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Interface investigation of BN particle and aluminosilicate short fibre hybrid reinforced Al-12Si alloy composite

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A BN particle and aluminosilicate short fibre reinforced hybrid Al-12Si composite was fabricated by squeeze casting. The interface microstructures between reinforcements and matrix were investigated by transmission electron microscopy (TEM). The experimental results showed that there is no reaction product formation at fibre/matrix and BN/matrix interface, and the matrix is in intimate contact with fibre and BN. Because of the addition of self-lubricant BN particles and good connection between BN and matrix alloy, the coefficient of friction of the hybrid composite is improved.

1. Introduction

Discontinuous reinforced metal–matrix composites (MMCs) have received much attention for various high-performance applications in automotive, aerospace, and transportation industries due to their high strength-to-weight ratio and superior wear resistance. Compared to the large number of studies on conventional discontinuously reinforced MMCs, limited effort has been directed toward composites containing different kinds of particulates, fibres, or whiskers. The broad varieties of ceramic reinforcements with unique properties allow one to design hybrid composites [1]. Recently, Gurcan and Baker [2] indicated that the ($Al_2O_3 + SiC$)/6061Al hybrid composites exhibit superior wear performance compared to the monolithic alloy and Al_2O_3/6061Al composites. Song *et al.* [3] have prepared Al composites reinforced with carbon and Al_2O_3 fibres by means of the squeeze-casting techniques. The wear resistance of ($C + Al_2O_3$)/Al hybrid composites is remarkably higher than that in the Al_2O_3/Al specimens. Jiang *et al*. [4] investigated the wear properties of alumina and hybrid alumina-aluminosilicate fibres reinforced Al-12Si alloy composites, their results showed that the wear resistance of the MMCs have been improved markedly, but the coefficient of friction of the composites was higher than that of the unreinforced matrix alloy, which limited the application of MMCs in the tribological areas. The graphite and BN are all hexagonal structure having self-lubricant properties which are expected to improve the wear resistance and coefficient of the friction of the hybrid MMCs. Du *et al.* [5] reported that the PM (powder metallurgy) fabricated BN/Al composite specimens are very fragile. Then they employed mechanical alloying (MA) process to fabricate the BN/Al composite and the further investigation indicated that BN powder tends react with aluminum during the composite processing, leading to the formation of AlN and AlB_2 phases. In [6] the Al-Si composite hybrid reinforced with BN particle and Al_2O_3 short fibre was successfully fabricated by centrifugal force infiltration route and the wear resistance and the coefficient of friction of such hybrid composite were improved a lot compared with Al_2O_3/Al-Si composite. Among these, the mechanical properties and wear and friction properties of the hybrid MMCs have been extensively investigated, however, information on the interfacial microstructures of hybrid reinforced composites is still limited. Since the interface between the matrix and the reinforcement plays a very important role in the properties of MMCs, it is necessary to characterize the interfacial structures of the composites. Interfacial studies usually include identification of the interfacial structures and/or reaction products and determination of crystallographic relationships [7, 8].

The objectives of the present work are to investigate the interface microstructures of BN particle and aluminosilicate ($Al_2O_3 \cdot SiO_2$) short fibre hybrid reinforced Al-Si alloy composites by using transmission electron microscopy (TEM). The major advantage of using aluminosilicate fibres instead of alumina fibres

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as the reinforcement is cost saving, because the price of the latter is 10 times that of the former [9].

2. Experimental procedures

The aluminum alloy matrix used in this work approximates to an Al-12Si alloy similar to SAE321 having a chemical composition (in wt%): Si:12.0, Mg:1.0, Ni:1.0, Cu:0.8, Fe:0.2, Mn:0.04, Zn:0.01 and the balance aluminum. The aluminosilicate fibres, with a chemical composition (in wt%) $58Al_2O_3$ and $42SiO_2$, were selected as the reinforcement of the composites. Such a fibre exhibits an amorphous structure.

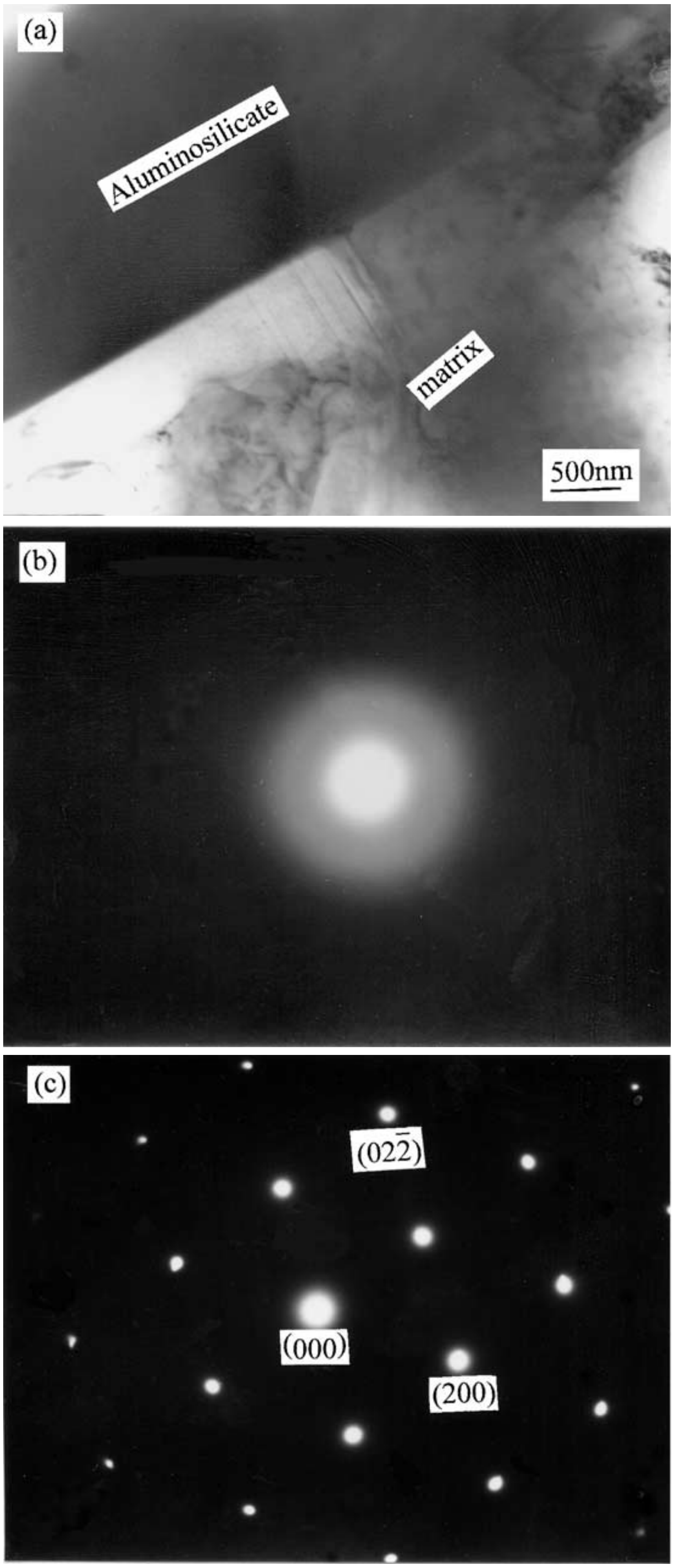

Figure 1 Bright field TEM image of $(BN + Al_2O_3 \cdot SiO_2)$/Al-12Si composite (a), electron diffraction patterns of the aluminosilicate fibre (b) and aluminum matrix: [011] (c).

The diameter of the aluminosilicate fibres is about 8–10 μm. The BN particles had a size of about 1–2 μm and a purity of 95%. The aluminosilicate fibres were chopped, mixed with BN particles and then made into preform, which has been described in [10]. The squeeze casting technique was used to fabricate the aluminosilicate short fibre and BN particle hybrid reinforced Al-12Si alloy composites. In this work, the preform, which was held in a die heated to 750°C, was infiltrated with the molten Al-12Si alloy. The melt temperature of the Al-12Si alloy was 780°C. The applied pressure was 30 MPa, and this pressure was maintained for 20 seconds. The volume fraction of the reinforcing short fibres and BN particles are about 10% and 5%, respectively.

The solution treatment was involved heating the composites at 500°C for 5 hours and quenching into cold water. Artificial aging was carried out at 185°C for 12 hours.

For TEM examination samples were cut into thin slices using a diamond saw and followed by mechanical grinding to thickness of ~50 μm, and then argon-ion beam thinning. The TEM investigations were preformed in a JEOL-2000EX instrument operating at 160 kV equipped with a double-tilt holder.

In order to measure the coefficient of friction of the composite, dry sliding wear tests were conducted in air temperature on a pin-on-disk machine. The pin specimens were 6 mm in diameter and 12 mm in length. The counterface disk material, made from spheroidal graphite cast iron with a hardness of 206 HV, was 70 mm in diameter and 10 mm thick. Wear tests were carried out at a linear sliding velocity of 1 m/s and various load levels within the range of 20–140 N. The sliding distance is 2500 m. The coefficient of friction of the pin specimens was calculated from the moment of the force measured by the test machine.

3. Results and discussion

Fig. 1a is a TEM image of $(BN + Al_2O_3 \cdot SiO_2)$/Al-12Si composite. The electron diffraction pattern (Fig. 1b) indicates that the upper left region in Fig. 1a is aluminosilicate fibre. The presence of a diffuse halo ring shows the typical amorphous structure of aluminosilicate fibre. Fig. 1c indicates that the lower right region shown in Fig. 1a is aluminum matrix. There is no reaction product (such as $MgAl_2O_4$) at fibre/matrix interface. The aluminosilicate fibre is in intimate contact with the matrix. Fig. 2a is also the TEM image showing

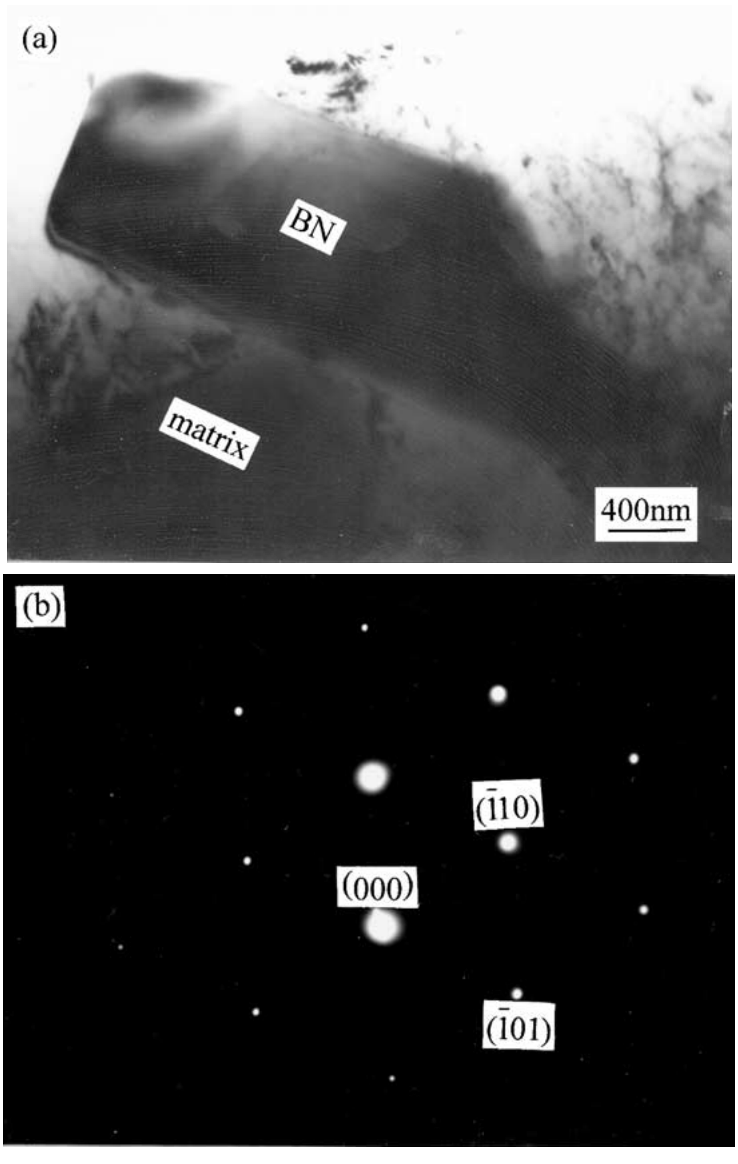

Figure 2 Bright field TEM image of $(BN + Al_2O_3 \cdot SiO_2)$/Al-12Si composite (a) and electron diffraction pattern of the BN particle: [111] (b).

the rectangular particle in the $(BN + Al_2O_3 \cdot SiO_2)$/Al-12Si composite. Fig. 2b is the electron diffraction pattern of the rectangular particle in Fig. 2a, after indexing the particle is identified as BN. The thin foil in TEM was examined under different diffraction conditions by tilting, but no reaction products (such as AlN and AlB_2 phase) at BN/matrix interface were observed. Fig. 3a is a TEM image of silicon in the composite. The presence of double diffraction pattern, Fig. 3b, indicates that the silicon particle exhibit twinning. The high magnification in Fig. 3c shows that lamellar twin plane is in edge-on. The twins have {111} habit plane and are related by 180° rotation along the $\langle 110 \rangle$ axis.

Fig. 4 is a plot of the coefficient of friction versus applied load for composite reinforced solely with aluminosilicate fibre and composite hybrid reinforced

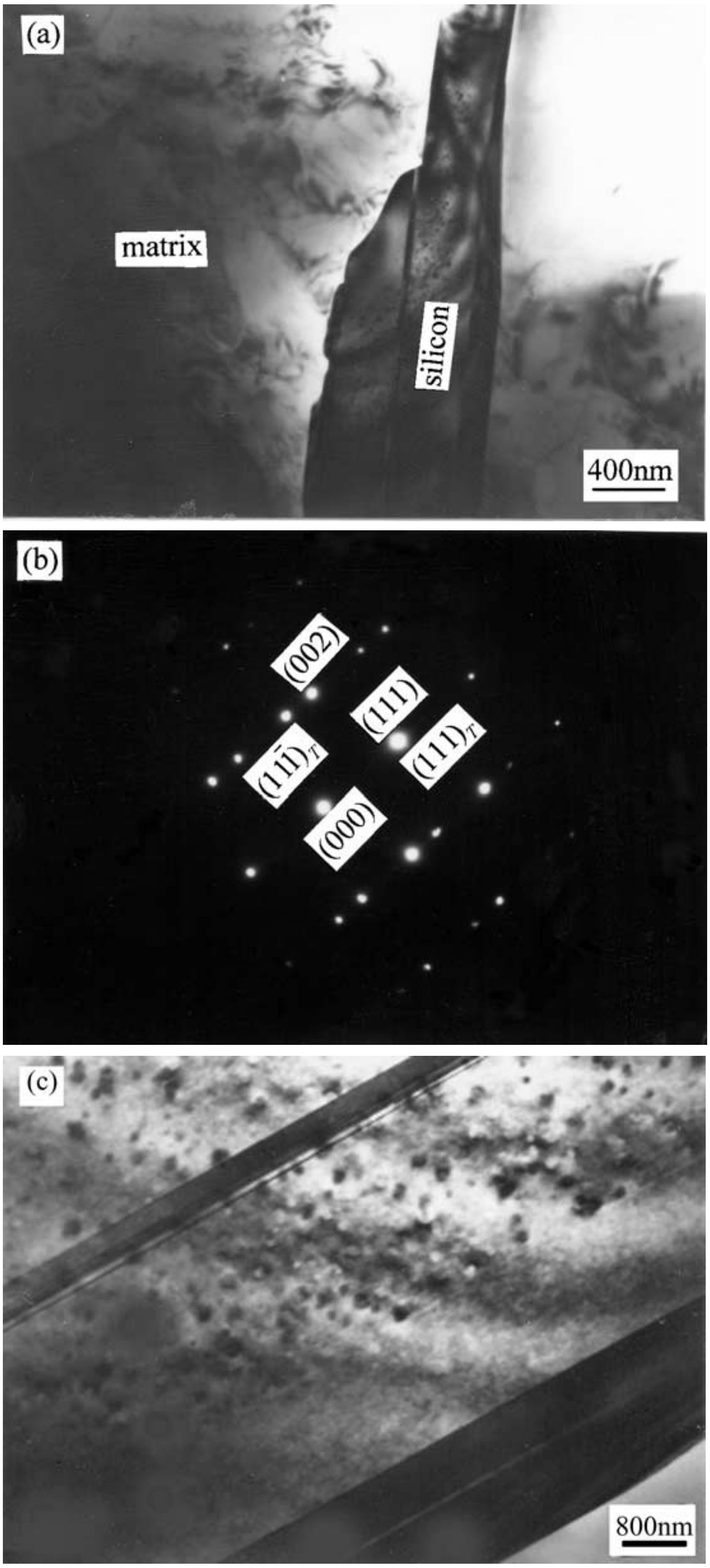

Figure 3 Bright field TEM image of the silicon particle in $(BN + Al_2O_3 \cdot SiO_2)$/Al-12Si composite (a), electron diffraction pattern of the silicon particle: $[1\bar{1}0]$, T refers to twinning (b) and high magnification of Fig. 3a (c).

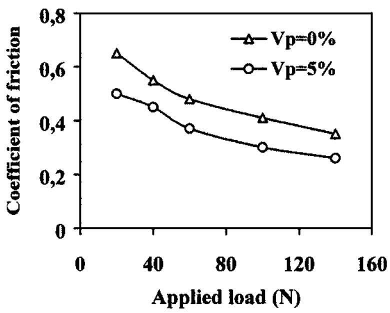

Figure 4 Effect of loads on the coefficient of friction of the composite reinforced only with aluminosilicate short fibres ($V_p = 0\%$) and composite hybrid reinforced with aluminosilicate short fibres and BN particles ($V_p = 5\%$).

with BN particle and aluminosilicate fibre, respectively. Fig. 4 indicates that the coefficient of friction decreases with increasing the applied load for all the test specimens. Compared with the composite reinforced only with aluminosilicate fibres ($V_p = 0\%$, $V_f = 10\%$) the coefficient of friction of the hybrid composite with 5 vol% BN particle addition ($V_p = 5\%$, $V_f = 10\%$) was reduced about 20%.

Different from the aluminosilicate and crystallized aluminosilicate short fibre reinforced Al-12Si alloy composites [11, 12], there is no reaction product $MgAl_2O_4$ formed at fibre/matrix interface in the present work. From thermodynamic consideration [13], magnesium in matrix alloy can react with SiO_2 (in aluminosilicate) rather than with Al_2O_3 (in aluminosilicate) due to $\Delta G^{(1)}_{1000K} > \Delta G^{(2)}_{1000K}$. The reactions are as follows:

$$Mg + 1/3\ Al_2O_3 \rightarrow MgO + 2/3[Al]$$

$$\Delta G^{(3)}_{1000K} = -39\ \text{kJ} \quad (1)$$

$$Mg + 1/2SiO_2 \rightarrow MgO + 1/2[Si]$$

$$\Delta G^{(4)}_{1000K} = -128\ \text{kJ} \quad (2)$$

The MgO generated from reaction (2) then react further with Al_2O_3 and SiO_2 in aluminosilicate fibre, which will result in the formation of $MgAl_2O_4$ or $MgSiO_3$ at fibre/matrix interface.

$$MgO + Al_2O_3 \rightarrow MgAl_2O_4 \quad \Delta G^{(5)}_{1000K} = -47\ \text{kJ} \quad (3)$$

$$MgO + SiO_2 \rightarrow MgSiO_3 \quad \Delta G^{(6)}_{1000K} = -34\ \text{kJ} \quad (4)$$

As $\Delta G^{(3)}_{1000K} < \Delta G^{(4)}_{1000K}$, the formation of $MgAl_2O_4$ at fibre/matrix is likely. However, different from the fabrication process in references 11 and 12, in present work the higher pressure (30 MPa) and smaller infiltration time (20 s) were used during squeeze-casting (20 MPa, 40 s in reference 11 and 12), which avoided $MgAl_2O_4$ formation at fibre/matrix interface.

Generally, MMCs with the addition of ceramic reinforcements have better wear resistance than monolithic alloys. However, if excessive reaction between reinforcement and matrix alloy occurs, interface cracks are easily initiated at this place during wear tests, which will lead to the delamination of the reinforcements. These ceramic fibres or particles delaminate from the composites will act as an abrasive thereby increasing the wear rate. In the present work there is no reaction products formation at aluminosilicate fibre/matrix and BN/matrix interface, the aluminosilicate fibre and BN particle show intimate contact with aluminum matrix alloy. Since the higher pressure and smaller infiltration time were taken during squeeze casting, which decrease the interaction time for aluminosilicate fibres and BN particles react with Mg and Al at high temperature (780°C), avoid reaction products such as $MgAl_2O_4$, AlN and AlB_2 phases formation at reinforcements/matrix interface.

The results presented above show that it is possible to decrease the coefficient of friction of the hybrid composite by adding BN particles. Hexagonal BN has a lamellar crystalline structure, in which the bonding between molecules within each layer is strong covalent, while the binding between layers is almost entirely by means of weak van der Waal's forces [14]. BN exhibits many similarities with graphite and MoS_2, which are highly solid lubricants. The mechanism of lubricating performance is understood to be owing to the ease of shearing along the basal (0001) plane of BN crystalline structure. During wear test the larger the applied load on the specimens, the larger areas covered by the sheared BN, the smaller the coefficient of friction is [6].

4. Conclusions

A BN particle and aluminosilicate short fibre hybrid reinforced Al-12Si alloy composite was successfully fabricated by squeeze casting. TEM results indicated that there is no reaction product formation at interfaces of fibre/matrix and BN/matrix, and the matrix is intimate contact with fibre and BN. The coefficient of friction of hybrid composites was significantly improved because of the addition of self-lubricant BN particles.

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