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The influence of viscosity on the friction in lubricated DLC contacts at various sliding velocities

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ABSTRACT

Diamond-like-carbon (DLC) coatings are one of the promising types of protective coatings for various mechanical applications, including those under lubricated conditions. In recent years the research focus of lubricated DLC contacts has been primarily on the chemical aspects of lubrication, while the physical properties of the oils and the other physical lubrication aspects were to a large extent neglected. In this work we analyse the friction behaviour of self-mated DLC/DLC contacts that use various viscosity grades of polyalphaolefin (PAO) base oils, i.e., 18, 30 and 46 mm^2/s, at a range of velocities from 0.04 to 0.41 m/s. For a comparison, we also investigated some steel/steel contacts. At low velocities (up to 0.08 m/s) we observed almost no effect of the viscosity for the DLC surfaces, suggesting a predominant influence of the DLC "solid–solid" contacts on the friction. However, relatively strong, physically adsorbed oil-film layers were present on the DLC surfaces, which were able to prevent the coatings from wearing out under low-speed conditions, that otherwise occur under dry conditions. In the high-velocity region (above 0.17 m/s), the viscosity has no effect on the steel contacts, but higher-viscosity oils tended to reduce the DLC friction, suggesting that for DLC surfaces, higher viscosities are required for the same film thickness and "quality" of lubrication than for steel surfaces. This is due to the poorer wetting and oil-adsorption properties of DLC compared to steel. However, at the same time, this effect leads to reduced friction in DLC contacts, which was about 15% lower for all the investigated sliding velocities.

1. Introduction

DLC coatings are one of the most promising types of protective, hard coatings for a variety of mechanical applications. DLC films are primarily made from carbon atoms that are extracted or derived from carbon-containing sources, such as solid carbon targets and liquid or gaseous forms of hydrocarbons and fullerenes [1]. Their main advantages are low friction, good anti-wear properties, and adhesive protection. However, their interactions with conventional oils and additives are limited, which makes achieving effective lubrication a complex task. Until now, studies of the lubrication of DLC coatings have focused mainly on verifying whether, and to what extent, any actual "lubrication" is possible. Different additives, oils, coatings, contacts, and their conditions have been analysed, and it is obvious today that DLC coatings do interact with additives [2,3], and that under specific conditions their performance can be much better than that of more conventional materials. However, so far it was mainly the chemical aspects of DLC lubrication that were investigated, focusing on the chemical adsorption or the chemical reactions between additives and coatings and the resulting tribological performance [4–6]. The state of the art, when it comes to understanding the effect of additives on DLC surfaces, has recently been summarized in several publications [7–10].

In the studies of the boundary lubrication of self-mated DLC contacts published so far, an oil viscosity of 46 mm^2/s was used almost exclusively. Fig. 1 shows the results from 16 different studies using DLC/DLC contacts under boundary-lubrication conditions, which are summarized in a recent review paper [9]. As many as 13 of these 16 studies used oils with a viscosity of 46 mm^2/s, and only three different viscosities were used in total. The same almost exclusive use of 46 mm^2/s viscosity-grade lubricants can also be found for DLC/steel contacts in more than 20 published papers [10]. Although different contact conditions and types of DLC coatings were used in the different studies, they were all performed under boundary conditions and, as is evident from Fig. 1, it is not possible to recognize any effect of the oil's viscosity from the studies presented so far, primarily because they mostly used a single viscosity type. Moreover, in any of these studies the viscosity of the oil was systematically changed or varied and/or discussed to a significant extent. However, viscosity plays an important role in all lubrication regimes; for example, to a large extent it determines the lubrication regime and oil-film thickness, and thus the surface separation, which is very

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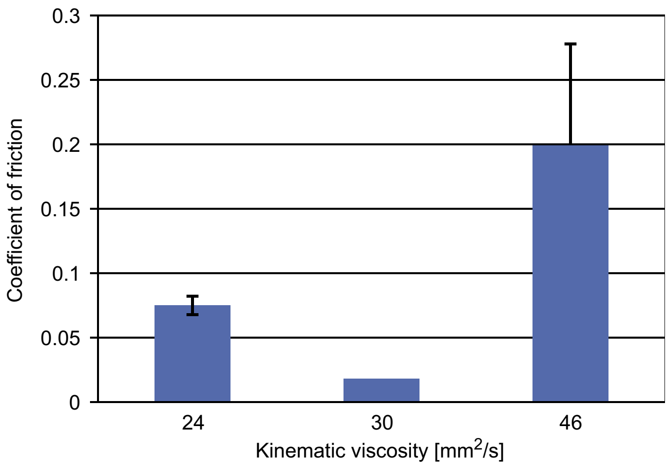

Fig. 1. Values of the coefficients of friction extracted from different studies of DLC/DLC contacts lubricated with different viscosity-grade base oils (without additives). The results are summarized from 16 studies of DLC/DLC contacts, analysed in a review reference [9]. The error bars represent the standard deviation of the values reported.

important, especially where an elastohydrodynamic regime is required. On the other hand, physical interactions and the physical adsorption between the oils and surfaces play a greater role in boundary-lubrication conditions. However, none of these effects have been discussed so far in a systematic way and, as a result, they are to a large extent unknown. Nevertheless, it was shown that DLC/DLC contacts lubricated with base oils having different polarity and saturation characteristics [11] varied in their friction and wear behaviours. Furthermore, different doping elements in the coating's structure, e.g., Si, Ti and W, which affect the coating's wetting and adsorption properties, were shown to affect the friction and wear, even when no additives were applied to the base oil [5,12].

Therefore, the tribo-physical effects of lubrication mechanisms are well known for conventional steel/steel contacts [13,14]; however, these properties are largely unknown for DLC coatings, both on the micro/macroscale and on the nanoscale [15,16]. In this work we analyse the friction behaviour of self-mated DLC/DLC contacts with the use of various viscosity grades of polyalphaolefin (PAO) base oils, i.e., 18, 30 and 46 mm^2/s, under a broad range of velocities that are often used in tribological experiments. We compare the tribological behaviour of the coatings at different velocities and viscosities with the behaviour of steel/steel contacts, which are well understood and can, therefore, serve as a good reference material. Furthermore, we also discuss the beneficial physical adsorption between the DLC coatings and the oils at low velocities, corresponding to the boundary-and/or mixed-lubrication regime, which was clearly noted in this work.

2. Experimental

The tribological tests were performed using the ball-on-flat testing geometry, with balls and flats made from DIN 100Cr6 steel. All the balls and flats had initially the same mechanical, thermal and surface characteristics. The steel balls were commercially available, standard bearing balls with a diameter of 10 mm, a hardness of 850 HV and a surface roughness better than 0.03 μm. The steel flat samples were cut from a rod into $\varnothing 24 \times 7.9$ mm discs and treated to the same hardness as the balls. The steel discs were ground and polished in several steps to a final roughness of 0.05 μm. Some of the samples were used as reference steel specimens in the tribological tests, while the rest of the discs and balls were further coated with the amorphous, hydrogenated DLC coating. A thin Si-based interlayer was used to improve the adhesion of the coating, which was deposited by radio-frequency plasma-assisted CVD at 13.56 MHz. The average H-content of DLC coating was around 30 at% and the hardness was 23 GPa. The total coating thickness was about 1.8 μm. DLC/DLC and steel/steel contacts were employed in the study. The tests were performed using three different polyalphaolefin oils with three different viscosities: 18, 30 and 46 mm^2/s, measured at 40 °C. Their density was about the same, i.e. 810–830 kg/m^3, while pressure–viscosity coefficient was in the range from 2.3×10^{-8} to 2.8×10^{-8} Pa^{-1}.

The tribological tests were performed using a reciprocating sliding machine (TE77, Phoenix Tribology Ltd., UK). This testing machine consists of a stationary base, a holder, a loading cell and a computer-based regulation system. All the experiments were conducted using a 6.8 mm stroke length at room temperature (about 20 °C). The disc was fully immersed in the same quantity of oil for each experiment. The friction was monitored throughout the test and the average values of the steady-state friction are reported. As is evident from the scatter bars in the results, the variation between the tests was very small, suggesting very repeatable results. The experiments were run for 100 m of total sliding distance under a load of 10 N, resulting in 1 GPa (max) Hertz pressure. A range of different sliding velocities was selected, typical for many tribological studies, as reported in [9,10]. We used 0.04, 0.08, 0.17, 0.35 and 0.41 m/s. Steady-state friction was achieved during all the tests, and this was used as a representative friction value. Every experiment was performed three to five times and the average and standard deviation were subsequently calculated. After the test the wear was measured and the coated surfaces were checked using a microscope to ensure that no wear-through or spalling occurred on the discs or the balls. For comparison, some experiments were performed under the same conditions without any lubricant being applied. Selected samples were examined using a scanning electron microscope (SEM) Jeol JSM-T330A.

3. Results

The experiments were performed for three different viscosities, with the differences in velocity ranging over a factor of 10, i.e., from 0.04 to 0.41 m/s. From the results it turned out that two distinctively different behaviours can be defined. Namely, the results at the low velocities, 0.04 and 0.08 m/s, showed completely different trends to those at, or above, 0.17 m/s. This was true for the DLC/DLC and the steel/steel contacts. Accordingly, we present these results as the "low-" and "high-speed" regions. Moreover, from the wear measurements, we can see a significant difference in the wear of the steel samples in these two regions, Fig. 2. The wear was very low at high velocities, and increased substantially at low velocities. A similar trend was found for the DLC surfaces, but the difference was less pronounced, most probably because of the well-known higher wear resistance of DLC surfaces. SEM images of the worn surfaces confirm the wear data. In low-speed regime there was a significant damage of the surfaces found with deformation and transfer of plastically deformed debris, indicating adhesive wear, Fig. 3a. On the other hand, at high velocities (Fig. 3b) there were almost no signs of wear on the steel surfaces observed; only some slight running-in can be proposed since all the original grinding scratches are almost identical in the war scar and away from the scar. Furthermore, normally direct asperity collisions in steel/steel contacts under 1 GPa of contact pressure without using any additives lead to adhesive wear, as also seen at low velocities, which implies that such asperity contacts occurred very seldom