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Dry sliding tribological properties of self-mated couples of B_4C-hBN ceramic composites

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ABSTRACT

In this paper, dry sliding tribological properties of self-mated couples of B_4C-hBN ceramic composites containing different amounts of hBN have been evaluated using a pin-on-disc friction and wear machine, and the worn surfaces of B_4C-hBN specimens have been observed and analyzed by scanning electron microscope (SEM). It is found that the dry sliding tribological properties of self-mated couples of B_4C-hBN ceramic composites take on obvious regularity: with hBN content increasing, the friction coefficient gradually decreases, but the wear coefficient gradually increases. The decrease of friction coefficient could be largely attributed to the formation of a transfer film formed on the wearing surface of the B_4C-hBN specimens. The formation of the film is investigated.

1. Introduction

Boron carbide (B_4C) is considered as the third hardest material in the world. In addition, B_4C also possesses many other excellent physical and mechanical properties such as low density, high strength, high melting point, high cross section for neutron absorption as well as good chemical inertness. This paves the way for use of B_4C in the fields of nozzles, bearings, sealing elements, high-speed cutting tools, aerospace, nuclear industry, and so on [1–15].

However, the widespread use of B_4C has been limited due to its poor tribological behavior. In recent years, more and more attention has been paid to the tribological performance of B_4C. Gogotsi et al. [16] pointed out that the friction coefficient of B_4C/45 steel friction pair could decrease from 0.4–0.8 at the sliding speed of 6 m s^{-1} or less to 0.12–0.16 at the sliding speed of 10 m s^{-1} or more. The primary cause for the decrease of friction coefficient was the formation of liquid B_2O_3 and graphite on the friction surfaces at higher sliding speed (10 m s^{-1} or more). Umeda et al. [17] found that the friction coefficient of self-mated B_4C could decrease from 0.95 to 0.25 when the testing relative humidity increased from 10% to 95%, however, the antifriction mechanism was unknown. Moreover, the tribological behavior of B_4C/ZrO_2 pair has been tested by Erdemir et al. and the friction coefficient was 0.3–0.4 [18]. Also Erdemir et al. [19] has studied on the friction behavior of B_4C/440C steel balls sliding pair, and found that, with increasing sliding distance, the friction coefficient increased from 0.3 to 0.7. From above literatures, it can be seen that the friction coefficient of B_4C pairs was normally in the range of 0.2–0.9, which is higher than the application criteria of friction materials proposed by Czichos et al. [20]. It is generally known that adding a second phase into ceramic matrix is an effective method to improve the properties of ceramics. As a famous solid lubricant, hexagonal boron nitride (hBN) has been used to enhance the lubricity of some types of ceramic.

Skopp et al. [21] has investigated the tribological properties of self-mated Si_3N_4-hBN ceramic composites and found that the friction coefficient decreased by 0.1 when the amount of hBN was increased from 5 wt% to 20 wt%. Also, Chen et al. [22] researched the tribological behavior of SiC-hBN/SiC ball pair at elevated temperature. It was found that SiC-hBN/SiC ball pair possessed a smaller wear coefficient and a lower friction coefficient than SiC/SiC ball pair at 800 °C. The preceding work of our project group found that hBN has a great influence on the tribological properties of B_4C ceramic under dry sliding condition. The friction coefficient of B_4C-hBN/B_4C sliding pair decreased from 0.586 to 0.179 when the amount of hBN was increased from 0 wt% to 20 wt%, which could be attributed to the formation of an H_3BO_3 lubricating film on the worn surface of the B_4C-hBN specimen [23]. However, the tribological behavior of self-mated couples of B_4C-hBN ceramic composites under dry sliding condition has not been reported so far.

In this work, the tribological properties of self-mated couples of B_4C-hBN ceramic composites under dry sliding condition were studied

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using a pin-on-disc type friction and wear tester. Furthermore, the worn surfaces of B4C-hBN specimens are observed and analyzed, and the wear mechanism is discussed. This investigation could offer some useful information on the engineering application of B_4C-hBN ceramic composites.

2. Experimental procedures

B_4C powder (purity: 99%; average particle size: 1.5 µm) and hBN powder (purity: 99%; average particle size: 1.5 µm) were used as raw materials to prepare B_4C-hBN ceramic composites using hot pressing technique, and Al_2O_3 powder (purity: 99.99%; average particle size: 0.5 µm) and Y_2O_3 powder (purity: 99.99%; average particle size: 20–30 nm) were used as sintering aids. First, the powder mixture was ball-milled in plastic bottles for 24 h using Al_2O_3 balls and absolute ethyl alcohol as the milling media. Then, co-evaporating method was used to clear away the absolute ethyl alcohol in order to minimize liquation during drying process. After that, the powders were sintered by hot-press in argon atmosphere. The main hot press parameters are: axial load 35 MPa, temperature 1800 °C, dwell time 60 min. The B4C matrix ceramic composites with 0, 5, 10, 20 and 30 wt% hBN are denoted by BC0, BC5, BC10, BC20 and BC30, respectively.

Density was determined using Archimedes' method. Bending strength was measured through three-point bending method on 3 mm×4 mm×36 mm bars with a span length of 30 mm at a cross-head speed of 0.5 mm min^{-1}. Microhardness was tested by Vickers' indentation with an applied load of 1 kg for a dwell time of 15 s. Fracture toughness was calculated by using Niihara et al. equation for Palmqvist cracks. Each measurement was repeated five times, and the data averaged. The corresponding results are shown in Table 1. It can be seen from Table 1 that, with the increase of hBN content, the density, bending strength, Vickers hardness and fracture toughness of sintered B_4C-hBN ceramic composites as a whole decrease.

Dry sliding tests were carried out on a pin-on-disc friction and wear machine, the experimental principle of which is shown in Fig. 1. Both pins and discs were taken from BC0–BC30. The size of pin specimen is 5 mm×5 mm×12 mm and one end polished to a hemisphere surface with a diameter of 5 mm. The size of disc specimen is 6 mm in thickness and 44 mm in diameter. The surfaces of both the pins and the discs were ground and polished to R_a=1.0 µm. Before wear test, the specimens were dipped into acetone and cleaned with ultrasonic washer for 10–15 min and then dried thoroughly in a vacuum drying oven. The normal load is 10 N, the sliding speed is about 0.656 m s^{-1}, and the sliding distance is 800 m. The ambient temperature and relative humidity were 25 °C and 50%, respectively.

During sliding test, friction force can be measured and automatically converted into friction coefficient by data processing software. Wear volume losses (ΔV) for pin and disc are evaluated by means of the following: for pin, two perpendicular diameters on worn surface were measured using a laser scanning profilometer and then ΔV can be calculated according to averaged diameter and initial tip radius; for disc, four cross-sectional areas on wear scar, each at 90° with respect to the previous one, are measured using a laser scanning profilometer. The four areas were averaged and multiplied by the wear scar length to get ΔV. Then, the wear coefficients (k) of pin and disc can be worked out via Eq. (1):

$$k = \frac{\Delta V}{PS} \tag{1}$$

where P is the applied load, and S is the total sliding distance. Friction coefficients and wear coefficients for each friction pair were the mean of the value of three repeated tests. The worn surfaces of the B_4C-hBN specimen were observed and analyzed by scanning electron microscope (SEM).

Table 1
The physical and mechanical properties of sintered B_4C-hBN ceramic composites.

Specimens	BC0	BC5	BC10	BC20	BC30
hBN amount (wt%)	0	5	10	20	30
Density (g cm^{-3})	2.568	2.534	2.496	2.475	2.406
Bending strength (MPa)	420	397	386	352	321
Vickers hardness (GPa)	28.34	22.25	17.31	11.42	8.94
Fracture toughness (MPa $m^{1/2}$)	5.62	5.09	4.65	4.41	3.85

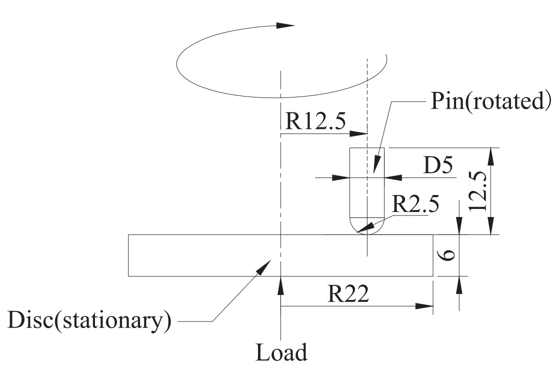

Fig. 1. Schematic diagram of the pin-disc type wear tester.

3. Results and discussion

Fig. 2 presents the steady-state friction coefficients and the complete set of the wear coefficients of self-mated couples of B_4C-hBN ceramic composites. It can be easily seen from Fig. 2 that, with hBN content increasing, the steady-state friction coefficients of the B_4C-hBN/B_4C-hBN sliding pairs decrease significantly, however, the wear coefficients of the B_4C-hBN/B_4C-hBN sliding pairs as a whole increase.

SEM was used to observe the worn surface morphology of self-mated couple of BC0 specimen, and the worn surface morphology of the pin is shown in Fig. 3. It can be seen from Fig. 3 that, some abrasive dusts can be found on the worn surface of the BC0 pin and the worn surface reveals micro-cutting. For self-mated couple of BC0 specimen, fracture occurs on the wear surfaces at the beginning stage of the friction process. The wear debris had nowhere to go and mainly accumulated on the wearing interface, leading to abrasive wear. So, the tribological behavior of self-mated couple of BC0 specimen is poor.

With the increase of hBN content, the mechanical properties of sintered B_4C-hBN ceramic composites as a whole decrease (see Table 1). On one hand, during the wear test, hBN tends to detach from the B_4C ceramic matrix and then the spalling of ceramic grains occurs on the hBN congregating area, resulting in subsequent formation of spalling pits on the wearing surface of the specimens. Fig. 4 presents the worn surface morphology of the BC5 pin and the BC10 pin after strong cleaned. From Fig. 4, it can be seen that there exist many spalling pits on the worn surfaces, and spalling pits become more with the increase of hBN content.

On the other hand, as the mechanical properties of sintered B_4C-hBN ceramic composites increase with the increase of hBN content, during the friction process, more and more abrasive dusts would be produced due to the cause of brittle fracture. The wear debris on the wear surface might accumulate in the spalling pits, which could weaken the effect of abrasive wear. Meanwhile, the wear debris accumulated on the wearing surface might be constantly crushed, resulting in the formation of a transfer film. With the increase of hBN content, the transfer film inclines to integrate and connect into