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Friction and wear properties of spark-plasma-sintered α-AlB_{12} and SiB_6 powder compacts in water

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ABSTRACT

In our present study, α-AlB_{12} and SiB_6 powder compact disk specimens were prepared by spark plasma sintering α-AlB_{12} and SiB_6 powders, respectively, and their X-ray diffraction patterns, microstructures, Knoop hardnesses were examined. Also, the friction and wear properties of the α-AlB_{12} and SiB_6 powder compact disk specimens were investigated when they were slid against Si_3N_4 ball specimens in water. Both the α-AlB_{12} and SiB_6 powder compact disk specimens exhibited friction coefficients lower than 0.1 while the blended elemental Al-92.3 at% B and Si-85.7 at% B powder compact disk specimens exhibited friction coefficients between 0.1 and 0.2. The specific wear rates of the α-AlB_{12} and SiB_6 powder compact disk specimens were lower than those of the blended elemental Al-92.3 at% B and Si-85.7 at% B powder compact disk specimens, respectively.

1. Introduction

Lubrication with water has been receiving attention in industries related to water pumps, food machinery and medical devices [1] because water is an ecological material. Currently, Si_3N_4-, α-Al_2O_3-, SiC-based ceramics are generally used as the sliding materials in such water-lubricated systems. In particular, a report has shown that Si_3N_4–Si_3N_4 and SiC–SiC tribopairs exhibited friction coefficients lower than 0.01 in water after sliding 1000 m and 4000 m, respectively [2]. However, these Si_3N_4–Si_3N_4 and SiC–SiC tribopairs exhibited friction coefficients higher than 0.5 immediately after the sliding began [2]. These tribopairs also exhibited friction coefficients higher than 0.5 at low sliding speeds under boundary lubricating conditions. Moreover, it has been reported that α-Al_2O_3–α-Al_2O_3 tribopairs exhibited relatively high friction coefficients in water. Saito et al. have reported that hexagonal BN–hexagonal BN tribopairs exhibited friction coefficients lower than 0.1 because low friction H_3BO_3 films with layered crystal structures had been formed on the worn surfaces through the following reactions (1) and (2) [3,4].

$$2BN+3H_2O\rightarrow B_2O_3+2NH_3 \quad (1)$$

$$B_2O_3+3H_2O\rightarrow 2H_3BO_3 \quad (2)$$

However, the hexagonal BN–hexagonal BN tribopairs exhibited low wear resistance in water. Their specific wear rates were as high as 10^{-4}–10^{-5} $mm^3/N\,m$ [3,4].

On the other hand, it was found in our previous study that α-AlB_{12}- and SiB_6-based ceramic disk specimens, which were prepared by spark plasma sintering blended elemental Al-92.3 at% B and Si-85.7 at% B powders, respectively, exhibited friction coefficients lower than 0.2 when they were slid against the Si_3N_4, α-Al_2O_3 and SiC ball specimens in water [5]. Also, the α-AlB_{12}- and SiB_6-based ceramic disk specimens in our study exhibited specific wear rates as low as 3.0×10^{-6} $mm^3/N\,m$. It is considered that the low friction coefficients of the α-AlB_{12}- and SiB_6-based ceramic disk specimens were due to the formation of low friction H_3BO_3 and $Al(OH)_3$ films with layered crystal structures [6] and low friction $Si(OH)_4$ gels on the worn surfaces. On the other hand, it is considered that the low specific wear rates of the α-AlB_{12}- and SiB_6-based ceramic disk specimens were due to their hardness higher than that of Si_3N_4 and Al_2O_3 [7–11].

However, the α-AlB_{12}- and SiB_6-based ceramic disk specimens contained a large amount of oxide phases because the blended elemental active Al-92.3 at% B and Si-85.7 at% B powders absorbed a small amount of oxygen during the spark plasma sintering although the sintering was performed in an Ar gas atmosphere. It is considered that sintering α-AlB_{12} and SiB_6 powders, not blended elemental powders, reduces the oxygen contamination because the α-AlB_{12} and SiB_6 forming reactions from the blended elemental Al-92.3 at% B and Si-85.7 at% B powders may promote their respective oxidation reactions. If the α-AlB_{12} and SiB_6 forming reactions are exothermic, the temperatures of the blended elemental Al-92.3 at% B and Si-85.7 at% B powders increase. The increase in the powder temperature generally promotes the oxidation reaction of the powder sample. On the other hand,

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H_3BO_3 films could not be detected on the worn surfaces of the α-AlB_{12}- and SiB_6-based ceramic disk specimens by x-ray photoelectron spectroscopy (XPS). Before the XPS analyses, both the α-AlB_{12}- and SiB_6-based ceramic disk specimens were cleaned in a mixture of 50 vol% acetone and 50 vol% petroleum benzene for 1.2 ks using an ultrasonic cleaner [12,13], and this cleaning might have removed the H_3BO_3 films.

In our present study, α-AlB_{12} and SiB_6 powder compact disk specimens were respectively prepared by spark plasma sintering commercially available α-AlB_{12} and SiB_6 powders, and their x-ray diffraction patterns, microstructures, Knoop hardnesses and friction and wear properties in water were examined.

2. Experimental procedures

The α-AlB_{12} and SiB_6 powder compact disk specimens with a diameter of 15 mm and a thickness of 3 mm were prepared in our present study by spark plasma sintering 99.8% pure α-AlB_{12} and 98% pure SiB_6 powders (Furuuchi Chemical Co., Ltd.), respectively, using a Sumitomo Coal Mining SPS-515 spark plasma sintering machine under the conditions shown in Table 1. Blended elemental Al-92.3 at% B and Si-85.7 at% B powder compact disk specimens were also prepared by spark plasma sintering as references. The Al-92.3 at% B and Si-85.7 at% B correspond to the compositions of α-AlB_{12} and SiB_6, respectively [14,15]. The blended Al-92.3 at% B powder was prepared by blending 99.9% pure Al powder (Rare Metallic Co., Ltd.) with a particle size of 3 μm and 99.9% pure B powder (Furuuchi Chemical Co., Ltd.) with a particle size of less than 1 μm in a hexane-filled standard ball mill for 18 ks. In the same way, the blended Si-85.7 at% B powder was prepared by blending the B powder and 99.99% pure Si powder (Furuuchi Chemical Co., Ltd.) with a particle size of less than 104 μm. After the spark plasma sintering, the surface of each disk specimen was polished using diamond paste with a particle size of 1 μm. Then all of the disk specimens were cleaned in a mixture of 50 vol% acetone and 50 vol % petroleum benzene (Kanto Chemical Co., Inc.) for 1.2 ks using an ultrasonic cleaner [12,13]. The Knoop hardness of each disk specimen was measured 20 times using a Shimadzu HMV-1 hardness tester at a load of 9.8 N and a loading time of 15 s while the x-ray diffraction pattern of each disk specimen was investigated using a Rigaku RINT-2000 X-ray diffractometer. In addition, the cross sections of each disk specimen were observed using a JEOL JSM-7400F scanning electron microscope (SEM) with an energy dispersive spectroscopy (EDS) attachment. Furthermore, differential thermal analysis (DTA) curves of the blended elemental Al-92.3 at% B and Si-85.7 at% B powders in an Ar gas atmosphere were obtained using a SETARAM TG-DTA 96 instrument at a heating speed of 10 °C per minute in order to investigate the respective AlB_{12} and SiB_6 forming reactions.

The friction and wear properties of each disk specimen sliding against the Si_3N_4 ball specimen were investigated twice using a Rhesca FPR 2001 rotating ball-on-disk tribometer. The diameters of the Si_3N_4 ball specimens were 9.52 mm, and their micro-Vickers hardness at a load of 9.8 N for a loading time of 15 s was 16.4 GPa. In each friction and wear test, the disk specimen was immersed in 100 ml of water, and the water was not replenished during the test. The friction and wear testing conditions were as follows; load: 9.8 N, sliding speed: 1.57 mm/s, testing time: 3.6 ks, and temperature: 25 °C. The specific wear rates of the disk specimens and the ball specimens were calculated using a Tokyo Seimitsu SURFCOM surface profilometer and a Shodensya GR3400J optical microscope [12,13,16–18]. In addition, the worn surfaces of each disk specimen were observed using a JEOL JSM-7400F SEM with an EDS attachment. Also, the worn surfaces of the α-AlB_{12} and SiB_6 powder compact disk specimens were examined using a Thermo VG Theta Probe XPS.

3. Results

Fig. 1 shows the DTA curves of the blended elemental Al-92.3 at % B and Si-85.7 at% B powders. Both of the DTA curves contained exothermic reactions, which indicate that the sintering of the α-AlB_{12} and SiB_6 powders, not the blended elemental powders, would reduce the oxygen contamination because the α-AlB_{12} and SiB_6 forming exothermic reactions are thought to increase the sample temperature and promote the oxidation reactions of the blended elemental powders. Al, B and Si contents oxidize very easily, and that their oxidation rates increase with the temperature as shown in an Ellingham diagram [19].

Fig. 2 shows the XRD patterns of the α-AlB_{12} and SiB_6 powder compact disk specimens and the blended elemental Al-92.3 at% B and Si-85.7 at% B powder compact disk specimens. The blended elemental Al-92.3 at% B powder compact disk specimen was composed of α-AlB_{12} and α-Al_2O_3 phases. It is considered that the α-Al_2O_3 phase was formed by the oxidation reaction of Al content in the blended elemental powder during sintering. On the other hand, only the α-AlB_{12} phase was observed in the α-AlB_{12} powder compact disk specimen, which indicates that sintering the α-AlB_{12} powder restrained the oxygen contamination more than

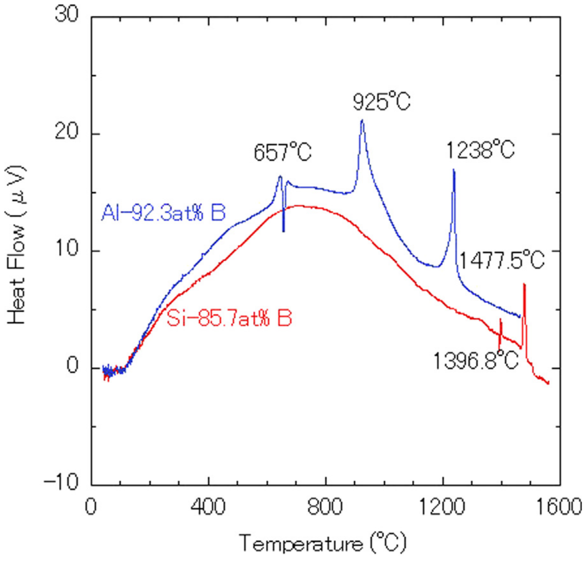

Fig. 1. DTA curves of the blended elemental Al-92.3 at% B and Si-85.7 at% B powders in an Ar gas atmosphere. The heating rate was 10 °C per minute.

Table 1
Spark plasma sintering conditions of α-AlB_{12} and SiB_6 powder compact disk specimens.

Specimen	Sintering temperature (°C)	Sintering pressure (MPa)	Sintering time (min)	Atmosphere
α-AlB_{12} powder compact	1800	40	20	Ar gas at 0.10 MPa
Blended elemental Al-92.3 at% B powder compact				
SiB_6 powder compact	1700			
Blended elemental Si-85.7 at% B powder compact				