Fabrication of Copper Matrix Composites and Simultaneous Bonding with Aluminum Alloy Using Combustion Reaction of Cu-Ti-B System

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TiB₂ particle reinforced Cu matrix composites were fabricated by a combustion reaction between Ti and B in a Cu-Ti-B system. Addition to the fabrication of the composite, its bonding with 1050 Al alloy were successfully carried out in a single-step process by using the high heat of the combustion reaction. When the combustion synthesis of Cu-50 vol%TiB₂ was attempted, a minute quantity of unfavorable Cu₃Ti was formed with TiB₂ in the Cu matrix. However, for Cu-60 vol%TiB₂, only fine TiB₂ particles below 4 μm in diameter were formed *in situ*, and homogeneously distributed in the Cu matrix. Also for Cu-70 vol%TiB₂, the combustion reaction occurred completely without forming any unfavorable phases, although some Cu was evaporated during synthesizing the composite. In a Ti-B binary system, any reaction was not generated in the temperature range from room temperature to 1473 K. However, in the Cu-Ti-B ternary system, the combustion reaction was generated near the melting point of Cu, suggesting that it was activated by molten Cu. Preheating before inducing the combustion reaction was effective in bonding with long Al rods and also in reducing bonding defects. Intermetallic compounds consisting of Al, Cu and Ti were observed with unreacted B in the bonded layer. For the bonded specimen with a Cu insert layer, a eutectic microstructure of Al and Cu was formed between the Al alloy and Cu insert, and unreacted B was observed with a compound of Cu and Ti between the composite and Cu insert. The bonding strength was improved by inserting the Cu layer and by preheating. The bonded specimen with no insert layer was fractured between the composite and the Al alloy. By inserting the Cu layer with preheating, the fracture occurred between the Al alloy and the Cu insert.

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1. Introduction

Much attention has been focused on Cu matrix composites with ceramic reinforcements, because of their excellent combination of thermal and electrical conductivities, microstructural stability and strength retention at elevated temperatures.¹⁻⁹⁾ Especially, Cu matrix composites with high volume fractions (more than 50 vol%) of the reinforcements have been studied due to their very low coefficient of thermal expansion (CTE).⁶⁻⁹⁾ This feature is very important in thermal management systems in electronic devices, such as heat sinks, packaging for high voltage chips and packaging base plates. In addition, these composites may also be useful in the fields where high wear resistance is also needed, such as valve sheets of automobile engines.

TiB₂ particle reinforced Cu matrix (TiB₂/Cu) composites have been considered one of the best candidates for the above-mentioned applications, because the TiB₂ addition greatly enhances the mechanical properties, such as stiffness, hardness and wear resistance, and decreases the coefficient of thermal expansion (CTE), while it reduces the electrical and thermal conductivities much less than the addition of most other ceramic reinforcements.⁶⁾

On the other hand, much effort has been concentrated on *in situ* processes including combustion synthesis among various processing techniques for metal matrix composites (MMCs). In these processes, the *in situ* formed reinforcement is generally fine and thermodynamically stable, and is homogeneously distributed with forming clean and strong inter-

faces with the matrix. Therefore, *in situ* processed MMCs exhibit many attractive advantages including excellent mechanical properties.¹⁰⁾ Especially, the combustion synthesis provides significant benefits from technical and economic viewpoints, such as (1) the process is relatively simple because there is no need for complex equipments, (2) the high reaction rate offers high productivity, (3) it is an energy-efficient technology because the combustion reaction can be generated by a small amount of energy, and (4) the evaporation of impurities allows production of high purity materials, which results from the fact that the materials are exposed at extremely high temperatures during processing.¹⁰⁻¹⁵⁾

In the meanwhile, combustion reactions have also been applied in bonding of various materials.¹⁶⁻²²⁾ However, most previous researches have been associated with the fabrication of coatings (less than several hundred microns in thickness) for surface modification of substrate materials or bonding using reactive insert materials. Namely, there is little information concerning simultaneous bonding of large bulk materials by using the high reaction heat generated during synthesizing the materials.

In this context, we have studied the combustion synthesis process not only as a manufacturing technology for large bulk MMCs but also as their simultaneous bonding process.^{23,24)} In the present research, TiB₂/Cu composites were combustion-synthesized and were simultaneously bonded with aluminum rods. This combination will be applicable to simultaneous bonding between aluminum alloy cylinder heads and valve sheets of automobile engines. The basic principle of the simultaneous bonding process by the combustion reaction in the present research is schematically illustrated in Fig. 1. Namely, (a) an Al rod is set on a compacted reactant, which is composed of Cu, Ti and B

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Fig. 1 Schematic representation of the basic principle of the simultaneous bonding process between the TiB_2/Cu composite and the aluminum alloy by the combustion reaction in the Cu-Ti-B system.

powders, and then the bottom surface of the reactant is heated by an ignitor. (b) The combustion reaction between Ti and B occurs at the bottom, with generating the high reaction heat, as described by a chemical formula.²⁵⁾ As a result, TiB_2 particles are formed *in situ* as the reinforcement phase in a Cu matrix. Shortly afterwards, the reaction self-propagates throughout the whole reactant, with converting it into the TiB_2/Cu composite. And then, (c) the excessive heat of combustion reaction produces a bonded layer between the composite and the Al rod. In this method, two kinds of processes, *i.e.* the fabrication process of a metal matrix composite and the bonding process of the composite with a metallic material, are simultaneously carried out in a single process by using only the high reaction heat generated during synthesizing the composite. This means that no additional heating is needed for the bonding between them. Therefore, it is believed that this process leads to reduction in production costs through process simplification and energy-saving benefits.

N. Sata investigated in detail the combustion reaction behavior in the Cu-Ti-B System.⁵⁾ However, in spite of the same reaction system, combustion reaction behavior can be easily changed by various parameters, such as characteristics of starting materials, porosity of compacted reactant, heating method.^{26–28)} Therefore, in the present research, combustion synthesis experiments for the Cu-Ti-B system were first carried out to determine optimum conditions for the simultaneous bonding between the combustion synthesized TiB_2/Cu composite and 1050 Al alloy. And then, the influence of preheating, length of Al rod and insert metal on the microstructure and strength of the bonded specimens was experimentally investigated.

2. Experimental Procedure

Cu (particle size: $<177\ \mu\text{m}$, purity: 99.9%), Ti (particle size: $<44\ \mu\text{m}$, purity: 99.9%), and B (particle size: $<44\ \mu\text{m}$, purity: 99%) powders were used as starting materials. It was assumed that all the Ti and B powders turn into TiB_2 particles with the mole ratio of $\text{Ti}:\text{B} = 1:2$ by the combustion

reaction. And then, the starting material powders were mixed in each ratio in order to produce Cu matrix composites including 50, 60 and 70 vol% TiB_2 particles, respectively. In the present research, these specimens were denoted as Cu-50, 60 and 70 vol% TiB_2 , respectively. The powder mixtures were compacted into a cylindrical shape by a pressure of 200 MPa. The diameter and height of the compacted reactants were 15 mm and 20 mm, respectively. A compacted powder mixture of Ti and B_4C was also used as an ignitor to generate the combustion reaction, due to its high exothermicity ($3\text{Ti} + \text{B}_4\text{C} \rightarrow 2\text{TiB}_2 + \text{TiC}$, $\Delta H^\circ = 761\ \text{kJ}$).^{25,29)} Commercially pure 1050 Al alloy rods with a diameter of 15 mm and a length of 20 to 60 mm were used for simultaneous bonding with the combustion synthesized TiB_2/Cu composite.

The combustion synthesis and simultaneous bonding experiments were carried out under an argon gas atmosphere. For the bonding experiments, a pressure of 0.05 MPa was applied to the Al rod from the top. To investigate the influence of preheating before generating the combustion reaction on the microstructure and strength of the bonded specimens, the bonding experiments were carried out at room temperature or after preheating at 433 K.

After the experiments, the phases and microstructures were characterized using X-ray diffraction (XRD), scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). In addition, an ignition temperature at which the combustion reaction starts was investigated by differential thermal analysis (DTA). It was carried out under an argon gas atmosphere in the temperature range from room temperature to 1473 K at a heating rate of $50\ \text{K}\cdot\text{min}^{-1}$. To examine the bonding strength, tensile tests were also performed at room temperature with a crosshead speed of $1\ \text{mm}\cdot\text{min}^{-1}$.

3. Results and Discussion

3.1 Combustion synthesis of TiB_2/Cu composites

Figure 2 shows XRD patterns of (a) Cu-50 vol% TiB_2 , (b) Cu-60 vol% TiB_2 and (c) Cu-70 vol% TiB_2 , which were

Fig. 2 XRD patterns of (a) Cu-50 vol%TiB₂, (b) Cu-60 vol%TiB₂ and (c) Cu-70 vol%TiB₂, which were ignited without preheating.

ignited without preheating. For the Cu-50 vol%TiB₂ composition (Fig. 2(a)), a minute quantity of Cu₃Ti, which was unfavorable phase, was detected with Cu and TiB₂. In contrast, for the Cu-60 vol%TiB₂ (Fig. 2(b)) and Cu-70 vol%TiB₂ (Fig. 2(c)) compositions, only Cu and TiB₂ were detected without any unfavorable phases. This result confirms that, in these compositions, the combustion reaction propagated throughout the whole reactants with completely converting them into the TiB₂/Cu composites. However, for the Cu-70 vol%TiB₂ (Fig. 2(c)), some copper-colored fume was observed during the combustion reaction, which was spewed from the specimen. Although not quantified, this means that some Cu was evaporated because the combustion temperature reached the boiling point of Cu (2843 K³⁰).

An adiabatic temperature (T_{ad}) was calculated in each composition in order to investigate a cause of these phenomena associated with the chemical composition. The result is shown in Fig. 3. This temperature is the theoretical maximum temperature calculated by equating the reaction enthalpy to the integrated heat capacity, taking into account any heats of fusion or evaporation and assuming that the combustion reaction occurs under the adiabatic condition. In most combustion reactions, the actual combustion temperature will be lower than the calculated adiabatic temperature, since heat loss is inevitable. However, the adiabatic temperature can be used as the estimated temperature at the front of a propagating combustion reaction.¹¹⁾ Therefore, it is believed that, for the Cu-50 vol%TiB₂ composition (Fig. 2(a)), the low combustion temperature, *i.e.* the low

Fig. 3 Relationship between the adiabatic temperature (T_{ad}) and the volume fraction (V_f) of the combustion synthesized TiB₂ in the Cu-Ti-B system.

reaction heat, which resulted from the small volume fraction of combustion synthesized TiB₂, is one of the causes of the formation of Cu₃Ti. On the other hand, for the Cu-60 vol%TiB₂ (Fig. 2(b)) and Cu-70 vol%TiB₂ (Fig. 2(c)) compositions, the combustion temperature increases with the volume fraction of TiB₂. In consequence, the complete combustion reaction would be generated between Ti and B without forming any unfavorable phases. These results suggest that the about 60% volume fraction of TiB₂ is required for the complete combustion reaction to occur without preheating before generating the combustion reaction in the Cu-Ti-B system. In addition, the adiabatic temperature reaches the boiling point of Cu (2843 K³⁰), when the volume fraction of TiB₂ is higher than 70%. Therefore, for the Cu-70 vol%TiB₂, the evaporation of some Cu is also one of experimental evidences that the adiabatic temperature is nearly equal to the actual combustion temperature.

Figure 4 shows an SEM micrograph of the combustion

Fig. 4 SEM micrograph of the combustion synthesized Cu-60 vol%TiB₂ composite.

Fig. 5 DTA curves of the compacted reactants with the mole ratios of (a) Ti:B = 1:2 and (b) Cu:Ti:B = 1.5:1:2.

synthesized Cu-60 vol%TiB₂ composite. It was revealed from the XRD (Fig. 2(b)) and EDS results that the darker part is the TiB₂ particles and the brighter part is the Cu matrix. Only the fine TiB₂ particles less than 4 μm in diameter were formed *in situ* by the combustion reaction, and were homogeneously distributed in the Cu matrix. Any unfavorable phases were not observed in the composite, coinciding with the XRD result (Fig. 2(b)). For a Cu-Ti-C system,²⁷⁾ a relatively large amount of unreacted C remained in combustion synthesized TiC/Cu composites, independently of the chemical composition, when it was assumed that all Ti and C turn into TiC with the stoichiometric composition by the combustion reaction. However, in the Cu-Ti-B system, no unreacted B remained in the combustion synthesized TiB₂/Cu composites with the relatively high volume fractions of TiB₂. This would be because TiB₂ has a very narrow solid solution range of 65.6 to 66.7 at% B, as described by the Ti-B binary phase diagram.³¹⁾

Figure 5 shows DTA curves of the compacted reactants with the mole ratios of (a) Ti:B = 1:2 and (b) Cu:Ti:B = 1.5:1:2. For Ti:B = 1:2 (Fig. 5(a)), neither an endothermic nor an exothermic reaction was detected in the temperature range of room temperature to 1473 K. Namely, the combustion reaction between Ti and B was not generated. This result confirms that, in the Ti-B binary system, the ignition temperature at which the combustion reaction starts is higher than 1473 K. On the other hand, for Cu:Ti:B = 1.5:1:2 (Fig. 5(b)), which is the same composition as the Cu-60 vol%TiB₂, a strong exothermic reaction was observed immediately after an endothermic reaction near the melting point of Cu (1358 K).³⁰⁾ This result suggests that, after Cu was melted in first by heating, the exothermic reaction between Ti and B was immediately generated. Therefore, it is believed that, in the Cu-Ti-B ternary system, the combustion reaction is activated by molten Cu and its ignition temperature is also decreased.

3.2 Simultaneous bonding

As mentioned above, only for the Cu-60 vol%TiB₂ composition, the TiB₂/Cu composite was fabricated without both the formation of unfavorable phases and the evaporation

Fig. 6 Length change of the 1050 Al alloy rod by the simultaneous bonding with the combustion synthesized Cu-60 vol%TiB₂ composite.

of Cu in the present research. Therefore, this composition was selected for simultaneous bonding with 1050 Al alloy rods. In the case without preheating before generating the combustion reaction, the composite was bonded only with the Al rods with lengths of 20 to 40 mm except for 50 and 60 mm. However, preheating at 433 K allowed the composite to be successfully bonded also with the Al rods of 50 and 60 mm. Therefore, it is believed that the preheating treatment is highly effective in the simultaneous bonding of relatively long Al rods. Figure 6 shows the length change of the 1050 Al alloy rods by the simultaneous bonding with the combustion synthesized Cu-60 vol%TiB₂ composite. The length change was almost attributable to the melting of Al rods by the high reaction heat generated during synthesizing the composite. Therefore, it is possible to characterize this length change as the amount of molten Al alloy. In both cases with and without preheating, the length change exhibited the same tendency. Namely, the severity of length change decreased with increasing the length of Al rod, and then became almost constant. This result suggests that thermal loss at the bonded interface increases with the length of Al rod but its limit exists. In addition, the length change was larger in the case with preheating than without preheating. This is because the combustion temperature increased with increase in the initial temperature resulting from preheating. Moreover, in the case without preheating, there was almost no length change for the Al rods of 50 and 60 mm. This result means that, the localized melting of the Al rod is required for the simultaneous bonding in this system.

Figure 7 shows SEM micrographs of the simultaneously bonded specimens between the 1050 Al alloy rod with the length of 30 mm and the combustion synthesized Cu-60 vol%TiB₂ composite, which were ignited (a) without preheating and (b) after preheating at 433 K, respectively. In the case without preheating (Fig. 7(a)), a lot of defects, such as pores and unbonded regions, were observed in the bonded layer. However, the microstructure was improved by preheating at 433 K (Fig. 3(b)). This result reveals that the preheating treatment is an important parameter, which affects not only the length of bondable Al rods but also the microstructure of bonded specimens. Figure 8①, ② and ③ show magnified SEM micrographs of the bonded layers on ①

Fig. 7 SEM micrographs of the simultaneously bonded specimens between the 1050 Al alloy rod with the length of 30 mm and the combustion synthesized Cu-60 vol%TiB₂ composite, which were ignited (a) without preheating and (b) after preheating at 433 K, respectively.

the Al rod side and ② the composite side with ③ the composite zone near the bonded interface in Fig. 7(b). On the Al rod side (Fig. 8①), a eutectic microstructure was formed, which contained an intermetallic compound CuAl₂ formed by a eutectic reaction between Al and Cu.³¹⁾ On the composite side (Fig. 8②), compounds consisting of Al, Cu and Ti were observed with unreacted B particles. These microstructure observations indicate that the bonding is mainly realized by the reaction between Cu and Al. On the other hand, in the composite zone near the bonded interface (Fig. 8③), TiB₂ particles smaller than those in Fig. 4 were formed in the Cu matrix. It is believed that, near the bonded interface, the growth of TiB₂ particles was inhibited by the release of the heat of combustion reaction through the Al rod.

Pure Cu powders (3 g in weight) were laid on top of the powder mixture for the combustion synthesis of the Cu-60 vol%TiB₂ composite. And then, these powders were compacted together. As schematically illustrated in Fig. 9(a), this compacted reactant was composed of two layers, *i.e.* the upper pure Cu layer and the lower powder mixture layer. Therefore, this reactant turns into a compositionally graded

Fig. 8 Magnified SEM micrographs of ①, ② and ③ zones in Fig. 7(b), respectively.

TiB₂/Cu composite by the combustion reaction. The Cu layer acts also as an insert metal to supply enough Cu required for the bonding between the TiB₂/Cu composite and the Al rod. Namely, this compacted reactant was used in order to investigate not only the influence of Cu insert on the bonding but also the possibility of a simultaneous bonding between a compositionally graded composite and a metallic material by the combustion reaction.

Figures 9(b) and (c) show SEM micrographs of the simultaneously bonded specimen between the 1050 Al alloy rod with the length of 30 mm and the combustion synthesized

Fig. 9 (a) Schematic illustration of the simultaneous bonding with the pure Cu insert and SEM micrographs of the bonded layers (b) between the Al rod and the Cu insert and (c) between the Cu insert and the composite of the bonded specimen between the 1050 Al alloy rod with the length of 30 mm and the combustion synthesized Cu-60 vol%TiB₂ composite with the pure Cu insert layer, which was ignited after preheating at 433 K.

Cu-60 vol%TiB₂ composite with the pure Cu insert layer, which was ignited after preheating at 433 K. A wide reaction layer was formed between the Al rod and the Cu insert, of which the thickness was about 900 μm (Fig. 9(b)). Magnified SEM micrographs of ①, ② and ③ zones in Fig. 9(b) are shown in Fig. 10①, ② and ③, respectively. These microstructures show that the same eutectic microstructure as Fig. 8① was formed between the Al rod and the Cu insert. Therefore, it is apparent that the bonding in this layer was mainly attained by the eutectic reaction between Al and Cu. On the other hand, between the Cu insert and the composite (Fig. 9(c)), unreacted B particles were observed with a compound consisting of Cu and Ti.

Figure 11 shows the bonding strength between the 1050 Al alloy rod and the combustion synthesized Cu-60 vol%TiB₂ composite. Although, in the case without preheating, the bonding strength exhibited about 2 MPa, it was enhanced to about 10 MPa by preheating at 433 K. However, in both cases, the bonding strength was hardly dependent on the length of Al rods. The maximum bonding strength of about 19 MPa was obtained by inserting the pure Cu layer with preheating at 433 K. Although the bonding strength is still low, this result means that inserting the Cu layer and preheating is effective in the simultaneous bonding between them.

XRD and microstructural observations were carried out for the fracture surfaces of the simultaneously bonded specimen between the 1050 Al alloy rod with the length of 30 mm and the combustion synthesized Cu-60 vol%TiB₂ composite without the pure Cu insert layer, which was ignited after preheating at 433 K. Figure 12 shows the XRD patterns of the fracture surfaces on (a) the Al rod side and (b) the composite side. On both sides, the same phases, *i.e.* Cu, TiB₂, CuAl₂ and Cu₃Ti, were detected, suggesting that the bonded specimen was fractured near the bonded interface between the composite and the Al alloy. Figure 13 shows an SEM micrograph of the fracture surface. Unreacted B particles were observed on the fracture surface, although they were not detected in the XRD results (Fig. 12). After the simultaneous

bonding, this unreacted B remains near the bonded interface, as shown in Fig. 8②. Therefore, it is clear that the fracture occurred near the bonded interface.

Figure 14 shows XRD patterns of the fracture surfaces of the simultaneously bonded specimen between the 1050 Al alloy rod with the length of 30 mm and the combustion synthesized Cu-60 vol%TiB₂ composite with the pure Cu insert layer, which was ignited after preheating at 433 K. On both sides, *i.e.* (a) the Al rod side and (b) the composite side, only Al and CuAl₂ were detected. Figure 15 shows an SEM micrograph of the fracture surface. Only a eutectic microstructure, which consists of Al and CuAl₂, was observed, coinciding with the XRD results (Fig. 14). This eutectic microstructure is formed near the bonded interface between the Al rod and the Cu insert by the simultaneous bonding, as shown in Fig. 9(b) and Fig. 10. Therefore, these results confirm that the bonded specimen was fractured near the bonded interface between the Al rod and the Cu insert.

In previous researches,^{32,33)} the microstructure and bonding strength between Al and Cu were investigated in detail. A variety of intermetallic compounds, such as CuAl₂, Cu₃Al, Cu₄Al₃, Cu₉Al₄ and CuAl, were formed in the bonded layer. The bonding strength decreased with increasing the thickness of the brittle intermetallic layer. Enjo *et al.*³²⁾ reported that the bonding strength was very low (about 23 MPa) in spite of the formation of the thin intermetallic layer with a thickness of 15 to 20 μm. In addition, the fracture occurred in the brittle intermetallic layer. These results exhibit that the formation of the thick intermetallic compound layer resulted in the low bonding strength between Al and Cu. In the present research, the thickness of the reaction layer between the Al rod and the Cu insert was about 900 μm. Furthermore, the reaction layer would contain many other intermetallic compounds as well as CuAl₂, as predicted from the Al-Cu binary phase diagram.³¹⁾ Therefore, it is believed that, despite inserting the Cu layer with preheating, the bonding strength resulted in the lower value than 20 MPa.

Fig. 10 Magnified SEM micrographs of ①, ② and ③ zones in Fig. 9(a), respectively.

4. Conclusions

The TiB_2 particle reinforced Cu matrix composites were fabricated by the combustion reaction between Ti and B in the Cu-Ti-B system. Furthermore, the simultaneous bonding between the composite and 1050 Al alloy was also attempted by using the high heat generated during the combustion reaction. The following results were obtained:

(1) For the Cu-50 vol% TiB_2 composition, a minute quantity of unfavorable Cu_3Ti was formed with TiB_2 in the Cu matrix. In contrast, for the Cu-60 vol% TiB_2 , only fine TiB_2 particles

Fig. 11 Bonding strength between the 1050 Al alloy rod and the combustion synthesized Cu-60 vol% TiB_2 composite.

Fig. 12 XRD patterns of the fracture surfaces of the simultaneously bonded specimen between the 1050 Al alloy rod with the length of 30 mm and the combustion synthesized Cu-60 vol% TiB_2 composite without the pure Cu insert layer, which was ignited after preheating at 433 K; (a) Al rod side and (b) composite side.

Fig. 13 SEM micrograph of the fracture surface of the simultaneously bonded specimen between the 1050 Al alloy rod with the length of 30 mm and the combustion synthesized Cu-60 vol% TiB_2 composite without the pure Cu insert layer, which was ignited after preheating at 433 K.

Fig. 14 XRD patterns of the fracture surfaces of the simultaneously bonded specimen between the 1050 Al alloy rod with the length of 30 mm and the combustion synthesized Cu-60 vol%TiB₂ composite with the pure Cu insert layer, which was ignited after preheating at 433 K; (a) Al rod side and (b) composite side.

Fig. 15 SEM micrograph of the fracture surface of the simultaneously bonded specimen between the 1050 Al alloy rod with the length of 30 mm and the combustion synthesized Cu-60 vol%TiB₂ composite with the pure Cu insert layer, which was ignited after preheating at 433 K.

below 4 μm in diameter were formed *in situ*, and homogeneously distributed in the Cu matrix. Also for the Cu-70 vol%TiB₂, the combustion reaction occurred completely without forming any unfavorable phases, although some Cu was evaporated during synthesizing the composite.

(2) In the Ti-B binary system, any reaction was not generated in the temperature range from room temperature to 1473 K, indicating that the ignition temperature at which the combustion reaction between Ti and B starts is higher than 1473 K. However, in the Cu-Ti-B ternary system, immediately after Cu was melted at its melting point, the combustion reaction was induced. These results suggest that the combustion reaction was activated by molten Cu, and its ignition temperature was also decreased.

(3) The fabrication and bonding with the Al alloy of the TiB₂/Cu composite were successfully carried out in a single

process by using the high reaction heat generated during the combustion synthesis of the composite.

(4) Preheating before generating the combustion reaction was highly effective in bonding relatively long Al rods and in reducing bonding defects. Compounds consisting of Al, Cu and Ti were observed with unreacted B in the bonded layer between the composite and Al alloy. For the bonded specimen with the Cu insert layer, the eutectic microstructure of Al and Cu was formed between the Al alloy and Cu insert, and unreacted B was observed with a compound of Cu and Ti between the composite and Cu insert.

(5) The bonding strength was enhanced by preheating before generating the combustion reaction and by inserting the Cu layer between the Al alloy and the composite.

(6) The bonded specimen with no insert layer was fractured near the bonded interface between the Al alloy and the composite. On the other hand, by inserting the pure Cu layer with preheating, the fracture occurred in the bonded layer between the Al alloy and the Cu insert.

REFERENCES

- 1) M. S. Nagorka, C. G. Levi, G. E. Lucas and S. D. Ridder: *Mater. Sci. Eng. A* **104** (1991) 277–289.
- 2) J. R. Groza and J. C. Gibeling: *Mater. Sci. Eng. A* **171** (1993) 115–125.
- 3) N. Zhao, Z. Liu, R. Su, Y. Cao and G. Li: *J. Mater. Eng.* **10** (1995) 23–25.
- 4) Y. V. Baikova and O. I. Lomovsky: *J. Alloy. Compd.* **297** (2000) 87–91.
- 5) N. Sata: *Ceramics Japan* **24** (1989) 514–520.
- 6) P. Yih and D. D. L. Chung: *J. Mater. Sci.* **32** (1997) 1703–1709.
- 7) S. Yilmaz and D. C. Dunand: *Compos. Sci.* **64** (2004) 1895–1898.
- 8) Q. Xu, X. Zhang, J. Han, X. He and V. L. Kvanin: *Mater. Lett.* **57** (2003) 4439–4444.
- 9) Hyun-Ki Kang: *Surf. Coat. Technol.* in press.
- 10) S. C. Tjong and Z. Y. Ma: *Mater. Sci. Eng. R* **29** (2000) 49–113.
- 11) Z. A. Munir: *Am. Ceram. Soc. bull.* **67** (1988) 342–349.
- 12) R. D. Torres, I. E. Reimanis, J. J. Moore and G. G. W. Mustoe: *Metall. Mater. Trans. B* **31** (2000) 433–438.
- 13) S. C. Deevi and N. N. Thadhani: *Metall. Mater. Trans. A* **192–193** (1995) 604–611.
- 14) S. C. Deevi: *International Journal of Refractory Metals & Hard Materials* **13** (1995) 337–342.
- 15) L. Chen and E. Kny: *International Journal of Refractory Metals & Hard Materials* **18** (2000) 163–167.
- 16) J. K. Wright, R. N. Wright and G. A. Moore: *Scr. Metall. Mater.* **28** (1994) 501–506.
- 17) T. Kimata, K. Uenishi, A. Ikenaga and K. F. Kobayashi: *Intermetallics* **11** (2003) 947–952.
- 18) C. Pascal, R. M. Marin-Ayral, J. C. Tédénac and C. Merlet: *Mater. Sci. Eng. A* **341** (2003) 144–151.
- 19) P. La, M. Bai, Q. Xue and W. Liu: *Surf. Coat. Technol.* **113** (1999) 44–51.
- 20) T. Kimata, K. Uenishi, A. Ikenaga and K. F. Kobayashi: *Sci. Technol. Adv. Mater.* **5** (2004) 251–254.
- 21) A. J. Swiston Jr., T. C. Hufnagel and T. P. Weihs: *Scr. Mater.* **48** (2003) 1575–1580.
- 22) S. Li, H. Duan, S. Liu, Y. Zhang, Z. Dang, Y. Zhang and C. Wu: *International Journal of Refractory Metals & Hard Materials* **18** (2000) 33–37.
- 23) Y. J. Kwon, M. Kobashi, N. Kanetake and T. Choh: *J. Japan Inst. Metals* **63** (1999) 1109–1112.
- 24) Y. J. Kwon, M. Kobashi, N. Kanetake and T. Choh: *Proc. 2nd Asian-Australasian Conf. on Composite Materials*, ed. by C. S. Hong and C. G. Kim, (The Asian Australasian Association for Composite Materials and The Korean Society for Composite Materials, 2000) pp. 329–334.

- 25) I. Barin, F. Sauert, E. Schultze-Rhonhof and W. S. Sheng: *Thermochemical data of pure substances*, 2. ed., 2. pt., (VCH, New York, 1993) p. 1528.
- 26) J. J. Moore and H. J. Feng: *Prog. Mater. Sci.* **39** (1995) 243–273.
- 27) Y. J. Kwon, M. Kobashi, T. Choh and N. Kanetake: *J. Japan Inst. Metals* **65** (2001) 273–278.
- 28) Y. J. Kwon, M. Kobashi, T. Choh and N. Kanetake: *J. JILM* **51** (2001) 351–355.
- 29) I. Barin, F. Sauert, E. Schultze-Rhonhof and W. S. Sheng: *Thermochemical data of pure substances*, 2. ed., 2. pt., (VCH, New York, 1993) pp. 110–1523.
- 30) M. W. Chase, Jr.: *NIST-JANAF thermochemical tables*, 4. ed., 2. pt, (the American Chemical Society and the American Institute of Physics for the National Institute of Standards and Technology, New York, 1998) p. 1005.
- 31) ASM International: *Binary alloy phase diagrams*, 2nd ed., version 1.0, plus updates on CD-ROM, (Materials Park, Ohio, 1996).
- 32) T. Enjo, K. Ikeuchi and N. Akikawa: *Journal of JWS* **48** (1979) 770–775.
- 33) M. Abbasi, A. Karimi Taheri and M. T. Salehi: *J. Alloy. Compd.* **319** (2001) 233–241.