. A Ti concentrated layer was formed at the interface between the SiC and the braze metal using laser brazing. This layer consisted of TiC, $\text{Ti}_5\text{Si}_3$, and Cu$_4$Ti compound layers, and the thickness of these compound layers increased with increasing Ti content in the braze metal.

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