Friction and wear properties of CN$_x$/SiC in water lubrication

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Amorphous carbon nitride coatings (a-CN$_x$) were deposited on SiC disk by ion beam assisted deposition (IBAD). The tribological behavior of a-CN$_x$ coating sliding against SiC ball in water was investigated and compared with that of SiC/SiC system at room temperature. The influences of testing conditions on friction coefficient and specific wear rate of both kinds of tribo-pairs were studied. The worn surfaces on disks were observed by scanning electron microscope (SEM). The results indicate that the running-in period of a-CN$_x$/SiC was shorter than that of SiC/SiC system in water. At a sliding velocity of 120 mm/s, the mean steady-state friction coefficients of SiC/SiC (0.096) was higher than that of a-CN$_x$/SiC (0.05), while at 160 mm/s, lower friction coefficient (0.01) was obtained for SiC/SiC in water. With an increment of normal load, the mean steady-state friction coefficients after running-in first decreased, reaching a minimum value, and then increased. For self-mated SiC, the specific wear rate of SiC ball was a little higher than that of SiC disk, while for a-CN$_x$/SiC, the specific wear rate of SiC ball were 10 times smaller than that of a-CN$_x$ coating. Furthermore, the specific wear rate of SiC ball sliding against a-CN$_x$ coating was reduced by a factor up to 100–1000 in comparison to that against SiC in water. The wear mechanism of SiC/SiC system in water is related to micro-fracture of ceramic and instability of tribochemical reaction layer. Conversely, wear mechanism for a-CN$_x$/SiC is related to formation and transfer of easy-shear friction layer.

KEY WORDS: amorphous carbon nitride coatings, SiC ceramic, friction, wear, water lubrication

1. Introduction

Due to excellent mechanical and chemical properties, SiC ceramics are increasingly used in tribological applications such as mechanical face seal rings, journal bearings, valves, nozzles, rotors, cutting tools, etc. [1]. Until now, most research about ceramic friction under water lubrication is focused on low friction behavior and its mechanism [2–12]. Although SiC ceramics have high corrosion resistance or chemical inertness under static conditions, they will undergo tribochemical reactions and suffer more severe wear during sliding in water [2,8–10,12]. Currently, there are two methods to enhance the anti-wear ability of SiC ceramics in water: (1) the addition of TiC and TiB$_2$ [11,12]; (2) surface coating [13–17]. When SiC–TiC and SiC–TiC–TiB$_2$ composites slid against SiC ball in water, the wear volumes of disk and ball in SiC/composites system were eight and four times smaller than those in SiC/SiC tribo-couples, respectively. The friction coefficient of SiC/composite systems however, was higher than that of SiC/SiC tribo-couple [12]. As diamond and highly disordered or amorphous carbon/graphite layers were deposited on SiC ceramic, low friction and low wear were obtained successfully [15,17]. But due to the dissociation energy of C–C bonds in a-C film lower than that of C–N bonds in a-CN$_x$ film, the thermal and oxidative stability temperature of DLC or a-C coating was much lower than that of a-CN$_x$ [18–20]. For a-CN$_x$ coatings, many scientists have paid more attention to their micro-and macro-tribological properties in various gas environments since 1996 [21–36], but most of researches are usually related to the performance of a-CN$_x$ coatings in hard disk drive applications. It is known that the usage of DLC or a-CN$_x$ coating with water-based lubricant containing a little additive might create the new, “green” lubricant [37–42]. However, the studies on the friction and wear behavior of a-CN$_x$ coatings in water have not been carried out.

In this paper, a-CN$_x$ coatings were deposited on SiC disks using ion-beam assisted deposition (IBAD). The tribological behaviors of a-CN$_x$ coating against SiC ball (a-CN$_x$/SiC tribo-pair) in water were investigated and compared with a SiC/SiC system using ball-on-disk tribo-meters at room temperature. The influences of testing conditions on the tribological behaviors for two kinds of tribo-couples in water were studied and analyzed.

2. Experimental procedure

2.1. Coating method

The IBAD machine (Hitachi Ltd, Japan) consists of a cryogenically pumped chamber, a sputter deposition source, an electron beam evaporator, two ion guns for sputtering and mixing, respectively, and a substrate
holder (figure 1). The diameter of the ion beam irradiation area is about 80 mm. The substrate holder consists of a water-cooled copper plate and can be rotated at a speed of 4 rpm during deposition.

Prior to IBAD process, SiC disks (ϕ 30 mm × t 4 mm) were ultrasonically cleaned in acetone and ethanol for 30 min. Then, a high purify carbon target was put into the electron beam evaporator and a substrate jig with SiC disk was installed on the substrate holder with two screws. After that, the deposition chamber doors were closed and the vacuum chamber was subsequently evacuated to lower than $2.0 \times 10^{-4}$ Pa. For further cleaning, the disk surface was bombarded using nitrogen ions for 5 min. After that, a-CN$_x$ coatings were synthesized by mixing carbon vapor and energetic N ions. Energetic nitrogen ions were produced under the acceleration voltage of 1.5 kV with acceleration current density of 90 $\mu$A/cm$^2$. Carbon vapor was formed by heating carbon target with electron beam evaporator. The deposition rate was 20 A/s, which was controlled by adjusting the carbon vapor emission current. The coating thickness was 0.5 μm. The deposition parameters are in detail listed in table 1.

### 2.2. Measurement of mechanical properties of a-CN$_x$ coating

The mechanical properties of a-CN$_x$ coatings were evaluated using a Nano Indenter MZT-4T. A paraboloid diamond tip was used as indenter. At least six indent sequences were made. The resultant displacements were continuously recorded during both loading and unloading.

### 2.3. Ball-on-disk wear test

Ball-on-disk unidirectional sliding testing in water was carried out on wear test machine (figure 2). Prior to each sliding test, SiC balls with the diameter of 8 mm and two kinds of disks were ultrasonically cleaned in acetone and ethanol for 30 min. The physical properties of SiC ceramics were shown in table 2. The contact point was designed at an eccentricity of 7.5 mm from the center of the rotary motion, which created a wear track of 15 mm in diameter on disk surface. The total sliding distance was 10,368 m. All tests were performed in 23 °C, immerging distilled water in normal atmosphere condition.

The friction force was detected by load cell. The load cell voltage signals were recorded through A/D converter using a compatible PC. The wear scar diameter of each SiC ball under each condition was measured using an optical microscope. To simplify the calculations, the flat wear scar was assumed. Thus, SiC ball wear volume, $V_b$, was calculated as

$$V_b = 3.14d^4 \frac{64}{64R} \tag{1}$$

where $R$ is ball radius, $d$ is the diameter of wear scar. The cross-section area of wear scar on disk, $A$, was...