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Compressive and tribological properties of Al_2O_3 fibre and hexagonal BN particle hybrid reinforced Al–Si alloys

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Al_2O_3 fibre-hexagonal BN particle hybrid reinforced aluminium–silicon alloys were fabricated by centrifugal force infiltration route. Hardness test and ultimate compressive test results are reported. The wear and friction properties of hybrid MMCs was investigated by means of a block-on-ring (bearing steel) type wear rig in a dry sliding condition. It is shown that the hardness and ultimate compressive strength of hybrid MMCs was evidently decreased with the addition of hexagonal BN particles, however, the wear rate and coefficient of friction of hybrid MMCs was improved simultaneously with increase of BN particle volume fraction, especially for the higher applied loads in the test.

1. Introduction

Discontinuous reinforced metal matrix composites (MMCs) based on aluminium alloys are well known for their specific modulus, strength and excellent wear resistance when compared to conventional alloys [1–7]. Recently, the authors investigated the wear properties of the Al–12%Si alloy reinforced only with alumina fibres and hybrid alumina–aluminosilicate fibres [8, 9]. It was found that the wear resistance of tested MMCs improved markedly, but the coefficient of friction was higher than that of unreinforced matrix alloy substantially, which limited the application of MMCs in tribological areas. The objective of the study summarized here was to investigate the effect of hexagonal BN particles on the mechanical properties, wear and friction behaviour of alumina fibre-reinforced Al–12% Si under dry sliding condition. The crystal structure of BN is similar to graphite, i.e. hexagonal system, so it has a self-lubricant property, which is expected to improve the wear resistance and coefficient of friction of hybrid MMCs simultaneously.

2. Experimental procedure

The MMCs studied in this work were based on an aluminium–silicon alloy. The chemical composition of matrix is (wt %): 12% Si, 0.8% Cu, 1.0% Mg, 1.0% Ni, which is similar to SAE321. The alumina fibres had a mean diameter of 8.0 μm, and an ultimate tensile strength of 1.8–2.0 GPa. The BN particles had a size below 5 μm, and a purity above 95% (<5% B_2O_3). The composites were fabricated by centrifugal force infiltration of a molten Al–Si alloy, which is detailed in Ref. 10. It consists of three parts: (1) a metal mould (60 mm i.d., 70 mm o.d., 25 mm *h*) in which a preform (40 mm i.d., 60 mm o.d., 25 mm *h*) was placed which is fixed at the end of the drive shaft; (2) a removable resistance furnace which contains a pouring cup and a thermocouple for preheating the mould and preform; and (3) a motor whose rotating speed can be changed steplessly in the range of 1000–6000 r.p.m. by using an inverter. The molten metal was poured into the rotating mould. After pouring, the furnace was shut off immediately, then a furnace cooled for the sample. The molten metal penetrated the preform and solidified under the centrifugal force, then a cylindrical MMC (φ 60 × 40 × 25 mm) was obtained. In the present investigation, the process parameters were as follows: pouring temperature was 740 °C, mould and preform preheated temperature was 580 °C, rotation speed was 6000 r.p.m., the process time was 15 min.

Prior to infiltration, the preforms containing hybrid alumina fibres and BN particles were produced by a process route similar to that employed for conventional short fibre preform [3]. In the context of this paper, preforms with different fibre to particle ratio were prepared as listed in Table I.

Specimens for hardness tests, compressive tests (8 × 8 × 15 mm) and wear tests (rectangular 7 × 10 × 20 mm) were cut from cylindrical composites and solution treated at 505 °C for 6 h, then quenched in warm water (70–80 °C). The specimens were then aged

TABLE I The volume fraction of reinforcements in preforms

Preform no.	1	2	3	4	5	6	7	8	9
Al_2O_3 fibre vol %	5	5	5	8	8	8	12	12	12
BN particle vol %	0	2	4	0	2	4	0	2	4

at 180 °C for 16 h. Hardness tests were performed with a Rockwell hardness number testing machine (B scale). Compressive tests were carried out using an hydraulic mechanical test system. Wear tests were carried out on a block-on-ring tester with a ring (44.5 mm in outside diameter, 5 mm in thickness) made of GCr15 bearing steel with a bulk hardness of HRc63 $\pm$ 2 under dry sliding conditions. The tests were performed at a sliding velocity of 0.93 m s^{-1} and at various constant applied load levels between 20 N and 150 N. The sliding distance was in a range of 500 m to 2500 m. At each load level, the wear volume loss and coefficient of friction of the block specimen was calculated from the width of the worn surface and the moment of the force measured by the test machine during the experiment, respectively, which was described in details in [8].

The fractography and worn surface was examined by scanning electron microscopy (SEM). The microstructure of the MMCs was observed by optical microscopy.

3. Results

3.1. Structure and mechanical properties

Two optical micrographs (Fig. 1) show that the alumina fibres were well dispersed in the aluminium alloy matrix. The BN particles laid on the fibre surface, since the particles were too small to form a skeleton independently. Thus, the greater the fibre to particle ratio, the larger is the fibre surface area that exists and the more homogeneous is the distribution of the BN particles, as shown in Fig. 1(b). Also, these composites were all infiltrated with no signs of residual porosity.

The effect of BN particles on the hardness of hybrid composites is illustrated in Fig. 2. Apparently, the values of the hardness of composites with various fibre volume fractions (5, 8 and 12%) were decreased markedly with the addition of BN particles. Fig. 3 shows the variation of ultimate compressive strength of hybrid composites with the volume fraction of BN particle, indicating that 2 vol % BN had a marked influence on the ultimate compressive strength, which was decreased by one-half. However, in the case of further increasing the amount of BN particle up to 4 vol %, the ultimate compressive strength was decreased slightly.

Fig. 4 shows the SEM micrographs of the fracture surface of composites after compressive tests. The fracture was about 45° away from the compressive axis, that is to say, these materials failed primarily via one principal crack which propagated at 45° to the compressive axis, and this generally initiated near to the specimen end, and initiation appeared to occur at the maximum stress. Fig. 4(a) shows the fractograph of composite reinforced only with alumina fibre, indicating that evident plastic deformation occurred before failure. Furthermore, there existed some broken fibres on the fracture surface, as further magnified in Fig. 4(b). This means that the fibre/matrix interface was strongly bonded, and can transfer the compressive load from matrix to fibre, so the ultimate compressive

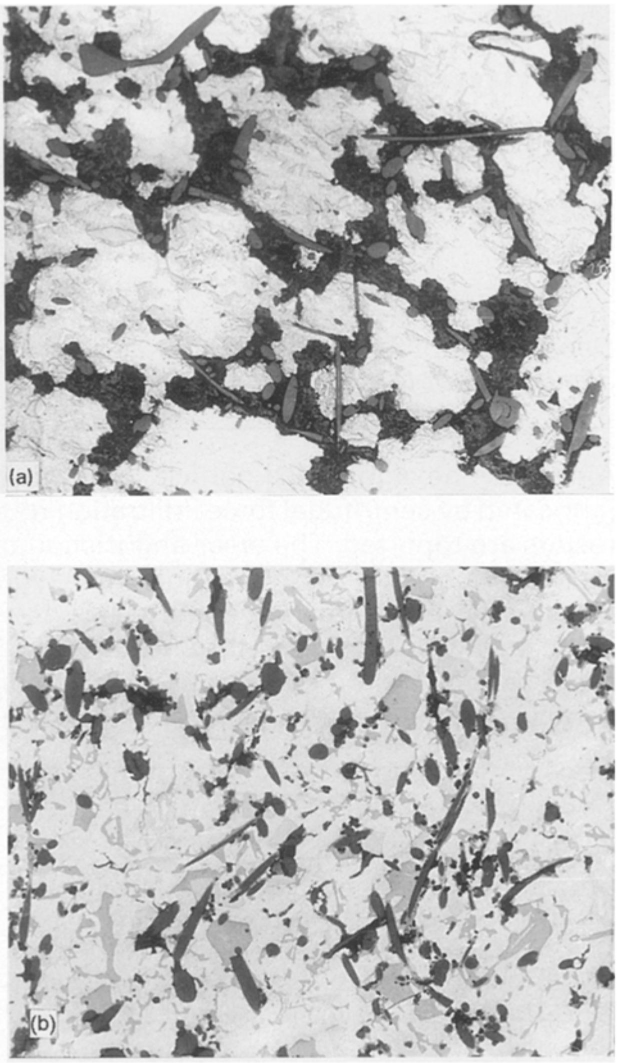


Figure 1 Optical micrographs of hybrid composites. 100× (a) $V_f = 5\%$, $V_p = 4\%$; (b) $V_f = 12\%$, $V_p = 2\%$.

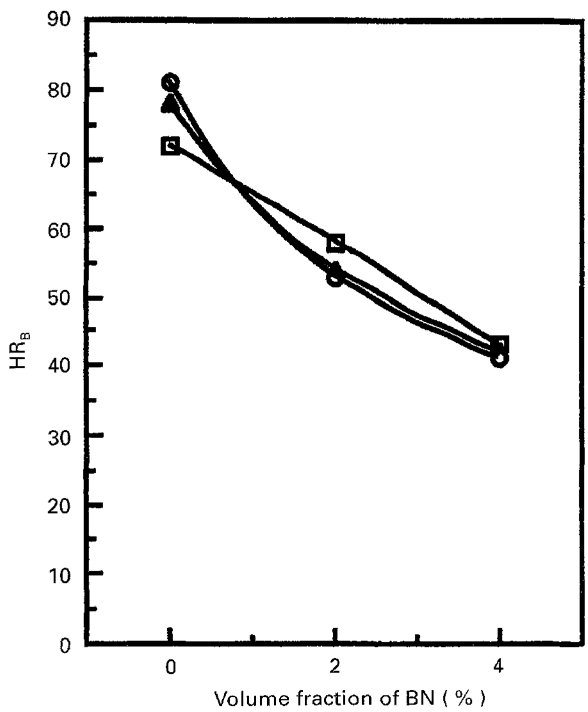


Figure 2 The effect of BN particle volume fraction on the hardness of hybrid composites. V_f □ 5%, ▲ 8%, ○ 12%.

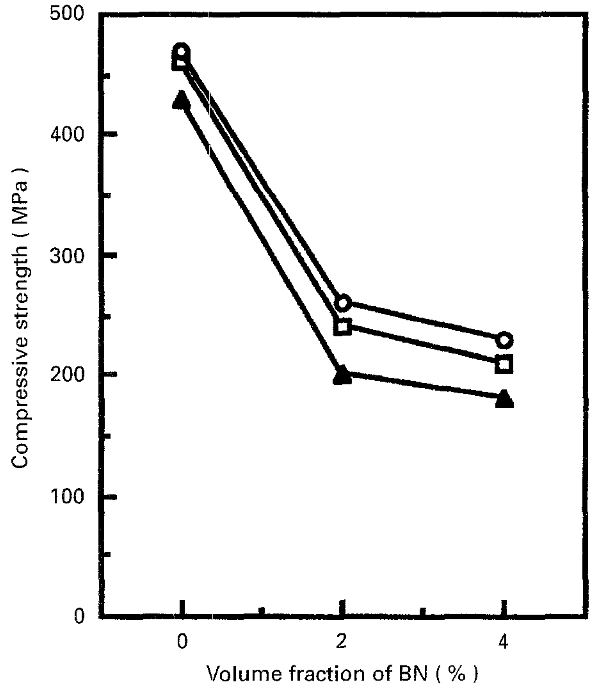


Figure 3 The effect of BN particle volume fraction on the ultimate compressive strength of hybrid composites. V_f □ 8%, ▲ 5%, ○ 12%.

strength of composites reinforced only with alumina short fibres was improved and increased slightly with increasing the fibre volume fraction (Fig. 3), though the ultimate tensile strength was decreased with increasing the fibre volume fraction at room temperature as reported in previous work [3]. In contrast, Fig. 4(c) shows the brittle fracture behaviour of the hybrid composite due to the addition of BN particles, corresponding to a lower ultimate compressive strength.

3.2. Volume wear rate

At several different loads between 20 and 150 N, the volume losses of the composite were determined as a function of sliding distance. Fig. 5 shows the volume loss (ΔV) increasing linearly with sliding distance for hybrid composites ($V_f = 8\%$ series) containing different amounts of BN particles at the applied load of 150 N, indicating a steady-state behaviour. Thus the wear rate can be calculated from the slope of volume loss versus sliding distance curves using a linear regression method. The ΔV-sliding distance behaviour of all the tested composites in this investigation was similar to that observed in Fig. 5 and hence will not be reproduced.

The effect of applied load on the wear rate ($\Delta V/S$, $mm^3\ km^{-1}$) is illustrated in Fig. 6 for three series of alumina fibre amount. Obviously, the wear rate of hybrid composites containing BN particles is much lower than that of the composites reinforced only with alumina short fibres. At the fibre volume fraction

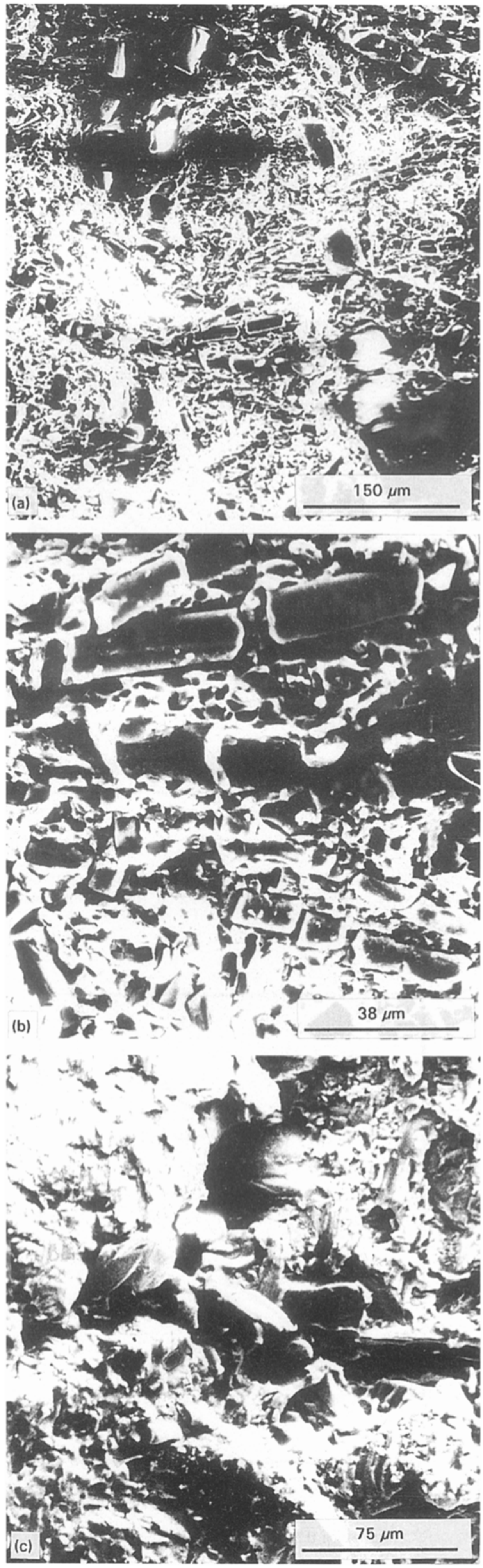


Figure 4 Scanning electron micrographs of the fracture surface of composites. (a) $V_f = 8\%$, $V_p = 0$; (b) high magnification view of (a); (c) $V_f = 8\%$, $V_p = 2\%$.

below 8% in hybrid composites, the wear rate is decreased slightly with increasing the amount of BN particles from 2 to 4% as given in Figure 6(a) and (b), however, at the fibre volume fraction of 12%, the wear resistance of the hybrid composite was no longer improved with increasing the amount of BN particle from 2 up to 4% as given in Fig. 6(c). Furthermore, the multiple effect of BN particles and alumina short fibres on the wear rate was illustrated in Fig. 7. At the lower applied load (40 N, Fig. 7(a)), the composite with 8% alumina fibres appears a lower wear rate in the case of the MMCs reinforced only with alumina fibre; with the addition of 2 vol % BN particles, the wear rate of the hybrid composites was decreased with increasing the volume fraction of fibre, but, for the 4 vol % BN particle series it shows the same variation pattern as the composites reinforced only with alumina fibre. At the high applied load (150 N, Fig. 7(b)), the wear rate of composites reinforced only with alumina fibres is decreased with increasing the fibre volume fraction. The addition of BN particles improved the wear resistance of the hybrid composite substantially, which illustrated little variation with alumina fibre volume fraction. For 4 vol % BN series,

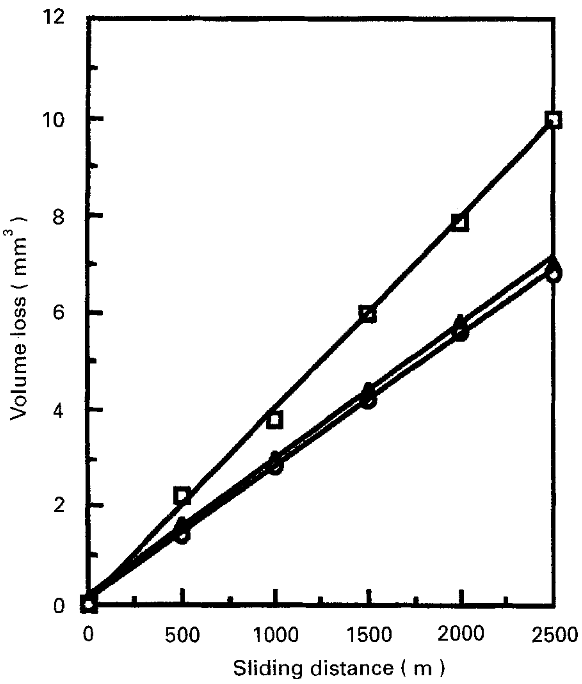
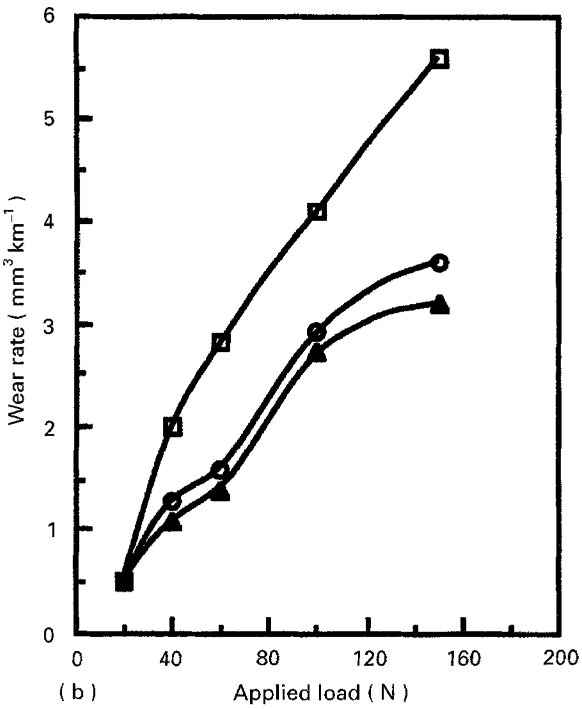


Figure 5 Variation of the volume losses of hybrid composites (8 vol % series) with the sliding distance at the applied load of 100 N. V_f □ 0, ▲ 2%, ○ 4% BN.



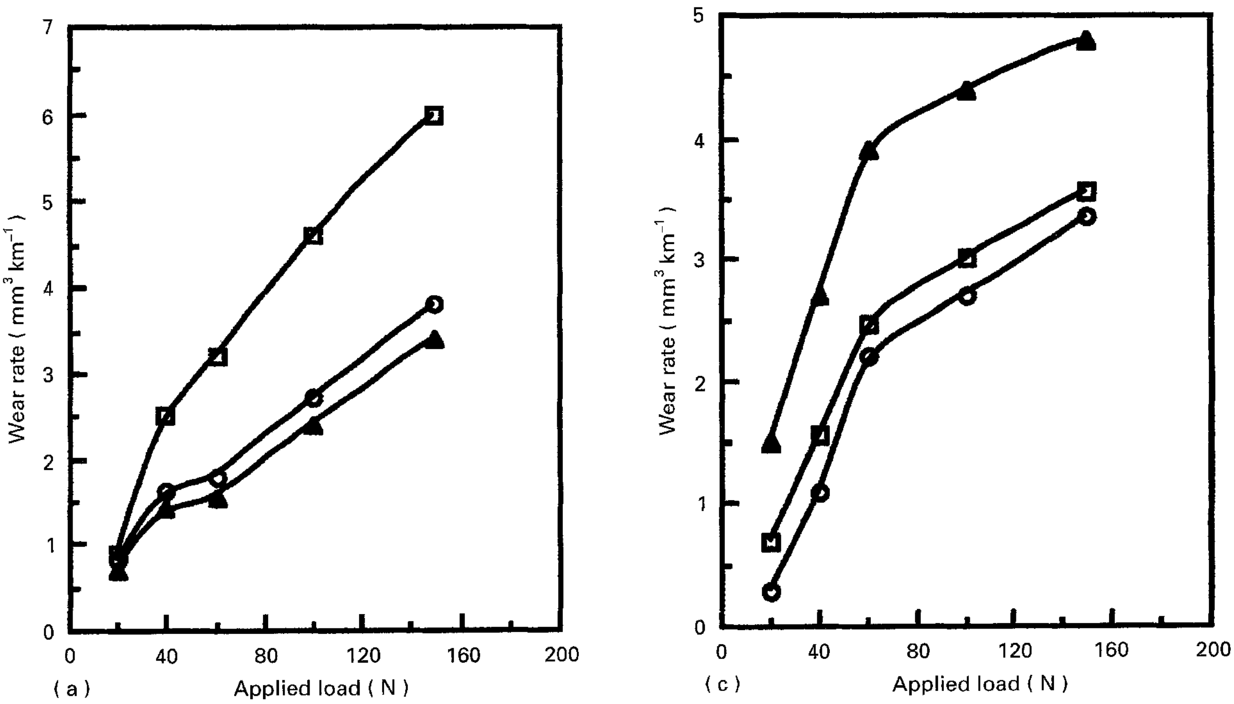


Figure 6 Variation of the wear rate of hybrid composites with the applied load. (a) $V_f = 5\%$ series V_f □ 0, ○ 2%, ▲ 4% BN; (b) $V_f = 8\%$ series V_f □ 0, ○ 2%, ▲ 4% BN; (c) $V_f = 12\%$ series, ▲ 0 vol % BN, ○ 2 vol % BN, □ 4 vol % BN.

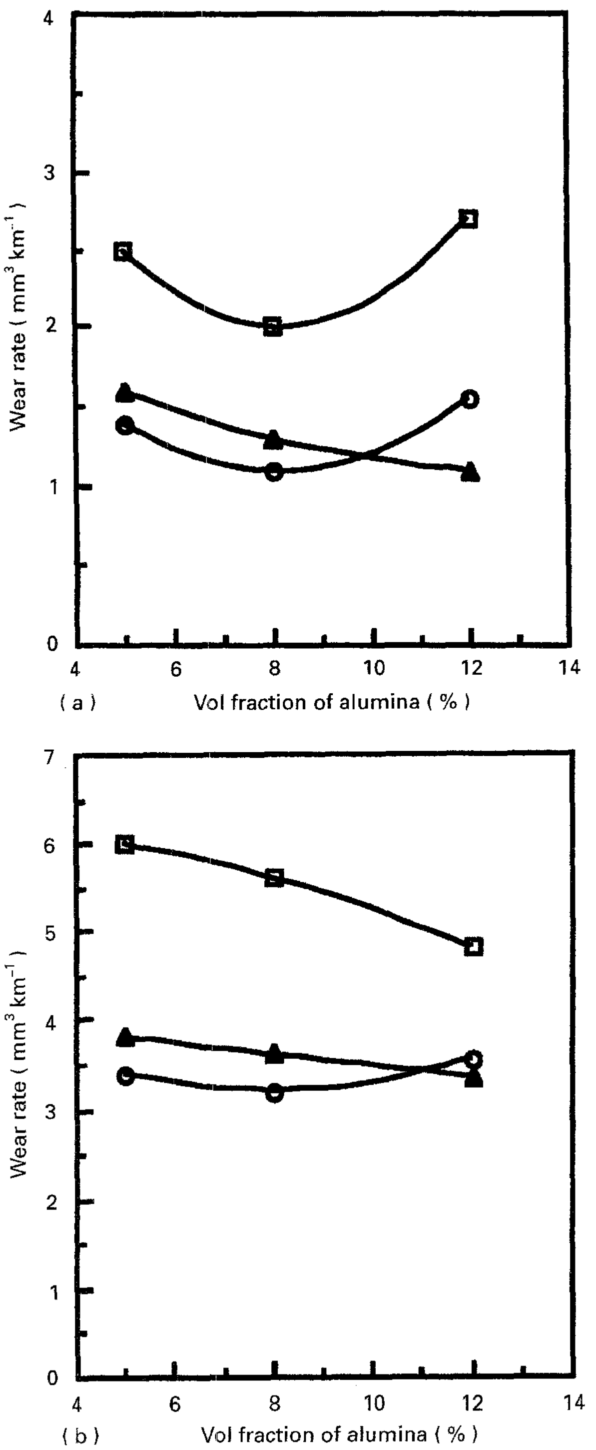


Figure 7 The multiple effect of BN particle and Al_2O_3 fibre on the wear rate of hybrid composites. Load (a) 40 N, (b) 150 N. □ 0 vol % BN, ▲ 2 vol % BN, ○ 4 vol % BN.

the wear rate of hybrid composites (5, 8 and 12% fibre) was 46, 41 and 27% lower than that of the composites reinforced only with alumina fibre, respectively.

3.3. Coefficient of friction

Fig. 8(a–c) is a plot of the coefficient of friction versus applied load for hybrid composites with three

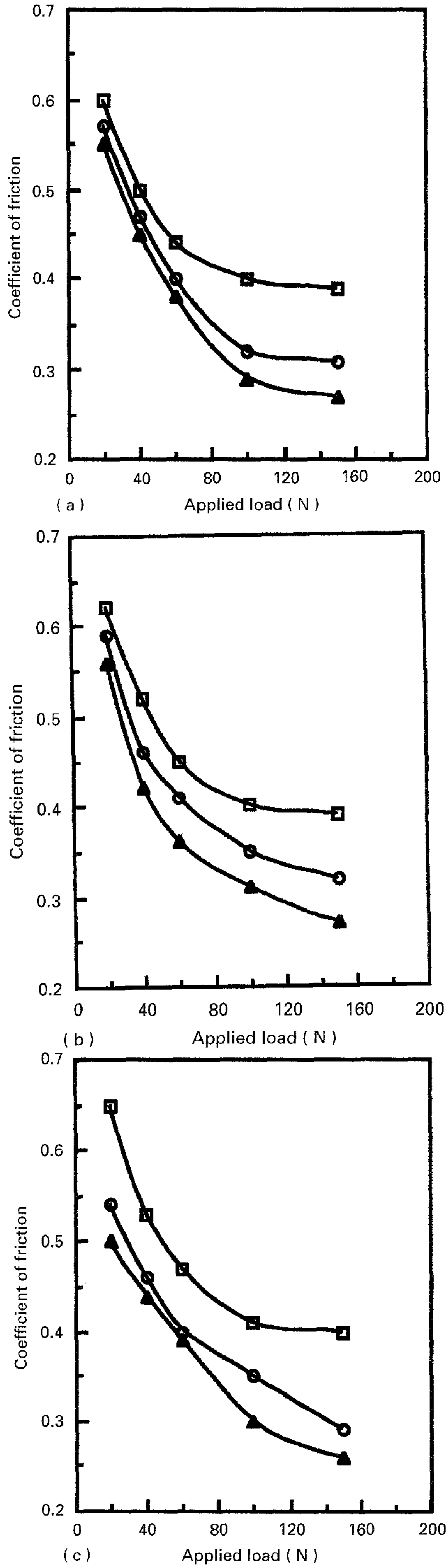


Figure 8 Variation of the coefficient of friction of composites with the applied load. (a) $V_f = 5\%$ series; (b) $V_f = 8\%$ series; (c) $V_f = 12\%$ series. □ 0 vol % BN, ○ 2 vol % BN, ▲ 4 vol % BN.

fibre volume fraction series. It was found that the coefficient of friction decreased with increasing the applied load for all the tested composites. The BN particles have a marked effect on the coefficient of friction. The greater the volume fraction of BN particles in hybrid composites is, the smaller the coefficient of friction is, particularly for higher applied loads in the test. Fig. 9 provided an illustration of multiple effect of BN particle and alumina fibre on the coefficient of friction. At the lower applied load (40 N, Fig. 9(a)), the coefficient of friction was increased with increasing the fibre volume fraction for the composites reinforced only with alumina fibre. With the addition of 2 vol % BN particle, the coefficient of friction reduced slightly with increasing the fibre volume fraction. At the high applied load (150 N Fig. 9(b)), it was found that the variation of the coefficient of friction of both the composites with 4 vol % BN and without BN particle with fibre volume fraction was small with the mean values of 0.39 and 0.27, respectively, as a consequence, the hybrid MMCs with 4 vol % BN had a coefficient of friction reduction of 31% compared with the composites reinforced only with alumina fibre.

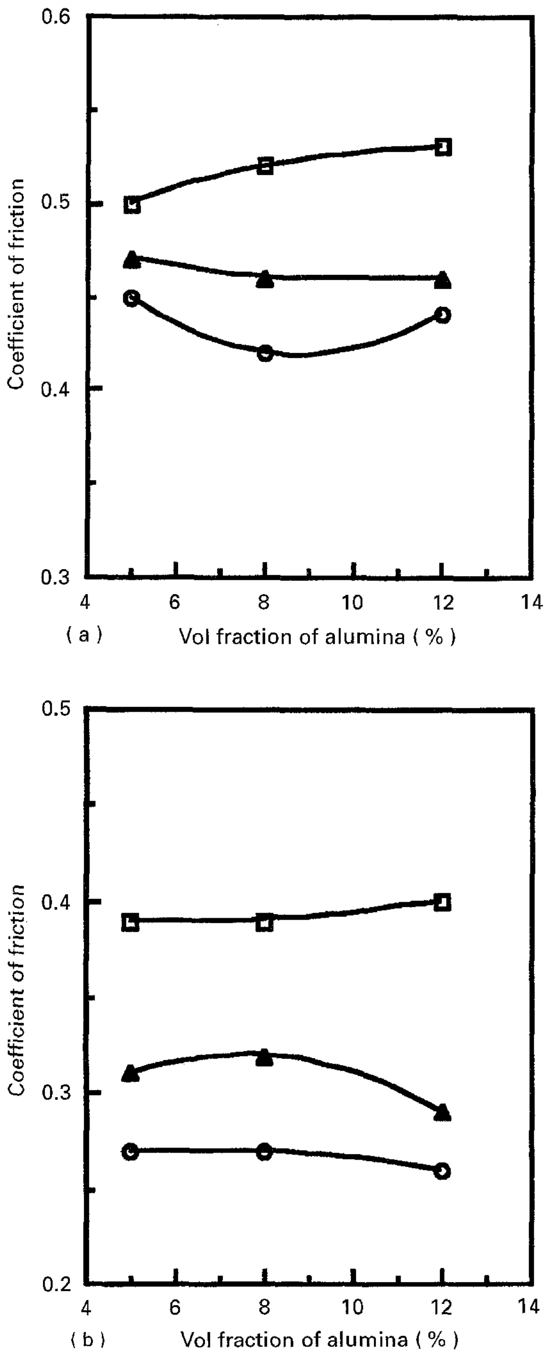


Figure 9 The multiple effect of BN particle and Al_2O_3 fibre on the coefficient of friction of hybrid composites. Load (a) 40 N, (b) 150 N. □ 0 vol % BN, ▲ 2 vol % BN, ○ 4 vol % BN.

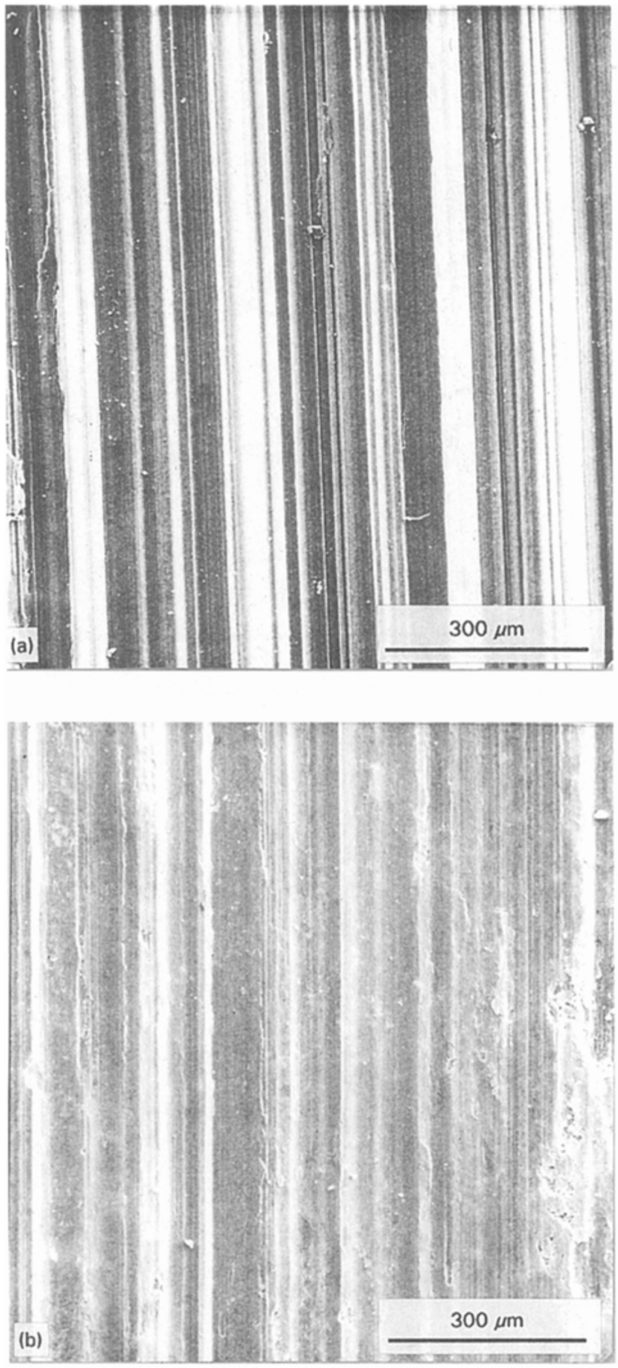


Figure 10 Scanning electron micrographs of worn surface of hybrid composites. (a) $V_f = 80\%$, $V_p = 0$; (b) $V_f = 6\%$; $V_p = 2\%$.

3.4. Examination of worn surface

Fig. 10 shows the SEM morphology of the worn surface of the composites at the applied load of 150 N after dry sliding for 2500 m, appearing as a homogeneous wearing, however, the morphology of the worn surface of the hybrid composite ($V_f = 8\%$, $V_p = 2\%$) that exhibited a small wear rate and low coefficient of friction was much smoother than that of the composite reinforced only with alumina fibre ($V_f = 8\%$, $V_p = 0$).

4. Discussion

The results presented above show that it is possible to produce Al_2O_3 fibres and BN particles hybrid MMCs components by the preform infiltration route. Since the crystal structure of the BN particles used in this investigation is hexagonal, similar to the graphite, and the atoms between the (0 0 0 1) faces are linked weakly by the Van der Waal's force, in addition, the oxidation resistance of BN is much better than that of graphite at the high temperature, so this kind of BN particle is a good self-lubricant for application in wear and friction purposes. With the addition of hexagonal BN particle to material, there is a conflict of effect between mechanical and tribological properties. On the one hand, the addition of BN particles to the composites is markedly detrimental to the mechanical properties as given in Figs 2 and 3, while on the other, the wear rate and coefficient of friction of hybrid composites with the addition of BN particles is decreased simultaneously due to the self-lubricant of BN particles. These data illustrate the need to balance material characteristics and the product requirements by adjusting the volume fraction of alumina fibre and BN particle.

In the present work, the coefficient of friction of all the composites is decreased with increasing the applied load, especially for the hybrid composites, which is probably related to the smearing process of BN particles during dry sliding, similar to the graphite–aluminium composites [11, 12]. The larger the applied load is, the greater the area covered by the smeared BN, the smaller the coefficient of friction is.

5. Conclusions

1. Al_2O_3 fibre–BN particle hybrid composites can be produced by the centrifugal force infiltration route.
2. The ultimate compressive strength and hardness of the hybrid composites containing alumina fibres and hexagonal BN particles is lower than that of the composites reinforced only with alumina fibres.
3. The wear rate and coefficient of friction of the hybrid composites was decreased simultaneously with the addition of hexagonal BN particles, especially for higher loads in the test. For the 4 vol % BN hybrid composites, the mean value of the coefficient of friction of hybrid MMCs was decreased by 31% in comparison with that of the composite reinforced only with Al_2O_3 fibre, and the wear rate of the hybrid composites (5, 8 and 12% fibre) was 46, 41 and 27% lower than that of the composites reinforced only with alumina fibre at the applied load of 150 N.

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