Tribochemical effects on the friction and wear behaviors of diamond-like carbon film under high relative humidity condition

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Friction and wear behaviors of diamond-like carbon (DLC) film in humid N\textsubscript{2} (RH-100\% ) sliding against different counterpart ball (Si\textsubscript{3}N\textsubscript{4} ball, Al\textsubscript{2}O\textsubscript{3} ball and steel ball) were investigated. It was found that the friction and wear behaviors of DLC film were dependent on the friction-induced tribochemical interactions in the presence of the DLC film, water molecules and counterpart balls. When sliding against Si\textsubscript{3}N\textsubscript{4} ball, a tribochemical film that mainly consisted of silica gel was formed on the worn surface due to the oxidation and hydrolysis of the Si\textsubscript{3}N\textsubscript{4} ball, and resulted in the lowest friction coefficient and wear rate of the DLC film. The degradation of the DLC film catalyzed by Al\textsubscript{2}O\textsubscript{3} ball caused the highest wear rate of DLC film when sliding against Al\textsubscript{2}O\textsubscript{3} ball, while the tribochemical reactions between DLC film and steel ball led to the highest friction coefficient when sliding against steel ball.

KEY WORDS: DLC film, friction, wear, tribochemical interaction

1. Introduction

In recent years, diamond-like carbon (DLC) films, which are well known as the hard forms of amorphous carbon and hydrogenated amorphous carbon, have been extensively studied as potential materials for many tribological applications because of their extraordinary properties of high mechanical hardness, low friction coefficient and high wear resistance [1–3]. The applications require a detailed understanding of the tribological properties of DLC films. Previous studies have shown that the tribological properties of DLC films are strongly dependent on the deposition methods and deposition conditions, and are very sensitive to the testing environment and the relative humidity (RH) [4–11]. Depending on the above-mentioned factors, the friction coefficients for DLC films have been reported to broadly range from 0.003 to more than 0.3.

Some theories have been proposed to explain the friction and wear behaviors of DLC films. The build-up of a friction-induced transfer film on the counterpart is the most frequently observed friction-controlling mechanism for DLC films [3,9,12]. Liu et al. [4] said that the steady-state low friction of DLC films was due to the wear-induced graphitization, i.e., the formation of a low friction graphitized tribolayer [4,13]. Erdemir et al. [10] argued that the low friction coefficient of DLC films was mainly attributed to the high chemical inertness of DLC films by passivating the surface dangling bonds by hydrogen [10,14]. However, these reported friction and wear mechanisms for DLC films are the subjects to controversy and the role of the environments in the friction and wear behaviors of DLC films is still not well understood. Furthermore, most of the friction and wear mechanisms for DLC films are focused on the friction-induced physical effects, and the tribochemical effects on the friction and wear behaviors of DLC films have not been elucidated [7,9,15].

In the present work, we investigated the friction and wear behaviors of the DLC film under higher relative humidity (RH-100\%) condition sliding against different counterpart ball, focusing on the tribochemical interactions in the presence of the DLC film, water molecules and balls and the tribochemical effects on the friction and wear behaviors of the DLC film.

2. Experimental details

2.1. Deposition and characterization of the DLC film

DLC film was deposited on Si (100) wafers by a PECVD technique, using CH\textsubscript{4} plus Ar as the feedstock. The details about the deposition equipment and process were described elsewhere [16,17]. Prior to deposition, the substrates were cleaned with Ar plasma sputtering at a bias voltage of ~400 V for 15 min so as to remove the native oxide on the Si surface. The deposition conditions and some properties of the resulting DLC film are summarized in table 1.

The deposited DLC film is dark brown in color and is extremely smooth and featureless when viewed with unaided eyes. The film thickness measured on a
2.2. Friction tests

The friction and wear behaviors of the DLC film were evaluated on a ball-on-disk test rig equipped with an environmental chamber with which the relative humidity and gaseous environment could be controlled. The friction tests were performed in humid N₂ (RH~100%) sliding against Si₃N₄ ball, Al₂O₃ ball and steel ball, respectively, at a normal load of 2 N, a sliding velocity of about 125 m/min, to a maximum sliding duration of 60 min.

The wear rate of the film was calculated from the profiles of the worn surfaces measured using surface profilometry. The worn surfaces of the film and the counterpart balls were characterized using a JSM-5600LV scanning electron microscope (SEM), and the chemical composition and chemical bond states of the worn surfaces were analyzed on a PHI-5702 X-ray photoelectron spectroscope (XPS) operating with monochromated Al-Kα irradiation at a pass energy of 29.4 eV.

3. Results

3.1. Friction and wear behaviors of the DLC film

Figure 1 shows the friction and wear behaviors of the DLC film in humid N₂ (RH-100%) sliding against different counterpart ball. When sliding against Si₃N₄ ball, the DLC film provides a low and stable friction coefficient of about 0.085 and a low wear rate of 5.53 × 10⁻⁸ mm³/mN. In the case of Al₂O₃ ball, the friction coefficient of DLC film increases to be about 0.145, and the DLC film shows the highest wear rate of 39.25 × 10⁻⁸ mm³/mN. The friction between the DLC film and steel ball is much unstable, and the friction coefficient increases to about 0.2 in the steady state. However, the wear rate of the film sliding against steel ball is 13.57 × 10⁻⁸ mm³/mN, which is lower than that of the film sliding against Al₂O₃ ball.

3.2. SEM analyses of the worn surfaces

To gain more insights into the friction and wear mechanisms of the DLC film, the worn surfaces of the film and counterpart balls were studied by SEM. Figure 2 shows the SEM pictures of the worn surfaces of the film and balls. As seen in figure 2(a), when sliding against Si₃N₄ ball, a discontinuous layer is formed in the middle of the worn surface of the DLC film, and the worn surface of the Si₃N₄ ball is much rougher (figure 2(b)). Contrary to the above, the DLC film sliding against the Al₂O₃ ball in humid nitrogen is characterized by obvious flake-like desquamation (figure 2(c)), while the worn surface of the counterpart Al₂O₃ ball is very smooth (figure 2(d)). From figure 2(e), it is seen that the worn surface of the DLC film sliding against steel ball shows obvious signs of severe scuffing. The worn surface of the steel ball in this case is relatively large, indicating a severe wear of the steel ball (figure 2(f)).

3.3. XPS analyses of the worn surfaces

Table 2 summarizes the changes in the concentrations (at%) of C, O, Si, Al and Fe determined by XPS anal-