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Tribological properties of hot-pressed boron carbide ceramic①

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[Abstract] Sliding friction experiments were conducted on hot-pressed B_4C ceramic under the condition of sliding contact with themselves in air. The tests were run at average sliding velocity of 1.41 m/s and normal forces ranging from 11.8 N to 37.6 N. The friction coefficients decrease with the increase of sliding distance and the increase of normal load. The lowest friction coefficient is as low as 0.09, compared to 0.35~ 0.40 as the initial friction coefficient. X-ray diffraction was used to analyze the sliding surface before and after friction tests. The results show that the tribochemical reaction between B_4C and O_2 produces B_2O_3, and B_2O_3 undergoes a secondary chemical reaction with moisture in the air to form H_3BO_3, which is responsible for the lower friction coefficients. The low-friction mechanism of boric acid is associated with its layered-triclinic-crystal structure. The atoms on each layer are closely packed and strongly bonded to each other, but the layers are widely separated and are held together by van der Waals force. Regarding the wear rate of B_4C ceramics used in friction experiments, there is not any wear could be measured by using a surface profilometer.

[Key words] boron carbide; friction coefficient; wear; tribochemistry

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1 INTRODUCTION

Boron carbide (B_4C) is a well-known ceramic suitable for a wide range of industrial applications. It is one of the hardest known materials and has high elastic modulus, high melting point and low specific gravity. Its industrial uses include grinding wheels for sharpening cutting tools, super-abrasives in polishing and grinding media, and fibers for reinforced ceramic composites. Because of its low specific gravity and high-resistance to piercing, it has also been used as a lightweight armor material[1,2].

Another kind of important application of hot-pressed boron carbide ceramic is the gas-bearing components operating in ambient atmosphere[3]. Whenever the starting and stopping of an operation, boron carbide components are sliding over each other, which becomes a self-friction pair. The primary goal of this paper is to describe a series of sliding tests of hot-pressed boron carbide ceramic to examine its tribological behavior in the type of environment in which gas bearing applications are likely.

2 EXPERIMENTAL

2.1 Test specimens

The test pieces used in the study were fabricated from B_4C by a hot-pressed method at a temperature of 2 323~ 2 423 K for 100 s and at a pressure of about 40 MPa in ambient atmosphere. Their physical properties are shown in Table 1. Before the sliding tests, their test surfaces were finished with paste containing diamond powders (≈ 1 μm) using an iron lapping plate. The surfaces were then thoroughly washed in an ultrasonic cleaner with acetone, followed by boiling for 10 min in distilled water, and finally dried in the air. Their average surface roughness (R_a) was of 0.2 μm.

Table 1 Properties of boron carbide materials specimen

Density /(kg·m^{-3})	Bending strength/MPa	Knoop hardness/GPa	Grain size/μm	Porosity /%
2 500~ 2 510	510~ 520	29.5~ 30.0	< 1	< 0.1

2.2 Friction tests

Friction tests were performed with boron carbide pair in a ring-on-disk tribometer. The configuration and the specimen size are shown in Fig. 1. The disk is firmly secured to a stationary holder and the ring is attached to a horizontal chuck driven by an electric motor. Frictional force is monitored by a linear-voltage displacement transducer attached to the disk holder and is continuously recorded by an *X-Y* recorder. All tests were performed at room temperature (about 23 ℃) in open air with relative humidity of 40% ~ 50%. Normal forces applied to the B_4C ring were 11.8 N, 18.6 N, 22.7 N, 30.8 N and 37.6 N, respectively. Since the rotational speed being kept to constant of 1 500 r/min, the sliding velocity varied as the wear track diameter varied. The average sliding velocity was 1.41 m/s. The sliding distance was 2 000 m, but for measuring wear rate, the sliding

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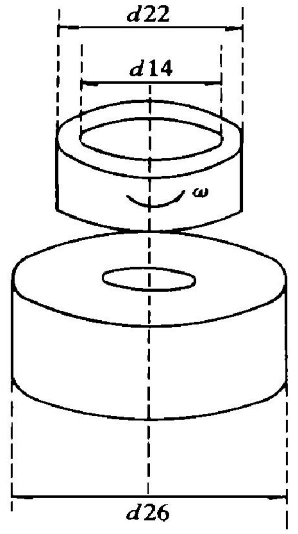

Fig. 1 Configuration and size of specimens pair for sliding test

distance was 10 000 m. X-ray Diffractometer 3014 Type was used to analyze the sliding surfaces before and after sliding tests. The profiles of worn surfaces of the disks were measured with a surface profilometer Talysurf 5-120.

3 RESULTS AND DISCUSSION

3.1 Effect of sliding distance on coefficient of friction

Fig. 2 shows the friction coefficients of boron carbide test pairs under normal loads of 11.8 N, 18.6 N, 22.7 N, 30.8 N, 37.6 N, respectively, as a function of the sliding distance. The friction coefficient under 11.8 N load is initially about 0.35 ~ 0.40, decreases during successive sliding and stabilizes at about 0.25. At a load of 18.6 N, the friction coefficient decreases with sliding distance from 0.30 ~ 0.35 to 0.20 and remains relatively unchanged. With a load of 22.7 N, the friction coefficient is approximately 0.23, but decreases with sliding to about 0.18 at steady state. Under load of 30.8 N, the friction coefficient of initial stage is approximately 0.20, and decreases with sliding to about 0.13 at steady state. With a load of 37.6 N, the initial friction coefficient is approximately 0.12 but decreases rapidly

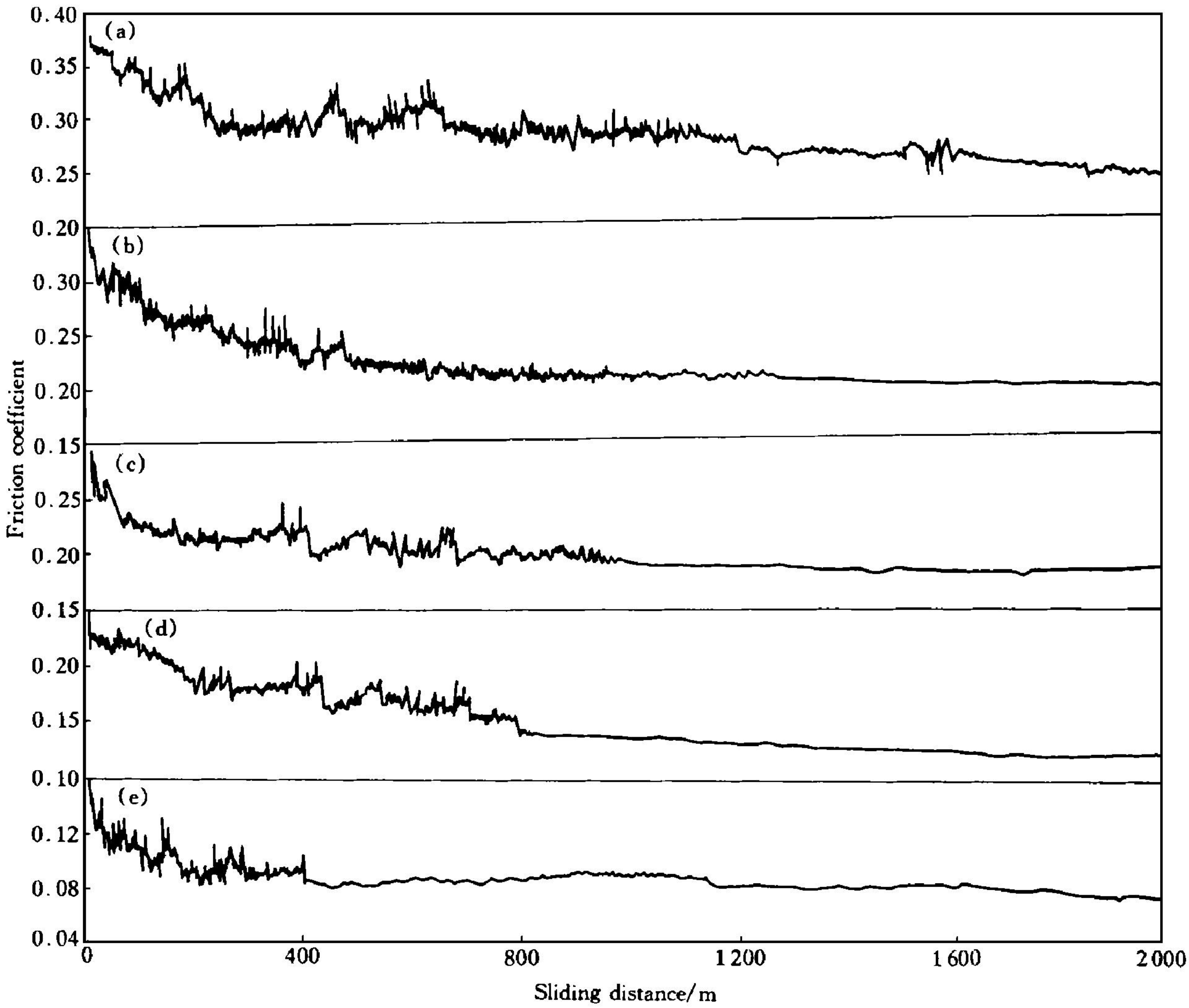

Fig. 2 Effect of sliding distance on coefficient of friction
(a) —11.8 N; (b) —18.6 N; (c) —22.7 N; (d) —30.8 N; (e) —37.6 N

and stabilizes at about 0.09.

Fig. 3 is the X-ray diffraction spectra of before and after friction test on B_4C surfaces under the load of 37.6N. As is clear, before and after the friction test, B_4C surface has a very different X-ray diffraction feature. B_2O_3 and H_3BO_3 appeared on the friction tested surface. It is elucidated that the tribochemical reaction happened as[4, 5]

$$B_4C + 4O_2 \longrightarrow 2B_2O_3 + CO_2 \quad (1)$$

Because of a negative standard heat of reaction, boron oxide reacts spontaneously with moisture in open air and becomes boric acid (H_3BO_3). This reaction is given as

$$B_2O_3(s) + 3H_2O(g) \longrightarrow 2H_3BO_3(s) \quad (2)$$

$$\Delta H^{\ominus}_{298K} = -90.2 kJ/mol$$

The boric acid formed on the friction interface has a layered crystal structure. The layers consist of strongly bonded boron, oxygen, and hydrogen atoms. The atomic layers are 0.318 nm apart and held together by van der Waals force[6]. When a surface film with lamellar structure as boric acid is presented at a sliding interface, the atomic layers align themselves parallel to the direction of relative motion; they can then slide over one another with relative ease to give low friction as shown in Fig. 2. In short, friction coefficients decrease with sliding distance are the direct consequences of sequential formation of, first, a B_2O_3 layer and then an H_3BO_3 film during the sliding by tribochemical reaction, and by reaction with the moisture in air, respectively. H_3BO_3 has a layered crystal structure similar to those of the MoS_2 and graphite[7], when presents at sliding interface all shear easily and provides low friction.

3.2 Effect of normal load on friction coefficient and initial friction coefficient

Fig. 4 and Fig. 5 show the initial friction coefficient and friction coefficient of boron carbide test pair as a function of the normal loads. And the very initial friction coefficients are quite high. The friction coefficients and the coefficients of initial friction decrease with increasing normal load. These observations contradict Amonton's law of friction, which states that the friction coefficient of a sliding interface is independent of contact pressure. However, load-dependent friction behavior has often been reported for materials. A details study of the phenomenon by Singer et al[8] has provided further evidence that the friction coefficient of sliding pair with a layered solid lubricant film, i.e. MoS_2, decreases with increasing

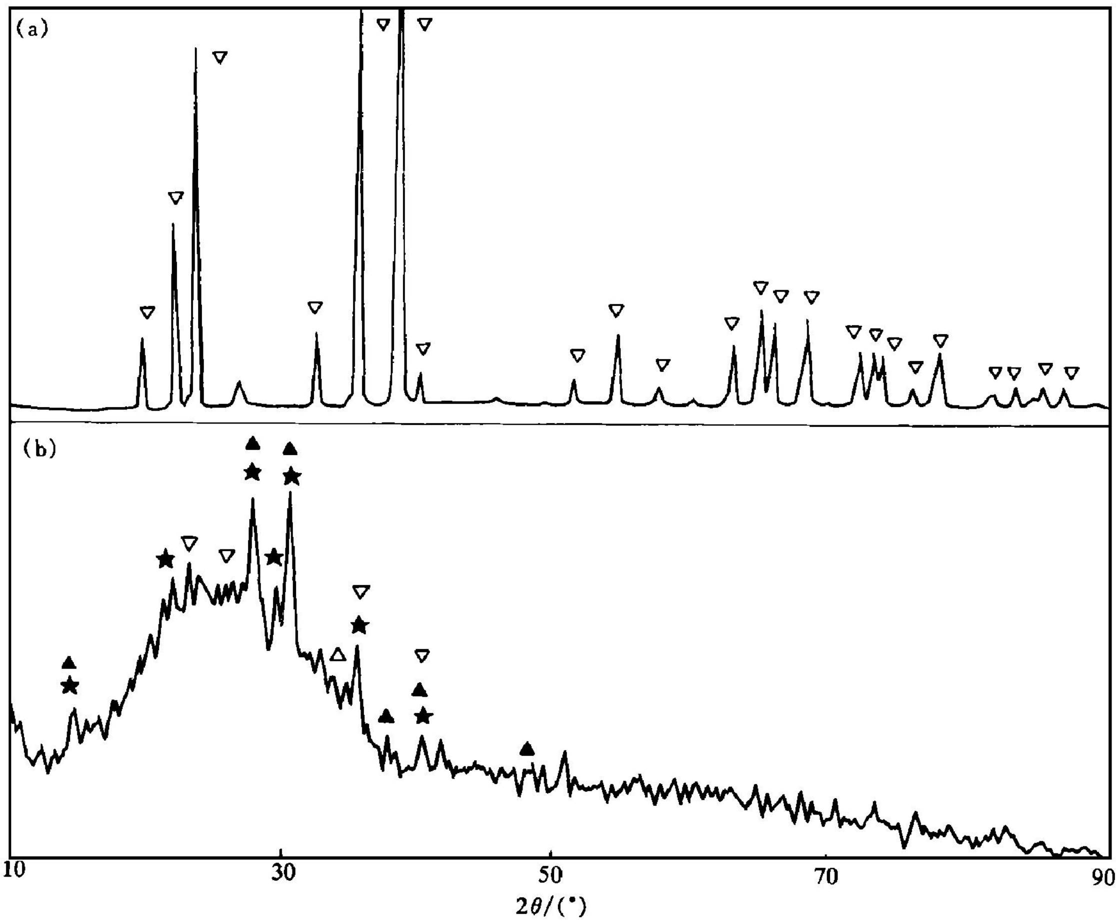

Fig. 3 X-ray diffraction spectra of before and after friction test B_4C surfaces

▽—B_4C; ▲—B_2O_3; ★—H_3BO_3

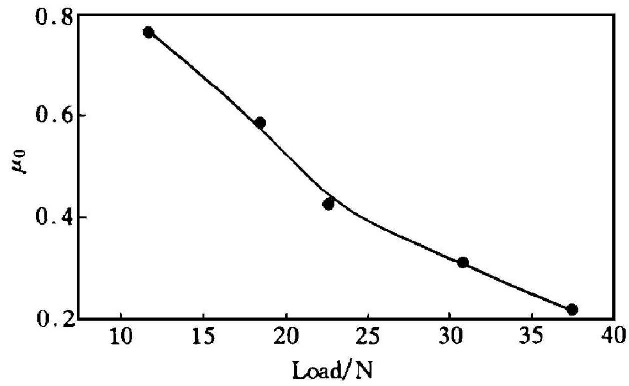

Fig. 4 Effect of normal load on initial friction coefficient (μ_0)

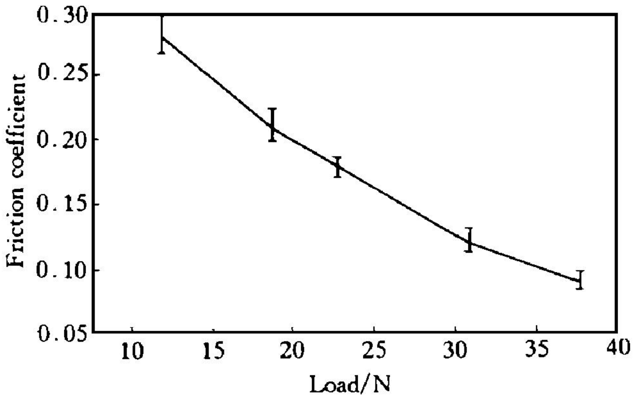

Fig. 5 Effect of normal load on friction coefficient (μ)

contact pressure. Erdemir et al[9, 10] observed a similar trend in the friction coefficients of steel-steel and ceramic-ceramic pair with a boric acid film at the sliding interfaces.

3. 3 Wear rate of test pieces

Long sliding distance test was conducted to measure the wear rate of B_4C pair under average sliding velocity 1. 41 m/s, normal load 11. 8 N and sliding distance 10000 m. There are no mass loss verified by using analytical balance to measure the B_4C samples before and after friction tests. It indicates that the specific wear rate is less than 10^{-7} $mm^3/(N\cdot m)$.

The profiles of worn surfaces of the rings and the disks were measured with a surface profilometer Talysurf 5-120. An interesting phenomenon is that rather than being rougher after friction tests, the surfaces of B_4C are finished during the sliding, i. e. before friction tests, the degree of finishing of B_4C surfaces is $R_a = 0.2\,\mu m$, but after friction tests, they become $R_a \leqslant 0.15\,\mu m$. Boron carbide ceramic shows a self-finishing behavior.

4 CONCLUSIONS

1) Under the test conditions of this study, friction coefficient of hot-pressed B_4C-B_4C pair decreases with increasing sliding distance and with increasing normal load. It changes from 0. 35~ 0. 4 under 11. 8 N load at initial stage to 0. 09 under 37. 6 N load at steady state.

2) X-ray diffraction of friction interfaces verifies the presence of B_2O_3 and H_3BO_3 on the tested sliding tests B_4C friction surfaces. Mechanistically, it is proposed that the low friction is due to the formation of layered crystal structure of H_3BO_3.

3) The wear rate of the hot-pressed B_4C-B_4C ceramic pair under the test condition is negligible. And an interesting phenomenon is that boron carbide ceramic has a self-finishing property.

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