Available online at www.sciencedirect.com
ScienceDirect
Surface & Coatings Technology 202 (2007) 1062–1066
SURFACE & COATINGS TECHNOLOGY
www.elsevier.com/locate/surfcoat

Influence of contact conditions on tribological behaviour of DLC coatings

B. Podgornik *, M. Sedlaček, J. Vižintin

Centre for Tribology and Technical Diagnostics, University of Ljubljana, Bogisiceva 8, SI-1000 Ljubljana, Slovenia

Available online 1 August 2007

Abstract

By providing excellent frictional properties and greatly improving wear resistance of sliding contact surfaces, diamond-like carbon coatings (DLC) offer a great opportunity for improving performance and durability, and reducing frictional losses in many mechanical systems. However, for the successful application of coated machine components, coatings have to perform reliably under dry and oil-lubricated conditions, with the majority of machine components still being oil-lubricated and operating under diverse contact conditions.

The aim of the present investigation was to determine the influence of contact conditions on the tribological behaviour of boundary lubricated DLC coatings, when using oils with extreme-pressure (EP) and anti-wear (AW) additives. Tests with ball-bearing steel ball being loaded against DLC coated discs were performed in the contact pressure range of 1.0 to 3.0 GPa, average sliding speeds of 0.01 to 0.15 m/s and at oil temperatures ranging from 20 to 200 °C.

While phosphorous-based AW additives had only minor effects, sulphur-based EP additives were found to reduce friction and wear of W-containing DLC coatings. Furthermore, increase in contact pressure or temperature accelerates the process of friction reduction and results in lower friction while increase in sliding speed has the opposite effect.

Keywords: DLC coatings; Contact pressure; Boundary lubrication; Friction; Additives

1. Introduction

Similar to the hard ceramic coatings (e.g., TiN, CrN, TiAlN,…) which became essential in the field of cutting and forming tools, low-friction coatings (i.e. diamond, DLC, MoS_2,…) are now becoming more and more important in the field of machine components, especially for automotive applications [1]. By giving excellent frictional properties and greatly improving wear resistance of contact surfaces [2–5], diamond-like carbon coatings (DLC) provide a great opportunity for further performance and durability improvement, and reduction of frictional losses in mechanical systems.

In the past, the development of efficient mechanical systems would have been impossible without advanced lubricant additive chemistry and proper lubricant formulation [6]. In order to meet durability and performance requirements, lubricants contain a wide range of additives which are blended with base oil. Especially anti-wear (AW) and extreme-pressure (EP) additives are crucial in minimizing friction and wear and protecting surfaces under severe contact conditions. In the case of metallic surfaces, action of extreme-pressure (EP) and anti-wear (AW) additives, used to reduce friction and wear of contact surfaces, is relatively well understood and controlled by complex tribochemical reactions between additive molecules and metallic surface [7–9]. However, this is not the case for DLC coated surfaces, especially when it comes to the influence of contact conditions.

Although DLC coatings show low friction and wear under dry sliding conditions [5,10,11] the majority of machine components will remain lubricated due to different reasons, at least for the near future. Therefore, for the successful application of coated components aimed for further performance enhancement coatings will have to perform adequately also under oil-lubrication while being exposed to diverse contact conditions. Some tribological studies suggest that the lubrication of DLC coatings is not successful and can, under certain conditions, make the tribological performance even worse than in non-lubricated systems [2,12,13]. But in other cases, DLC coated surfaces may show improved tribological properties [1,14,15], especially in the cases of coated/uncoated combinations [16].

The aim of the present investigation was to determine the influence of contact conditions on the tribological behaviour of boundary lubricated DLC coatings, when using additive-containing oils. For this purpose metal doped DLC coatings

* Corresponding author. Tel.: +386 1 4771 463; fax: +386 1 4771 469.
E-mail address: boja.podgornik@ctd.uni-lj.si (B. Podgornik).

0257-8972/$ - see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.surfcoat.2007.07.040

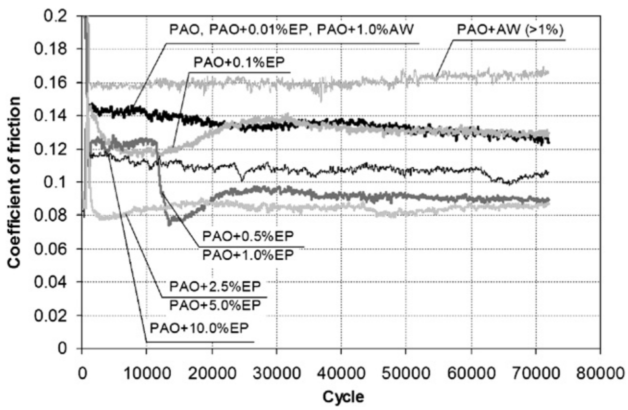

Fig. 1. Friction curves for boundary lubricated steel/W-DLC combination (p_H=1.5 GPa, v_s=0.02 m/s, T=50 °C).

(Me–C:H) paired with ball-bearing steel under reciprocating sliding were tested in terms of contact pressure, sliding speed and oil temperature.

2. Experimental details

W-doped hydrogenated amorphous carbon coatings with a multilayer structure of WC and a-C:H (WC/a-C:H), denoted W-DLC were used in this investigation. W-DLC coatings with a thickness of about 2 µm and a hardness of 1200 HV were deposited by a reactive sputtering process at a deposition temperature of ~230 °C. Coatings were deposited on hardened ball-bearing steel samples (AISI 52100), with a hardness value of 850 HV and a surface roughness value of $R_a \approx 0.05$ µm.

Boundary lubricated wear and friction tests (λ=0.005÷0.95) were performed in a high frequency test rig, with the standard 10 mm diameter steel ball bearing loaded against a coated stationary disc. Both test samples were ultrasonically cleaned in ethanol and dried in air prior to testing. Tests for up to 2 h, corresponding to a total sliding distance of up to 1 km, were performed in the contact pressure range of 1.0 to 3.0 GPa, range of averaged sliding speed of 0.01 to 0.15 m/s and testing temperature in the range of 20 to 200 °C. Lubricants included in the investigation comprise pure poly-alpha-olefin (PAO) oil (v_{40}=46.6 mm^2/s), and PAO mixed with EP or AW additive, using additive concentrations from 0.01 to 10%. The sulfur-based EP additive was a commercially available sulfurized olefin polysulfide, and the phosphorus-based AW additive a mixture of diamine monohexyl phosphate and amine dihexyl phosphate.

During testing, the coefficient of friction was monitored continuously as a function of the number of cycles. Wear of the specimens was determined at the end of the test using optical microscopy and profilometric techniques and worn surfaces analyzed by means of SEM, EDS, AES and XPS.

3. Results and discussion

3.1. Influence of additive concentration

As described in refs. [1,15–17], coating of discs with W-DLC results in faster and smoother running in, and lower friction and wear under boundary lubrication as compared to steel/steel combination. Furthermore, addition of EP or AW additives to PAO oil leads to further improvements in the tribological behaviour of steel/W-DLC material combination, especially when using sulphur-based EP additives [1,15]. In the case of pure PAO oil-lubricated steel/W-DLC combination tested at a contact pressure of 1.5 GPa, an average sliding speed of 0.02 m/s and an oil temperature of 50 °C displayed coefficient of friction of about 0.13 and wear rate of $8 \cdot 10^{-7}$ mm^3/Nm. Friction level remained almost the same with the AW additive concentrations of less than 1%, while higher AW additive concentrations led to friction (~0.16) and wear rates similar to uncoated steel contacts [1]. EP additive concentration, on the other hand, had much more pronounced influence on the tribological behaviour of W-DLC coatings [1,19], with the optimum additive concentration leading to coefficient of friction as low as 0.08 (Fig. 1).

As described in refs. [1,17] EDS, AES and XPS analyses of worn surfaces show that beneficial tribological behaviour of steel/W-DLC combination lubricated by oils containing S-based EP additives can be attributed to WS_2 containing tribofilm formation.

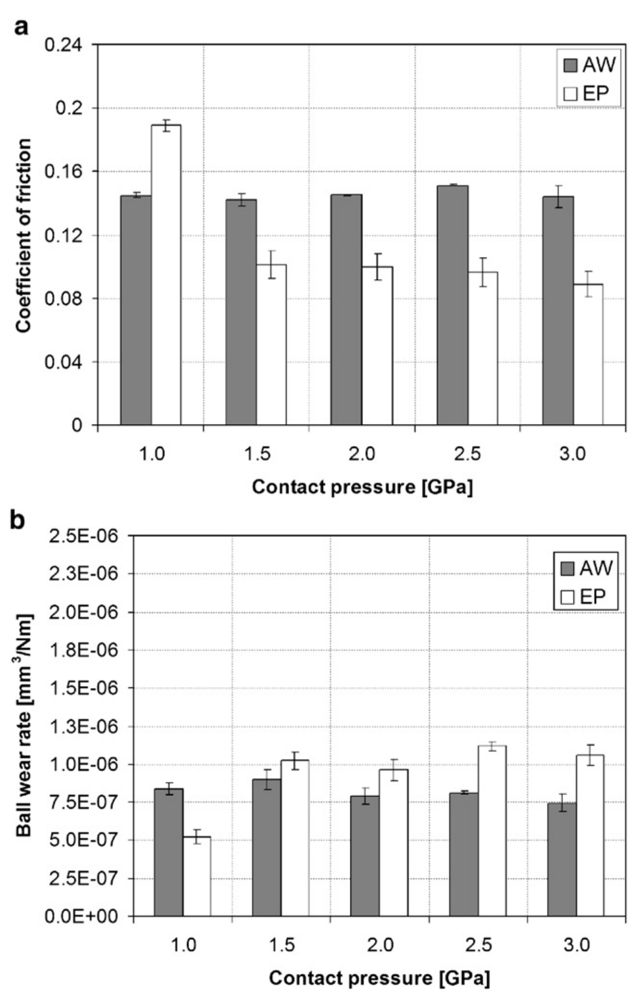

Fig. 2. Influence of contact pressure on (a) steady-state friction and (b) steel ball wear rate after 36,000 sliding cycles for steel/W-DLC combination (v_s=0.02 m/s, T=50 °C).