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Friction-induced physical and chemical interactions among diamond-like carbon film, steel ball and water and/or oxygen molecules

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Abstract

Friction and wear behaviors of diamond-like carbon (DLC) film sliding against steel ball were investigated on a ball-on-disk test rig at different relative humidity (RH) in a nitrogen environment. The worn surface morphology of the steel ball was observed on a scanning electron microscope (SEM), while the chemical states of some typical elements on the worn surface of DLC film were investigated by means of X-ray photoelectron spectroscopy (XPS). The result showed that the DLC film recorded continuously increased friction coefficient and wear rate with increasing relative humidity from 5% to 100%. In dry nitrogen (RH < 5%), thick and compact transferred carbon-rich layer was observed covering on the worn surface of steel ball, while the chemical states of the original and worn film surface showed no obvious change. In humid nitrogen, distinct changes of the chemical states on the worn surface of DLC film took place, indicating that tribochemical reactions such as the oxidation of DLC film and the interactions between DLC film and steel ball were involved in the friction process. Therefore, it was proposed that the friction and wear behaviors of DLC film were dependent on the friction-induced physical and chemical interactions among DLC film, steel ball and water and/or oxygen molecules. The roles of environment in the friction and wear behaviors of DLC film were discussed in terms of the friction-induced physical and chemical interactions.
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Keywords: DLC film; Friction; Relative humidity; Interaction; XPS

1. Introduction

Diamond-like carbon (DLC) films exhibit attractive mechanical and tribological properties (e.g. high hardness, low friction, high wear resistance, etc.), which make them suitable for numerous potential tribological applications such as magnetic hard disks, gears, bearings, cutting tools and other moving mechanical assemblies [1–3]. However, previous studies have shown that the tribological properties of the DLC films are strongly dependent on the nature of the films and on the deposition methods and conditions, and are very sensitive to the testing environment, especially to the relative humidity (RH) [4–12]. Depending on the above-mentioned factors, the friction coefficients for the DLC films have been reported to broadly range from 0.003 to more than 0.5 [6–8,11,13–16].

Various 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, followed by easy shear within the interfacial material is the most frequently observed friction-controlling mechanism for DLC films [3,10,17,18]. Liu et al. 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 [6,19]. Erdemir et al. investigated the tribological properties of different DLC films in open air and dry nitrogen, and argued that the general low friction coefficient of hydrogenated DLC films was mainly attributed to the high chemical inertness of the DLC films by passivating the surface dangling bonds of hydrogen [14,20]. Donnet and Erdemir et al. investigated the friction and wear behaviors of DLC film in high vacuum and concluded that DLC film needed to contain at least 40% hydrogen to give ultralow friction in vacuum [3,14]. Other researchers proposed that the tribochemical reactions in the tribo-system played an important role in determining the friction and wear behaviors of DLC films [2,3,7,17]. However,

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Table 1
Summary of the deposition conditions and some properties of DLC film

Item	Parameters
CH_4 gas flow rate	11.6 sccm
Ar gas flow rate	11 sccm
Deposition pressure	5 Pa
FR power	300 W
DC negative bias	−200 V
Deposition time	3 h
Thickness	640 nm
Hardness	15.2 GPa
Young's modulus	120 GPa

these reported friction and wear mechanisms for the DLC films are the subjects to controversy and the role of the environments on the friction and wear behaviors of DLC films is still not well understood.

In the present work, we investigated the friction behaviors of the DLC film sliding against steel balls at different relative humidity in nitrogen, with emphasis on the friction-induced physical and chemical interactions among the DLC film, steel ball and water and/or oxygen molecules. Based on the results, it is hoped that the friction mechanisms of DLC film can be better understood.

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_4 plus Ar as the feedstock. The details about the deposition equipment and process were described elsewhere [21,22]. 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 profilometer is about 640 nm. The hardness and Young's modulus of the film are determined to be about 15.2 and 120 GPa, respectively, using a nano-indenter.

2.2. Friction tests

The friction behaviors of the DLC film sliding against steel ball (AISI 52100, diameter 4 mm, surface roughness Ra 0.1 μm) 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 a nitrogen environment of relative humidity ranging from 5% to 100%, 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 DLC film was calculated from the profiles of the wear tracks measured using surface profilometry. The worn surfaces of steel balls were analyzed on a JSM-5600LV scanning electron microscope (SEM) equipped with a KEVEX SIGMA energy dispersive X-ray spectrometer (EDX). The chemical compositions and chemical states of the worn surface of DLC film were analyzed on a PHI-5702 X-ray photoelectron spectroscope (XPS) operating with monochromated Al–K irradiation at a pass energy of 29.4 eV.

3. Results

3.1. Friction behaviors of DLC film at different relative humidity

Fig. 1 shows the friction and wear behaviors of DLC film at different relative humidity in nitrogen environment. It is obvious that the friction and wear behaviors of the film are strongly dependent on the relative humidity. In dry nitrogen (RH < 5%), the DLC film provides a very low and stable friction coefficient of about 0.035 (Fig. 1(a)) and a low wear rate of 1.25×10^{-8} mm^3/mN (Fig. 1(b)). The friction coefficient and wear rate of the DLC film were continuously increased with increasing relative humidity. As the relative humidity was increased to 100%, the friction between DLC film and steel ball was much unstable, and the friction

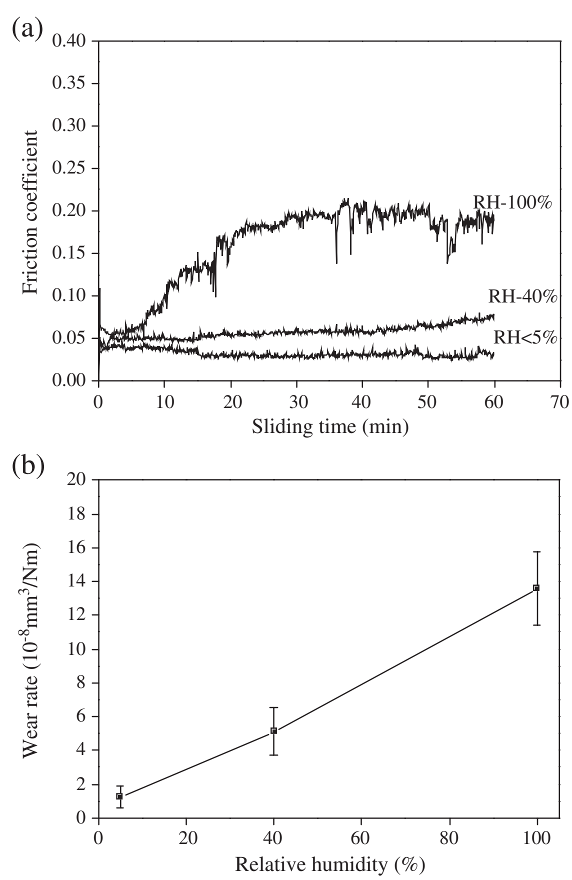

Fig. 1. Friction and wear behaviors of DLC film at different relative humidity in nitrogen environment: (a) friction coefficient of DLC film as a function of sliding time at different relative humidity; (b) wear rate of DLC film at different relative humidity.

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