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Influence of humidity on the friction of diamond and diamond-like carbon materials

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Abstract

The friction of diamond and diamond-like carbon (DLC) materials was evaluated in reciprocating sliding wear testing under controlled relative humidity. The testing conditions were a displacement stroke of 100 μm, an oscillatory frequency of 8 Hz and a normal load of 2 N. The coefficient of friction of diamond and hydrogen-free DLC (a-C) coatings against a corundum sphere in the steady regime decreased with an increase in relative humidity. A water layer physisorbed at the interface between the mating surfaces played two major roles: acting as a lubricant and increasing the true area of contact. However, it was noticed that the friction coefficient of the hydrogenated DLC (a-C:H) coatings first increased and then decreased with increasing relative humidity in the steady state. There appeared to be a critical relative humidity for the a-C:H coatings, at which the steady-state friction reached the maximum value. The frictional behaviour of the a-C:H coatings also showed dependence on the wear test duration. The interaction between hydrogen and oxygen at the interface between the a-C:H coating and water layer was mainly responsible for such behaviour.

Keywords: Friction; Humidity; Diamond; Diamond-like carbon (DLC).

1. Introduction

The tribological behaviour of a single crystal diamond varies with respect to its crystallographic plane and direction [1–3]. The formation of strong carbon–carbon bonding across the clean interface formed between sliding diamond mating surfaces under vacuum is believed to be the cause of a high coefficient of friction [4]. A coefficient of friction of 0.05–0.1 has been obtained from a diamond stylus sliding over a polished diamond (0 0 1) face in air [5], and it is believed that the adsorbed layers such as water, some other liquids and gases on the surface of diamond play an important role. On the contrary, Hayward et al. [6] has reported that the coefficient of friction of diamond is independent of humidity.

Diamond-like carbon (DLC) may have a frictional behaviour different from that of diamond and graphite [7,8], depending on the structure and elements contained in the DLC. Pure carbon DLC (a-C) coatings mainly contain a mixture of sp^3 and sp^2 carbon bonding, while hydrogenated DLC (a-C:H) coatings also contain a significant amount of hydrogen. An a-C coating with a high content of sp^3-bonded carbon may have optical, electrical and mechanical properties close to those of diamond. However, the graphitic particles involved in an a-C coating [9] can deteriorate the coating. Zaidi et al. [10] reported that a-C:H films had a longer lubricating life with a low coefficient of friction and a low wear rate in an inert environment, while the films without hydrogen showed a low friction coefficient in ambient air. Tanaka et al. [11] reported that the wear of DLC films, in dry air, was greater than that in wet air. The transfer behaviour of wear debris from the DLC films under different wear test conditions appeared to be correlated with their friction values. Michler et al. [12] reported that the wear coefficient of DLC coatings on cylindrical substrates increased linearly with absolute humidity.

It was reported that the coefficient of friction of a-C:H coatings decreased with decreasing relative humidity

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[13,14]. Kokaku et al. [15] reported that when an a-C:H film was exposed to a humid environment of RH 90%, oxidation of the surface layer took place. Yoon et al. [16] suggested that the formation of a friction layer might result from the formation of a carboxylic acid soap where oxidized DLC films chemically react with ferrous oxide during the testing against a steel ball. Huu et al. [17] proposed that hydrogen is weakly bonded under vacuum and strongly bonded in a moist environment. Hydrogen desorption in vacuum was suggested [18] to be the main reason for a deceased coefficient of friction for the a-C:H coatings. In a low humidity environment, adhesion may be a dominant source of friction. As a result, graphitization of DLC can occur by shear as well as by frictional heating within the real area of contact during the sliding [19]. For a DLC film deposited on a SiC substrate, increasing the level of environmental humidity was found [20] to decelerate the graphitization process. Grill et al. [21] suggested that the deposition conditions influence the surface chemistry of DLC films during friction testing.

This paper investigates the frictional behaviour of diamond, a-C and a-C:H materials by using reciprocating sliding test under controlled relative humidity.

2. Experimental details

Two synthetic bulk diamonds with a polished (0 0 1) and a cleaved (1 1 1) surface, respectively, a-C coatings deposited with a cathodic vacuum arc, and a-C:H coatings deposited via an RF CVD process, were used in this study. The detailed preparation conditions for the DLC samples have been described elsewhere [8]. The a-C:H coatings used in this study had a lower hydrogen content of about 30 at%, in order to obtain a higher hardness and Young's modulus.

Reciprocating sliding wear test, with a linear displacement of the sample stage, was used to characterize the frictional behaviour of the samples, where a ball-on-disk contact geometry was adopted (Fig. 1). The tester consisted of an *xyz*-positioning system. The sample was mounted on an air-bearing carrier moving horizontally, and the vertical stage held a normal force actuator with a corundum ball of 10 mm diameter mounted at its lower end. A normal force was applied by compressing a double spring system against the ball. The counterbody was horizontally linked to the stage by a quartz force transducer. The linear contact displacement, normal contact force and responding friction force were all measured as a function of time [22].

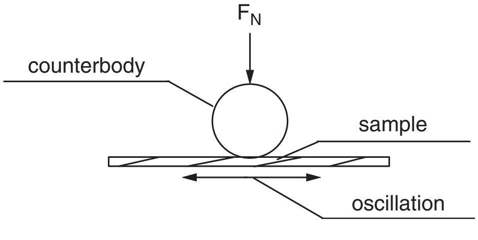

Fig. 1. Schematic diagram of ball-on-disk contact geometry for reciprocating sliding wear testing.

The wear tests were conducted at various relative humidities (RH) between 5% and 90% without lubrication at room temperature (~22 °C) under the conditions: normal load of 2 N, displacement stroke of 100 μm, vibration frequency of 8 Hz and up to 100,000 cycles.

For the polished (0 0 1) bulk diamond, the oscillation direction was perpendicular to the polishing lines, while for the cleaved (1 1 1) bulk diamond, the oscillation direction was perpendicular to the cleavage lines.

The hardness and Young's modulus of the DLC coatings were measured with nanoindentation (Nanoscope II, NanoInstruments).

The surface roughness of the samples was measured using a surface profiler (Talysurf) with a diamond stylus in contact mode.

3. Results and discussion

The surface morphologies of (0 0 1) diamond and DLC samples have been described elsewhere [8,23] and the surface roughnesses of the samples and corundum sphere are shown in Table 1.

The hardness and elastic modulus of the a-C coatings are about 24.5 and 360 GPa, respectively, and that of the a-C:H coatings are around 22 and 200 GPa, respectively.

The general tendency for the diamond and DLC samples sliding against the corundum counterbody is that the coefficients of friction are higher at the beginning of the wear tests, and then rapidly decrease to relatively constant values during the following cycles as shown in Figs. 2–5. For the a-C:H coatings after an initial rapid drop of the coefficients of friction to minimum values at the initial stage, the coefficients of friction rise again with increasing cycles and then reach the steady regime (Fig. 5).

The coefficient of friction for the a-C coatings in the stable regime is much lower than that for the a-C:H coatings. It can be noted that the a-C coatings mainly contain a mixture of sp^3 and sp^2-bonded carbon, while the a-C:H coatings also contain a significant amount of hydrogen which either forms the terminated sp^3 bonds with the carbon atoms or is trapped in the coatings. Hydrogen in the a-C:H coatings may strongly interact with oxygen in the testing environment during wear testing, leading to a higher friction than that of the a-C coatings.

Table 1
Surface roughness of the samples and corundum sphere used in this study

Sample	Ra (nm)	Rq (nm)
(1 1 1) diamond	2.8	3.9
(1 0 0) diamond	2.0	2.6
a-C	125.0	162.0
a-C:H	6.6	8.6
Corundum ball	6.0	10.0

iCAT '04—Liu et al. [23].