Dissimilar joining of nickel aluminide with spheroidal graphite cast iron and Cu alloy by hot pressing

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Abstract

Joining of copper alloys (BC6) on spheroidal graphite cast iron (FCD) is effective to enhance the wear resistance of sliding parts. By applying combustion synthesis to a joining to FCD and BC6 has possibilities to enable the process at a lower temperature or for a shorter time. In this study, we examined the application of this process as joining of FCD and BC6 by using Ni–Al–Si compact as filler. Then the effects of the interface microstructure on joining were examined. As a substrate, FCD and BC6 cut into a column of 10.5 × 3 mm were prepared. Ni, Al and Si powders were mixed in the composition of Ni–28 at.% (Al–8 at.% Si), or Ni–78 at.% (Al–8 at.% Si). These powders were die-pressed with a load of 400 MPa for 60 s to the disc shape compact of 10 mm in diameter and 0.5 mm or 0.25 mm in thickness. Dense Ni–Al–Si intermetallic compound coating layer was formed by the combustion synthesis from the elemental mixture of Ni, Al and Si, and was simultaneously bonded with the FCD and BC6 substrate. The composition of the filler was Ni3Al, Al3Ni2 and Ni solid solution. Unreacted Ni was almost consumed by the reaction with Al–Si. Densification was achieved in the interface between filler and substrate as well as in the filler due to molten Al–Si in the filler during hot pressing infiltrates well into the interface between filler and substrates and the boundary of each powder. Reaction layer of Ni–Al–Cu was formed in the interface between filler and BC6 achieving chemically bonding.

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1. Introduction

Spheroidal graphite cast iron (FCD: JIS G 5502) has many advantages such as high strength and damping capacity so it is widely used for the frame of machines. Joining of copper alloys (BC6) on spheroidal graphite cast iron is effective to enhance the wear resistance of sliding parts. Although there have been many techniques practically applied to the joining, such as brazing, inserting or others, these methods have many technical problems like weak adhesion to substrate or heat affection to substrate. Combustion synthesis is known to be one of the powder metallurgical techniques for obtaining intermetallics like nickel aluminide, ceramics from the mixture of composing elemental powders. Application of this process to a joining to FCD has possibilities to enable the process at a lower temperature or for a shorter time [1–6].

The authors have applied the reaction synthesis of Ni–Al–Si compounds to the surface modification of FCD with high adhesion between substrate and coating. In the previous work [7], dense Ni–Al–Si intermetallic compound coating layer was formed by the combustion synthesis from the elemental mixture of Ni, Al and Si, and was simultaneously bonded with the FCD substrate. The study examines the application of this process as joining of FCD and BC6 by using Ni–Al–Si compact as filler. Then the effects of the interface microstructure on joining were examined.

2. Experimental procedure

Tables 1 and 2 show the chemical composition of spheroidal graphite cast iron (FCD) and Cu alloy (BC6), respectively. FCD and BC6 substrate cut into a column of 10.5 × 3 mm were prepared as a substrates and the surface
was cleaned by polishing with alumina. Ni, Al and Si powders with 99.9% purity and average sizes of 3, 3, 3–10 \( \mu \)m, respectively, were mixed in the composition of Ni–28 at.% (Al–8 at.% Si), or Ni–78 at.% (Al–8 at.% Si).

Table 3 shows the composition of these mixtures. These powders were die-pressed with a load of 400 MPa for 60 s to the disc shape compact of 10 mm in diameter and 0.5 mm or 0.25 mm in thickness. The relative density of the compact was 60%. Sintering was performed by hot pressing under a vacuum of 5.0 \( \times \) \( 10^{-2} \) Pa as shown in Fig. 1. The sample was heated at the heating rate of 6.66 K/s by a high frequency induction heating equipment and held at the sintered temperatures. The pressure was applied from the beginning of heating and to the end of cooling.

### Table 1

| C   | Si  | Mn  | P   | S   | Mg  | Cr  | Cu  |
|-----|-----|-----|-----|-----|-----|-----|-----|
| 3.56 | 2.65 | 0.20 | 0.019 | 0.014 | 0.053 | 0.013 | 0.06 |

### Table 2

| Cu  | Sn | Pb | Zn |
|-----|----|----|----|
| 85.0 | 5.0 | 5.0 | 5.0 |

### Table 3

| Sample name | Chemical composition (at.%) |
|-------------|-----------------------------|
| Ni–28 at.% (Al–8 at.% Si) | 72.0 25.8 2.2 |
| Ni–78 at.% (Al–8 at.% Si) | 22.0 71.8 6.2 |

3. Results and discussion

3.1. Bonding with BC6 and FCD by hot pressing

Fig. 2 shows the microstructures of bonding interface, which was hot pressed at 973 K for 300 s with 6 MPa. As a filler, the composition of Ni–28 at.% (Al–8 at.% Si) applied. The filler was confirmed to be bonded well with the BC6 and FCD substrate. The thickness of the filler was about 500 \( \mu \)m. Ni3Al, Al3Ni2 and Ni solid solution formed in the filler. Unreacted Ni was almost consumed by the reaction with Al–Si. Densification was achieved in the interface as well as in the filler. It is considered that molten Al–Si in the filler during hot pressing infiltrates well into the interface between filler and substrates and the boundary of each powder. Since bonding was also achieved when the thickness of the filler was 250 \( \mu \)m (Fig. 3), sufficient heat by combustion synthesis between Ni and molten Al–Si assured even the decreasing the volume fraction of the mixture of Ni–Al–Si.

When applying the filler with the composition of Ni–78 at.% (Al–8 at.% Si), higher hardness of Al3Ni (700 HV) formed in the filler. After cooling, the specimen fractured in the filler. Fractures occurred in the inside of the filler (Fig. 4). The interface between filler and substrates (FCD, BC6) were as bonded, respectively. Probably due to the difference of thermal expansion between FCD and BC6, brittle Al3Ni formed in the filler has not endured and causing fracture. Although Al3Ni showed a superior wear property when applying on coating on FCD in our previous study [7], it is not adequate when applying the compound as a filler of the bonding because of its brittleness.

3.2. Reaction layer formed in the bonding interface

As shown in Fig. 2(a), the reaction layers with a thickness of 5–10 \( \mu \)m formed in the interface between

![Fig. 1. Schematic illustrations of hot press apparatus using high frequency induction heating.](image-url)
FCD and BC6 substrate. Since the layer was composed of Ni–Al–Cu by EDX analysis, Ni, Al in the filler diffused to BC6 substrate by hot pressing. Although reaction layers has not found in the interface between the filler and FCD substrate, a small amount of Ni and Al in the filler diffused in FCD substrate was confirmed by EDX analysis. These results show that the filler chemically bonded well with BC6 and FCD substrate, respectively.

3.3. Hardness of the bonding

Fig. 5 shows the Vickers hardness profiles of the joining. No brittle layer was formed on the bonding interface. The hardness of the filler with composition of Ni–28 at.% (Al–12 at.%Si) was approximately 150HV. A higher hardness area corresponds to the hardness of Ni₃Al, Al₃Ni₂ and a lower hardness area corresponds to that of Ni solid solution. Joining was achieved because of the hardness of the filler was softened in contrast to that of filler with composition of Ni–78 at.% (Al–12 at.%Si) (700HV).

4. Conclusions

Ni–Al–Si intermetallics were fabricated by combustion synthesis from elemental powders and these layers were joined with FCD and BC6 substrate.
The results are summarized as follows.

1. Joining of FCD and BC6 were achieved by using Ni–28 at.% (Al–8 at.% Si) as a filler when hot pressed at 973 K for 300 s with 6 MPa. Microstructures of joining were chemically bonded and achieving densification.

2. Ni$_3$Al, Al$_3$Ni$_2$, and Ni solid solution mainly formed in the filler with composition of Ni–28 at.% (Al–8 at.% Si) and densification was achieved.

3. 5–10 $\mu$m thick reaction layer of Ni–Al–Cu was formed in the interface between filler and BC6 by diffusion of Ni and Al to BC6 (Cu) substrate.

References

[1] K. Uenishi, Combustion synthesis of intermetallic compound Al$_3$Ti and its simultaneous joining with TiAl, Z. Metallkd. 90 (1999) 163–167.
[2] T. Matsubara, Fabrication of thick intermetallic compound Al$_3$Ti layer on metal substrate by combustion synthesis of ball-milled powder, Mater. Trans. JIM 41 (2000) 631–634.
[3] T. Matsubara, Fabrication of thick intermetallic compound Al$_3$Ti layer on Ti substrate by reactive-pulsed electric current sintering, Intermetallics 8 (2000) 815–822.
[4] K. Uenishi, Nanostructured titanium-aluminides and their composites formed by combustion synthesis of mechanically alloyed powders, Scripta Mater. 44 (2001) 2093–2097.
[5] K. Uenishi, Wear and oxidation resistance of Al$_2$O$_3$ particle dispersed Al$_3$Ti composite with a nanostructure prepared by pulsed electric current sintering of mechanically alloyed powders, Intermetallics 10 (2002) 105–111.
[6] T. Kimata, Formation of thick Ni–Al composite coating on spheroidal graphite cast iron substrates by reaction synthesis processing, Mater. Trans. 44 (2003) 407–410.
[7] T. Kimata, Enhanced densification of combustion synthesized Ni–Al intermetallics compound by Si addition, Intermetallics 11 (2003) 947–952.