Tribological Behavior and Topography of Friction Surfaces of Diamond-Like Coatings in Contact with Steel, Silicon Nitride, and Quartz Glass


Abstract—The paper presents the study results of the tribological behavior and surface topography formed at friction of diamond-like coatings against indenters made of silicon nitride, quartz glass, and steel. It is shown that the tribological behavior depends on the nature and hardness of the counterbody material whose wear causes changes in the surface topography of the diamond-like coating at the nanometer level. At friction of the diamond-like coating against the silicon nitride indenter surface asperities are deformed plastically and the deformation rate is governed by the coating structure.

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Key words: tribological characteristics, diamond-like coating, topography, nanoasperities, atomic force microscopy.

INTRODUCTION

Carbon-based diamond-like coatings (DLC) are widely used to prolong the life of fast-worn friction units owing to their high physical-mechanical properties. Unlike hydrogen-containing DLC (hardness ≈ 15 GPa) deposited at ≈ 600–1000°C, DLC free of hydrogen are produced by the ion-plasma method at considerably lower substrate temperature (< 100°C) [1] that provides their high hardness (up to 65 GPa) as well as a number of technological and service advantages. In addition, hydrogen-free DLC are characterized by an increased concentration of \( sp^2 \) bound carbon that favors the formation of smooth surfaces and graphite-like structures. Self-lubrication that occurs in friction owing to the \( sp^3 \rightarrow sp^2 \) phase transition allows increasing the wear resistance of the coating [2–5].

Recently multilayer DLC have been widely spread in which nanometer metal and diamond-like carbon layers alternate. Such design solution allows for increasing the life of DLC owing to reducing internal stresses arising at coating deposition. Moreover, it has been found that the alteration of nanolayers with different physical-mechanical properties inhibits the propagation of surface micro-cracks in coating at friction [6]. Good results are achieved when using interlayers of transition metals. For example, titanium is used as the sublayer and/or interlayer material [5].

The fatigue wear of DLC can cause the severe wear of the counterbody material since the fatigue damage of friction surface asperities of the super-hard material (DLC) is accompanied by the accumulation of wear particles in the friction zone that produce abrasive effect on the surface layer of the softer mated material. This appears as severe counterbody wear. The counterbody material, in its turn,
can induce tribochemical reactions that inhibit or catalyze the transformation of the DLC structure into various allotropic forms of carbon, e.g. graphite-like structures, which can change the tribological behavior of the contacting materials [2–4]. Tribochemical reactions that produce polymerization products in the friction zone also should be considered as one of the factors affecting the tribological behavior of DLC and the pair as a whole.

The aim of the study is to investigate the tribological behavior and features of the surface topography of DLC rubbing against materials of different nature.

1. EXPERIMENTAL METHODS

Titanium-modified multilayer and bulk-heterogeneous DLC have been chosen as the objects of study. They were deposited to substrates made of hardened ball-bearing steel. Balls with the radius of 3 mm made of silicon nitride Si₃N₄, quartz glass, and hardened ball-bearing steel were used as indenters. Some physical-mechanical characteristics of the materials are presented in Table 1.

Multilayer and bulk-heterogeneous titanium-carbon DLCs were produced by industrial vacuum setup. The titanium nitride layer 30 nm thick was the first layer to which DLCs with different structures were deposited. The multilayer coating consisting of twelve alternating layers of carbon and titanium 20 and 25 nm thick, respectively, was formed by the subsequent deposition of carbon and titanium. The heterogeneous coating ≈ 250 nm thick containing 18 wt % of Ti was produced by the simultaneous deposition of carbon and titanium.

Tribotests were carried out in a reciprocating friction machine [7]. The specimen with the coating under testing was mounted to the holder and then brought in contact with the spherical indenter. The friction force produced the displacement of the elastic element that was transformed into a digital file by an inductive gage and analog-to-digital transducer.

The tribotests were carried out in air at the sliding velocity $V = 3 \times 10^{-3}$ m/s and under the load $N = 0.2$ N. The length of the friction track was 6 mm. In testing variations in the friction force and the friction track width were recorded. After the tests wear spots on different counterbodies were measured by an optical microscope and these data were used to determine the wear rate.

2. RESULTS AND DISCUSSION

The dependences of the friction coefficient of DLC in contact with different indenters on the number of friction cycles are presented in Fig. 1. From the data it follows that the friction coefficient and the pattern of its variation with time essentially depend on the counterbody material. At reciprocating friction of different indenters against DLC without lubricant a relatively high friction coefficient is recorded. In contact with quartz glass a stable friction coefficient is achieved for the multilayer and heterogeneous DLC (0.63 and 0.47, respectively).

**Table 1.** Physical-mechanical characteristics of materials under investigation

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, g/cm³</th>
<th>Modulus of elasticity, GPa</th>
<th>Hardness, GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>7.81</td>
<td>211</td>
<td>6.8</td>
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