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Wear mechanisms of silicon carbide subjected to ultrasonic nanocrystalline surface modification technique

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ABSTRACT

A modified surface layer with a thickness of about 4 μm was produced at the top surface of sintered silicon carbide (SiC) by ultrasonic nanocrystalline surface modification (UNSM) technique. The objective of this study is to investigate the effectiveness of modified surface layer on the tribological properties and to give insight into the wear mechanisms of SiC. The tribological properties of the untreated and UNSM-treated SiC disk specimens against silicon nitride (Si_3N_4) ceramic ball were investigated using a ball-on-disk tribometer at normal loads of 1 N, 5 N and 10 N under water-lubricated conditions. Results revealed that the friction coefficient was found to be 0.08 and 0.065 for the untreated and UNSM-treated specimens at a normal load of 1 N which may be attributed to the modified surface layer at the top surface having higher hardness and smoother roughness with a small number of porosity, respectively. This reduction in friction coefficient enables to reduce energy consumption of water-based tribological systems. Wear track analysis was conducted using a nanoscale hybrid microscopy (NHM). NHM images showed that severe polishing and grooving marks were observed on the untreated specimen, while only mild grooving marks were observed on the UNSM-treated specimen. It was also confirmed that the UNSM technique changes the wear mechanisms of SiC: oxidative-adhesive-abrasive-micro fracture wear takes place in the untreated specimen, while adhesive-abrasive wear takes place in the UNSM-treated specimen. Application of UNSM technique would be highly advantageous for water-lubricated ceramic bearings.

1. Introduction

Silicon carbide (SiC) ceramic is a refractory material that can be used in hydrostatic/aerostatic/hybrid bearings under water-lubricated conditions [1,2]. These bearings have drawn attention because of their superior characteristics, such as high load-carrying capacity, large fluid-film stiffness, high support dumping, long fatigue life, better tolerance in manufacturing, low wear from vibration and low operating temperatures compared to all-steel bearings in most applications [3]. Water-lubrication in ceramics is considered as a promising combination to replace the oil in those bearings because of the non-pollution, low viscosity of water, low coefficient of thermal expansion, low friction coefficient, high resistance to wear and other excellent properties and features. Also, water-lubricated ceramic systems are being improved due to endogenous technological development acceleration. A great deal of experimental investigation on the friction and wear behavior of SiC under water-lubricated conditions has been studied by many researchers [4–6]. Many studies have revealed that self-mated SiC and silicon nitride (Si_3N_4) sliding pairs exhibited excellent friction and wear behavior under water-lubricated conditions [7,8]. It has been found that mechanisms and improvements in the friction and wear behavior commonly associated with: hydrodynamic lubrication by a thin water-film thickness at the interface; boundary lubrication by silica (SiO_2) film formed at the interface; and mixed lubrication involving the first two mechanisms could represent a contribution to the tribo-reactions at the interface [9].

Nowadays, the continuing demand for low-energy consumption and less wear of materials by surface modification became more intense [10,11]. In this study, the effectiveness of pore-elimination and nondestructive ultrasonic nanocrsytalline surface modification (UNSM) technique on the tribological properties of SiC was investigated. This UNSM technique is a cold-forging process in which the surface of a workpiece is being struck with a single ball made of tungsten carbide (WC) and/or Si_3N_4 at a frequency of 20 kHz. It has been demonstrated that this UNSM

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technique is a simple method to produce a nanocrystalline surface layer at the top surface of metallic materials without changing the chemical composition. UNSM technique has successfully improved the tribological and increased the mechanical properties of various metallic materials and alloys [12,13]. A more detailed description of UNSM technique can be found in our previous studies [12–14]. Moreover, it is worth mentioning here that the UNSM technique has a significant effect on the mechanical, structural, and tribological properties of SiC sliding against bearing steel and alumina (Al_2O_3) ceramic at various temperatures under dry and oil-lubricated conditions, respectively. [15,16]. However, in spite of excellent results, there is still a lack of knowledge about the effectiveness of UNSM technique on the tribological properties and wear mechanisms of SiC ceramic under water-lubricated conditions.

It is well known that pores often exist in many materials produced by material manufacturing processes such as sintering, casting, etcetera. Some pores may be eliminated, while some would be finally left in grain boundaries or within grains if migration of boundaries is too fast. Pores are a little bit far from grain boundaries and difficult to be completely eliminate due to long distance for diffusion. Lindstedt et al. have reported earlier that the relatively high stress concentration at pores and pore clusters is responsible for localized slip leading to crack initiation and propagation [17]. Bertillson et al. has reported that not only the total volume percentage of porosity effects on the mechanical and tribological properties, but also size, shape, depth and interconnectivity of pores play an important role in determining the final wear rate of materials [18]. In general, at high porosity, ceramics have more interconnected pores, low strength and high wear rate. Tough good hardness is required for resistance against abrasive and adhesive wear, higher elastic modulus is necessary for better resistance against Hertzian contact damage.

The tribological properties and wear mechanisms of a combination of Si_3N_4 with the UNSM-treated SiC under water-lubricated conditions are not well known yet because of the diversity and complexity in generation of modified surface layer at the top surface. In this paper, it has been reported for the first time that a modified surface layer at the top surface of SiC was produced by UNSM technique. Hence, the objective of this study is to investigate the effectiveness of UNSM technique on the tribological properties and wear mechanisms of SiC sliding against Si_3N_4 under water-lubricated conditions. As a comparison, the friction and wear behavior of as-received SiC specimen was also evaluated under identical test conditions. This work is believed to be helpful for providing guidance to tribological applications of SiC ceramic under water-lubricated medium.

2. Experimental details

2.1. Specimen preparation

The present study is based on ball-on-disk test with SiC disk sliding against Si_3N_4 ball under water-lubricated conditions. In this study, commercially available SiC (SC1000) specimens with a diameter of 24 mm and thickness of 7.9 mm were supplied by Kyocera Co., Ltd., Japan. Table 1 summarizes some mechanical properties of SiC specimens. The specimens have very high amounts of large single and interconnected pores, which exert a substantial influence on the mechanical, tribological properties and applications of ceramics. Therefore, the specimens were further subjected to UNSM technique in order to decrease the quantity of micro-pores and to reduce the surface roughness. The specimens were treated under strictly controlled UNSM treatment parameters as shown in Table 2. Prior to UNSM treatment, the specimens were cleaned in acetone $(CH_3)_2CO$ and petroleum benzene (C_6H_6) mixture (ratio 1:1) for 10 min each using an ultrasonic bath to remove the impurities and particles from the surface.

2.2. Tribological test

The tribological properties of the specimens were investigated using a ball-on-disk tribometer (HHS-2000, Heidon, Shinto Scientific Co., Ltd., Japan). The schematic view of a tribometer is shown in Fig. 1. The Si_3N_4 ball was pressed against the SiC disk specimen using an automatic weight system and slid against disk specimen which was attached to the reciprocating disk specimen holder. All of the tests were performed at normal loads of 2 N, 5 N and 10 N and at a reciprocating speed of 5.0 mm/s with a stroke of 2.0 mm for 60 min at room temperature under water-lubricated conditions with deionized (DI) water. A certain amount of DI water was poured using a syringe. Commercially available Si_3N_4 ball with a diameter of 2.0 mm was used as the counter surface. Each specimen was tested at least three times due to the data scattering.

2.3. Surface characterization

The surface morphology of the specimens was observed using an atomic force microscopy (AFM; SPA-400, Seiko, Japan), while the wear track and its surface roughness that formed after tribological tests on the surface of the specimens were investigated using a nanoscale hybrid microscopy (NHM; KEYENCE VN-8010, Japan). The modified surface layer at the top surface of the specimen by UNSM technique was observed using a field-emission scanning electron microscopy (FE-SEM; ZEISS SUPRA 40, Germany). Chemical composition of the specimens before and after tribological tests was investigated using an energy dispersive X-ray spectroscopy (EDS; RÖntec QuanTax QX1, Germany) system installed in a FE-SEM. All of the specimens were weighted to 0.0001 g on an electronic balance which was calibrated using an internal calibration routine. Bulk densities of the specimens were then calculated using the geometric volume and mass. The specific wear rate and the corresponding standard deviation were quantified as the ratio of wear volume loss over the normal load multiplied by total reciprocating sliding distance.

Table 2
UNSM treatment parameters.

Frequency, kHz	Amplitude, μm	Horn speed, m/min	Impact load, N	Interval, μm	Ball diameter, mm
20	30	3	60	70	2.38

Table 1
Some properties of the untreated SiC specimen used in this study.

Material	Preparation method	Hardness, GPa	Young's modulus, GPa	Poisson's ratio	Bulk density, g/cm^3	Fracture toughness, $MPa \times m^{1/2}$
SiC	P/M	23	440	0.17	3.16	2∼3[a]

[a] Fracture toughness of SiC ceramic was evaluated using a single edge pre-cracked beam (SEPB) method.