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Tribological Characteristics of DLC Films against Si_3N_4 and 316L Stainless Steel When Lubricated with Oil and Water

Bai Yue

Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China

Abstract: The aim of this study was to compare the performance of DLC film on 316L plates against Si_3N_4 and 316L steel balls, in contact with in air (24% RH), synthetic oil and distilled water. The results show that there is the lowest friction coefficient and wear volume in the DLC/Si_3N_4 pair with synthetic oil; adding oil decreases friction coefficient by 45.8% and wear volume by 94.4% in comparison with their friction coefficients and wear volume in air (24% RH). Adding distilled water decreases the friction coefficient by 44.8% in the DLC/Si_3N_4 pair, 51.3% in the DLC/316L, in comparison with their respective friction coefficients in air (24% RH).

Key words: DLC; Si_3N_4; friction; wear; water; oil

In industrial design, friction and wear volume affects productivity and machine lifetime directly. As competition increases in the global economy, more attention has dedicated to understanding the physics and chemistry of moving part and to finding advanced lubricants. Diamond-like carbon (DLC) coatings are nowadays used in many applications with aim of reducing friction and wear. The main reason for their use is the well-known intrinsic characteristics of DLC films, namely high hardness and low surface roughness, affording low friction volume and low wear rate[1-4].

The tribological characteristics of DLC films significantly change with the change in environment such as vacuum, room atmosphere[5], and different relative humidity[6]. In addition, the tribological properties of the DLC film in industrial applications may be influenced by presence of liquid, such as oil and water. Thus, study is required to understand friction and wear behavior in various environments. However, most of the studies focused on uncoated and DLC-coated metal substrates against metal and alloy balls in controlled humidity conditions, or in dry, unlubricated conditions[7-10].

Silicon nitride (Si_3N_4) ceramics material has shown very promising properties as wear resistant material for tribological applications. Its unique physical properties, such as low density, high elastic modulus and high hardness at low and high temperatures make it particularly attractive candidates for advanced mechanical designs. The successful application of Si_3N_4 material in tribological service requires good understanding of the mechanical and chemical properties of the material. For this reason much effort has been made to understand the wear mechanisms of Si_3N_4 under different materials and conditions[11,12].

Although the tribological properties of DLC and Si_3N_4 film under different against materials and conditions were studied extensively, different observations were reported in the literatures. There is no similar experimental study on the tribological properties of DLC films against Si_3N_4 when lubricated with oil and water.

In this study, DLC films were deposited on a 316L stainless steel substrate by the RF-PECVD method. The aim of this study was to compare the performance of DLC film on 316L plates against Si_3N_4 and 316L steel balls, in contact with in air, distilled water and synthetic oil and to determine which sample pair would show the lowest friction coefficient and lowest wear volume. The tests with the synthetic oil and distilled water worked in a boundary lubrication regime.

1 Experiment

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Corresponding author: Bai Yue, Ph. D., Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, P. R. China, Tel: 0086-431-86176292-841, E-mail: baiy@ciomp.ac.cn

The DLC film with 1.3 μm thickness and hardness of 22.8 GPa was deposited on 316L steel plates (*Φ*23 mm×4 mm) by means of radio frequency plasma-enhanced chemical vapor deposition (RF-PECVD) process. To guaratee adherence and avoid bumps, the 316 L plates were polished and then cleaned in ultrasonic bath in isopropyl alcohol for 10 min, and then cleaned in a vacuum chamber under 10 Pa pressure of argon discharge for 40 min. For tests, the analyzed pairs were 4 mm-diameter Si_3N_4 balls and 316L stainless steel plates, as well as 4 mm-diameter 316 L steel balls and plates, The 316L stainless steel plates were ground and polished in several steps to a final roughness R_a of 0.04 μm and hardness of 3.3 GPa.The 316L steel ball and Si_3N_4 balls had a hardness of 3.3 GPa and 18.3 GPa, a surface R_a roughness of better than 0.03 μm, respectively.

The tests were carried out by a ball-on-plate reciprocating sliding device (MFT-R4000, China). The environment was strictly controlled to keep 24±1% relative humidity (RH) and temperature 20±1 ℃. The stroke was 2 mm and the frequency 25 H_Z, which provided 0.1 m/s of relative contact speed. The load of 10 N was applied for the test pairs through a stationary loading system, and this resulted in about 1 GPa of initial maximum Hertzian contact pressure. The calculated Tallian's lambda value[13] was lower than 0.06, which suggests boundary lubrication conditions. The test with the addition of synthetic oil and distilled water worked in a boundary lubrication regime. In this regime, the friction coefficient is considered as a function of the oil viscosity (η), sliding speed (U), and applied load (W). This relationship is usually known as the Stribeck Curve[14]. $\eta U/W$ correspond to λ factor that is proportional to the liquid lubricant thickness. For the oil-lubricated tests, was used commercial Poly-Alpha-Olefin (PAO) Synthetic oil was used that contained detergent, dispersant, and additives as corrosion and oxidation inhibitors, with a viscosity of 53.4 cSt/104 ℃. For the water-lubricated tests, distilled water with a viscosity of 1.0 cSt/20 ℃ was used.

The representative wear loss of all the experiments was determined by measuring the diameter of wear scar on the ball and subsequent calculation of the volume of the corresponding worn spherical cup, and the wear loss of the plates was also calculated[15]. After the friction measurements, the characterization of the plate worn surfaces was carried out by atomic force microscopy (AFM). The total sliding distance in each experiment was 100 m.

2 Results and Discussion

2.1 DLC/Si_3N_4 pairs

The results in Fig.1 below are comparing the friction coefficient and the wear volume for the DLC films against Si_3N_4 and 316L balls in different test environments.

In contact with synthetic oil, the sample shows a friction coefficient of 0.115 and a wear volume 4.2 e^{-5}mm^3. Adding

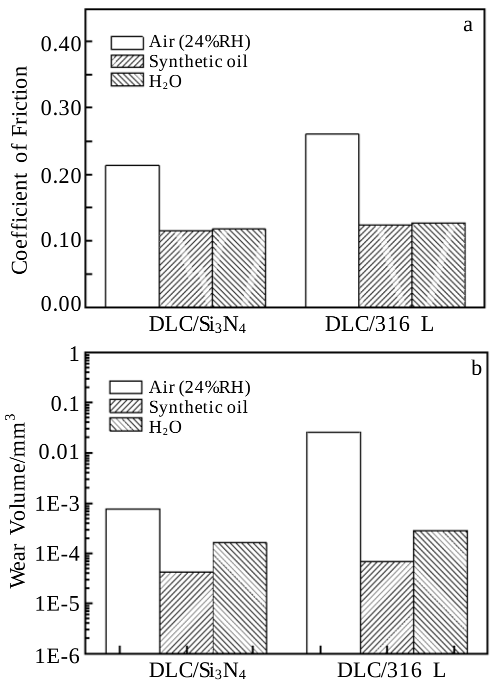

Fig.1 Friction coefficient (a) and wear volume (b) vs different test environments at 0.1 m/s of sliding speed and 10 N load

synthetic oil decreases friction coefficient by 45.8% and wear volume by 94.4% in comparison with their friction coefficients and wear volume in air (24% RH). This behavior is due to the ability of synthetic oil to form a lubricant film between the surfaces, changing the tribo-mechanism. The oil composition allows the formation of a strong boundary layer of carboxylic acid through tribo-chemical reactions in the body and counter-body contact area preventing the formation of a tribolayer. A lower friction coefficient 0.118 and higher wear volume 2.6 e^{-4} mm^3 was obtained in samples in contact with distilled water (Fig.1a and 1b). Adding distilled water decreases friction coefficient by 44.8% and wear volume by 78.9% in comparison with their friction coefficients and wear volume in air (24% RH), respectively. In a water environment, the low friction is due to the formation of hydroxyl and carboxyl groups on the DLC film surfaces preventing the adhesion between the sliding materials. The formed hydrophilic groups are considered to be responsible for low friction and high wear volume of DLC film[16].

Fig.2 shows the most representative AFM images of the various DLC/Si_3N_4 pairs contacts tested in air (24% RH), synthetic oil, and distilled water. As measured, the wear volume with synthetic oil is smaller, the surface is very smoother and the wear scar is shallower (Fig.2b).

2.2 DLC/316L pairs

In air (24% RH), the highest friction coefficients and wear volume were obtained. The friction coefficient and wear volume is increased by 22% and two orders of magnitude higher than DLC/Si_3N_4 tested in air (24% RH). In contact with synthetic oil, the samples show the friction coefficient and wear volume increase by 7.8% and 61.9% in comparison with DLC/Si_3N_4 in contact with synthetic oil (Fig.1a and 1b). In contact with distilled water, it is 7.6% and 75% in comparison with DLC/Si_3N_4 in contact with distilled water (Fig.1a and 1b). This behavior is due to the formation of effective anti wear film on the sliding surface of the DLC film. The synthetic oil triglyceride structure promotes a strong Fe adsorption contained in the stainless steel surface[17].

It is interesting to note that, in comparison with DLC/Si_3N_4 pair in contact with distilled water, the friction coefficient of the DLC/316L pair in contact distilled water is basically the same, and the wear volumes on distilled water is higher about half. In a water environment, the tribolayer on the ball consists of C from the DLC film, Cr, Fe from ball debris and O mainly from water which is rich in hydroxyl.

Fig.3 shows the most representative AFM images of the various DLC/316L pairs contacts tested in air (24% RH), synthetic oil, and distilled water. As measured, it clearly can be seen that the wear scar of sample in air (24% RH) is deeper and the surface is rougher (Fig.3a).

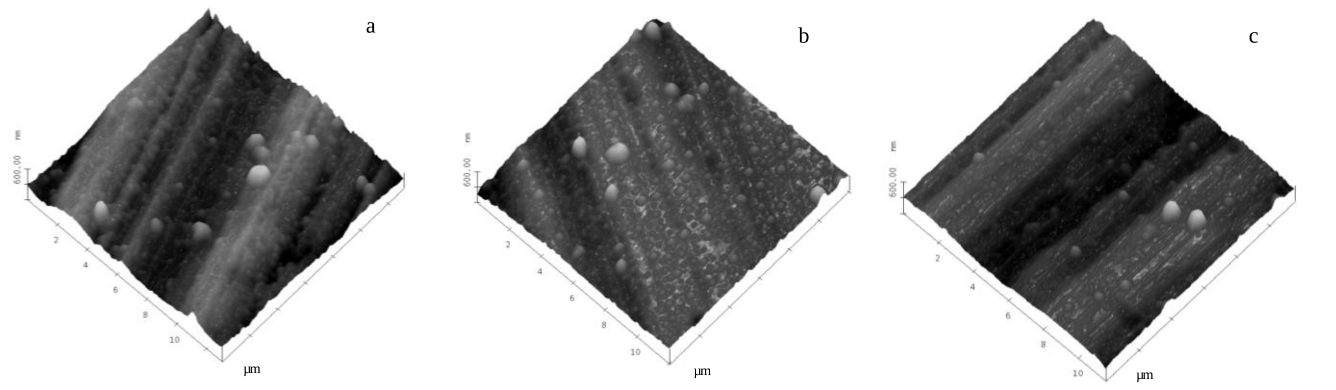

Fig.2 Topography of DLCs tested with Si_3N_4 ball in air (24% RH)(a), synthetic oil(b), and distilled water(c)

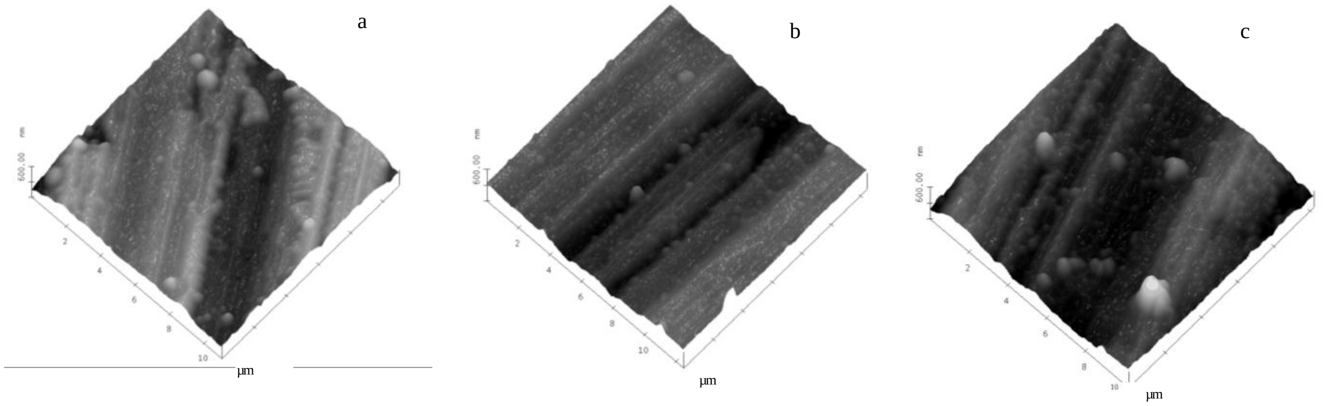

Fig.3 Topography of DLCs tested with 316L ball in air (24% RH)(a), synthetic oil(b), and distilled water(c)

3 Conclusions

1) Adding synthetic oil decreases the friction coefficient by 45.8% in the DLC/Si_3N_4 pair and 52.5% in the DLC/316L pair in comparison with their friction coefficients in air (24% RH). Wear volume is decreased by 94.4% in the DLC/ Si_3N_4 pair and decreased two orders of magnitude in the DLC/316L pair in comparison with their wear volumes in air (24% RH).

2) The addition of distilled water decreases the friction coefficient by 44.8% in the DLC/Si_3N_4 pair, and 51.3% in the DLC/316L, in comparison with their friction coefficients in air (24% RH). Wear volume is increased by 78.9% in the DLC/Si_3N_4 pair and decreased 98.9% in the DLC/316L pairs in comparison with their wear volumes in air (24% RH).

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类金刚石薄膜在油和水润滑下与氮化硅和316L钢材料的摩擦性能研究

白　越

(中国科学院　长春光学精密机械与物理研究所，吉林　长春　130033)

摘　要：采用射频等离子体增强化学气相沉积(RF-PECVD)方法在316L钢衬底上沉积类金刚石薄膜，比较类金刚石薄膜在油和水润滑下分别与氮化硅和316L钢材料对磨的摩擦和磨损性能。实验结果显示：类金刚石/氮化硅摩擦对偶在合成油的润滑下具有最低的摩擦系数和磨损率；在空气中的摩擦系数和磨损量相比，类金刚石/氮化硅摩擦对偶添加合成油减小了45.8%的摩擦系数和94.4的磨损量。添加蒸馏水可以有效减小类金刚石薄膜的摩擦系数和磨损量，与空气中的摩擦系数相比，类金刚石/氮化硅摩擦对偶和类金刚石/316L钢摩擦对偶在蒸馏水润滑下的摩擦系数分别减小了44.8%和51.3%。在对磨损要求较为宽松的应用场合，蒸馏水可以为类金刚石/氮化硅摩擦对偶和类金刚石/316L钢摩擦对偶提供足够的润滑。

关键词：类金刚石薄膜；氮化硅；摩擦；磨损；水；油

作者简介：白　越，男，1979 年生，博士，副研究员，中国科学院长春光学精密机械与物理研究所，吉林 长春 130033，电话：0431-86176292-841，E-mail: baiy@ciomp.ac.cn