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The tribological performance of DLC coatings under oil-lubricated fretting conditions

Mitjan Kalin*, Jože Vižintin

University of Ljubljana, Center for tribology and technical diagnostics, Bogišičeva 8, 1000 Ljubljana, Slovenia

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Abstract

Whether or not the process of fretting occurs is to a large extent dependent on the coefficient of friction, because the coefficient of friction directly affects the amount of shear stress. As a result, the key factor when it comes to reducing the amount of fretting damage is to reduce the coefficient of friction. Various surface coatings, and especially hard, diamond-like carbon (DLC) coatings, are known to be able to produce surfaces with a low level of friction. Despite some such attempts in the past, which did not result in major improvements, the developments and improvements in DLC coatings in recent years suggest the need for a re-evaluation of these coatings for fretting applications. Another way to reduce the amount of friction in mechanical components is to apply lubricants, and recent studies on the lubrication of DLC coatings suggest that this combination could be very successful in preventing failures under boundary-lubrication conditions. Therefore, in this work we present the results of friction and wear measurements from three types of fretting contacts: steel/steel, steel/DLC and DLC/DLC. Boundary oil-lubrication conditions were investigated and a wide range of displacement amplitudes, i.e., from 25 to 500 μm, were selected to assess the fretting and sliding behaviours. The results show a significant difference between the fretting and sliding regimes. In the fretting regime, the DLC-containing contacts, and especially the self-mated DLC/DLC contacts, performed much better than the steel/steel contacts, and significantly reduced both the wear (a 3–10 times reduction with steel/DLC and DLC/DLC) and the friction (a more-than-two-times reduction with DLC/DLC). In the sliding regime, the lubrication effects governed the tribological performance, making the results for all three material combinations very similar.

Keywords: DLC; Coating; Fretting; Sliding; Oil; Lubrication

1. Introduction

Fretting wear and/or fretting fatigue are mechanisms that can cause failures in many machines and components as a result of wear that is generated by small relative displacements between contacting bodies and/or due to cyclic stress loading. The occurrence of fretting depends significantly on the coefficient of friction, because this directly affects the shear stress, which is one of the important parameters in the promotion or suppression of fretting damage. As a result, the key factor when it comes to reducing the amount of fretting damage is to reduce the coefficient of friction.

Some surface coatings, and especially hard, diamond-like carbon (DLC) coatings, are well known as low-friction coatings. Applying such coatings to components that are exposed to fretting damage has been investigated in the past, primarily under dry conditions, to improve the behaviour in comparison with conventional un-coated systems. Fretting studies of hard coatings have included W–Si–N-coatings [1], Ti- and Cr-based coatings [2–5], DLC coatings [5–7], whereas for soft coatings, MoS_2 has been the most investigated material [8,9]. For the DLC coatings it was shown that at high frequencies [5,7] and/or high temperatures [6], DLC coatings thermally degrade, leading to a transformation from sp^3 to sp^2 bonds, i.e., graphitisation, which results in a low wear resistance [5,7]. On the other hand, at lower frequencies [5], the tribological behaviour of DLC coatings is, for example, better than that of TiN, but still not capable of providing very high levels of protection. However, in the years since these earlier studies, the understanding of DLC coatings and their tribological performance have increased significantly.

*Corresponding author. Tel.: +386 1 4771 462; fax: +386 1 4771 469.
E-mail address: mitjan.kalin@ctd.uni-lj.si (M. Kalin).

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Another way to reduce friction and improve fretting performance is to use a lubricant. Several studies have already dealt with the various aspects of fretting lubrication, for example, Refs. [10–14], using both oils and grease. Generally, a reduced coefficient of friction was observed, and, in many cases, so was reduced wear; however, this depends significantly on the fretting amplitude [10–14].

Combining the two techniques, i.e., improved, modern DLC coatings and lubricants, seems to be a potential method for improving the tribological performance of various components under fretting conditions. Until recently, the effects of lubricating DLC coatings were quite unknown, and only a little information was available. However, many efforts have been made in recent years in the field of lubricated DLC coatings within the European scientific framework actions [15], primarily relating to the effects of oils, additives and doping elements on their "conventional" sliding performance. Some of the important and encouraging conclusions are that lubricated DLC contacts perform better in terms of lower friction and wear than non-lubricated DLC contacts [16–20]. These effects were especially pronounced when using additivated oils and doped coatings, both in steel/DLC and DLC/DLC contacts [18–20].

As a result of these findings, combined with the many improvements in deposition techniques and the technology of hard DLC coatings, a re-investigation of the wear and friction behaviours of DLC coatings under fretting conditions seems to be appropriate. Moreover, new information about the positive effects of lubricated DLC coatings suggests that better fretting performance can also be expected when combining lubricants and DLC coatings, and, to our knowledge, this combination has not yet been investigated. Since these positive results were found in conventional sliding systems, the differences in the sliding and fretting behaviours are certainly of interest. Accordingly, in this study we have investigated and compared the tribological performance of DLC/DLC, steel/DLC and steel/steel contacts over a wide range of displacement amplitudes, i.e. from 25 to 500 μm, with all the contacts lubricated with mineral base oil under severe boundary-lubrication conditions.

2. Experimental

Single-layer a-C:H DLC coatings deposited by a hybrid PVD/CVD process with a TiN adhesion-promoting interlayer were used in this investigation. The thickness and some of the other properties of the coatings are presented in Table 1. The hardness and the Young's modulus of the coatings were measured using a depth-sensing indentation (DSI) technique (NanoTest 600 instrument with a Berkovich indenter, Micro Materials Limited, UK), while the roughness was measured with a stylus-tip profilometer (T8000, Hommelwerke GmbH, Schwenningen, Germany). The adhesion of the coatings was investigated with a scratch tester (Revetest, CSM Instruments SA, Switzerland) and the Lc1, Lc2 and Lc3 values [21] were found to be 16.0, 28.0 and 29.5 N, respectively. These values suggest rather good adhesion properties of this coating, in particular when compared to comparable similar coatings [18].

The substrate material for all the coated samples was conventional ball-bearing DIN 100Cr6 steel with a hardness of 8.3 (±0.3) GPa. The tribological tests were performed using a ball-on-flat testing geometry, using balls and flats made from the DIN 100Cr6 steel. The commercially available steel balls had a diameter of 10 mm and a surface roughness (R_a) better than 0.03 μm. The steel flat samples were ϕ24 mm × 7.9 mm discs that were ground and polished in several steps to a final R_a roughness of 0.05 (±0.01) μm. Some of the flat and ball samples were used in tribological tests as steel specimens, while the rest of the discs and balls were further coated as described above. The selected testing-material combinations were steel/steel, steel/DLC and DLC/DLC, as schematically shown in Fig. 1. All the experiments were performed using a paraffinic mineral base oil (denoted as M) of viscosity grade ISO VG 46 under ambient laboratory conditions (RH ≈ 45%, T ≈ 21 °C).

The wear experiments were performed in a reciprocating sliding machine, driven in a linear oscillating motion. In all the experiments, 10 N of normal load was applied through the loading system, which resulted in an initial Hertzian contact stress of about 700 MPa (1 GPa max). A wide

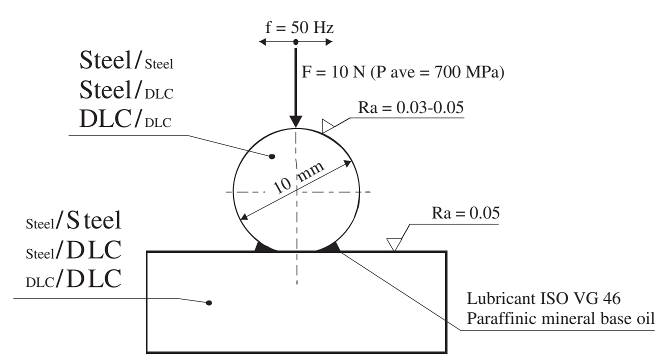

Fig. 1. A schematic of the selected testing-material combinations: steel/steel, steel/DLC and DLC/DLC.

Table 1
Important characteristic parameters of the coating

Thickness (μm)	Hardness (GPa)	Young's modulus (GPa)	R_a roughness (μm)	Interlayer
2.7±0.1	25.6±3.2	188.0±15.8	0.05±0.01	TiN