

DLC coatings for hydraulic applications

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Abstract: Replacement of lubricating oils with water or low-viscosity fluids is highly desirable in many industrial fields, on account of the environmental and economical advantages. Low lubricity of water might be insufficient for proper operation of hydraulic components, and diamond-like carbon(DLC) coatings are very attractive as solid lubricant films. A remote-plasma PACVD process was utilized to deposit hydrogenated DLC coatings (a-C:H) on different substrates. Microindentation measurements show that the coating hardness is around 35 GPa. Tribological behavior was evaluated by block-on-ring tests performed in water and water with alumina. The wear rate was calculated after measuring the wear volume by a laser profilometer. Morphological and compositional analysis of the wear tracks reveal that coating failure may occur by abrasive wear or delamination, depending on the substrate properties. Hard and smooth substrates give the best results and dispersed alumina particles increase the wear rate.

Key words: DLC; PACVD; chromium plating; water; wear; friction

1 Introduction

Substitution of water for lubricating oil in many industrial activities would be beneficial for several reasons, including prevention of fire hazard and avoidance of environmental risks related to leakage in service.

The present work is part of a research project supported by the European Community (Stream Project) to develop an innovative water-powered drilling hammer for excavation of ornamental stone. Inside the hammer, the piston that strikes the digging bit is required to slide with low friction and minimal wear, to ensure high energy efficiency and low water consumption. Diamond-like carbon(DLC) film was selected to coat the piston surface, in order to achieve these properties.

Recently, tribological behavior of DLC films in water[1–8] and water-based lubricants[9–10] attracted increasing attention, and features like hydrogen content, film hardness and Si-doping were investigated[1–7].

Friction and specific wear rate of a-C:H films deposited on silicon wafers were reported to be not influenced by the hydrogen content[1]. Superior anti-wear property of these films in water is ascribed to the difference in transfer phenomena, with respect to

tests in air. Hydrogenated and hydrogen-free DLC films with different hardness were deposited on precipitation hardened stainless steel[2–3] and their specific wear rate in water was found to decrease as their hardness increased, while the opposite trend was observed for the wear rate of a metallic counter part. Undoped a-C:H coatings deposited by rf-plasma technique exhibited severe wear in water, but silicon incorporation and modification of the deposition process (Ion Beam) demonstrated effective in improving the coating performance[4–5].

Tribo-tests on silicon-doped DLC films[6–7] showed that higher Si content reduced the friction and the wear of the mated body, although it increased the wear of the coating. It was suggested that tribochemical reaction of Si-DLC coating occurred in water and $\text{SiO}_x(\text{OH})_y$ gel was formed on the mated surface, with reduction of friction and counter-body wear. On the other hand, a large amount of Si caused severe chemical wear of the coating[6].

The tribological behavior of DLC coatings in water will be affected also by the properties of the substrate and this aspect was examined in the present work. Hydrogenated DLC coatings were deposited on different substrates and their wear resistance and failure mechanism were compared.

2 Experimental

DLC coatings were prepared by a PACVD process which operated in remote-plasma configuration. The details of the deposition equipment were described elsewhere[11].

The coatings were 1 μm thick and the microindentation measurements showed that their hardness is (35 ± 3) GPa and their elastic modulus is (251 ± 16) GPa (Poisson's ratio was taken equal to 0.2).

Substrates were selected to cover a wide range of hardness values, amongst materials that can ensure corrosion resistance in natural water. They are the following ones:

1) Martensitic stainless steel (AISI 420: Cr 13%, C 0.3%) in the annealed condition, with hardness of 2.4 GPa;

2) Cemented carbide (WC 94%, Co 6%) with hardness of 15 GPa;

3) Chromium-plated low-carbon steel (EN32b: C 0.15%, Mn 0.75%).

The chromium coating is 50 μm thick and its hardness is 11 GPa.

The tribological tests were performed in the block-on-ring configuration. During the test, a rotating ring was pressed against a stationary block, which was coated by the DLC layer. The sliding speed of the ring was 0.1 m/s and the normal load was 30 N. After the test, the worn volume was measured by a laser profilometer and the wear rate was calculated.

The wear tracks were also examined by SEM to investigate the failure mechanism.

The ring was made of Cr-plated steel (EN32b); its diameter was 45 mm and its thickness was 10 mm. The tests were performed in deionised water and alumina particles (size < 50 μm) were also added (1.5 g/L), to simulate the action of stone fragments which may be dragged in the contact areas during the hammer operation.

The wear rate and friction coefficient measured in these tests are reported in Table 1.

Table 1 Wear rate of DLC coating and coefficient of friction (COF) in water

Substrate	Wear rate/($\text{mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$)	COF
Stainless steel	8.1×10^{-6}	0.08
WC-Co	5.5×10^{-7}	0.06
Cr-plated steel	2.3×10^{-6}	0.06
Cr-plated steel (deionised water+ Al_2O_3)	4.9×10^{-6}	0.06

3 Result and discussion

The wear rate of the DLC coating on stainless steel is the highest one, presumably because of the lowest hardness of this substrate, in comparison with WC-Co and Cr-plated steel. Under the action of the normal load, asperities in the surface profile of the counter-part can locally plasticize the soft stainless steel, while the DLC film cannot accommodate so large deformations. Then, the coating becomes fractured and the fragments can be rapidly removed by the sliding asperities. Actually, the delamination of the cracked coating is observed at the edge of the wear track (Fig.1).

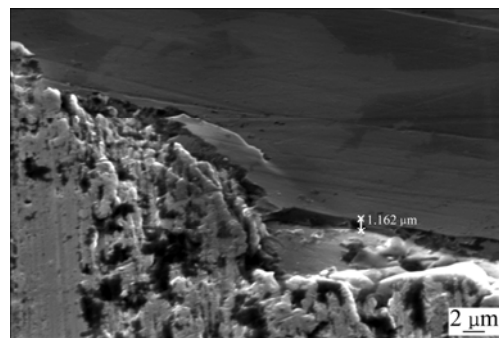


Fig.1 SEM image of DLC on stainless steel at edge of wear track

The DLC layer on WC-Co exhibits a wear rate remarkably lower and tests were performed to elucidate the failure mechanism. In the SEM image acquired by secondary electrons (Fig.2(b)), the wear track is hardly discernible, but the observation by backscattered electrons (Fig.2(a)) shows that the DLC coating becomes thinner in the wear path; indeed, it appears brighter because of the presence of heavier elements in the substrate (W and Co).

The analysis of the surface topography by AFM (Fig.2(c)) reveals that a micro-cutting morphology exists on the worn DLC film. This morphology consists of thin grooves parallel to the sliding direction and is typically produced by the abrasive action of the asperities of the counterpart.

The DLC coating on chromium shows a peculiar failure mechanism. In the SEM image shown in Fig.3, acquisition by backscattered electrons enhances the contrast between DLC (black) and uncoated chromium (white) and points out that the DLC detachment follows a branched pattern.

Each branch goes along the path of a microcrack existing in the chromium layer; and these cracks are usually present in electroplated chromium as a consequence of tensile stresses retained during deposition.

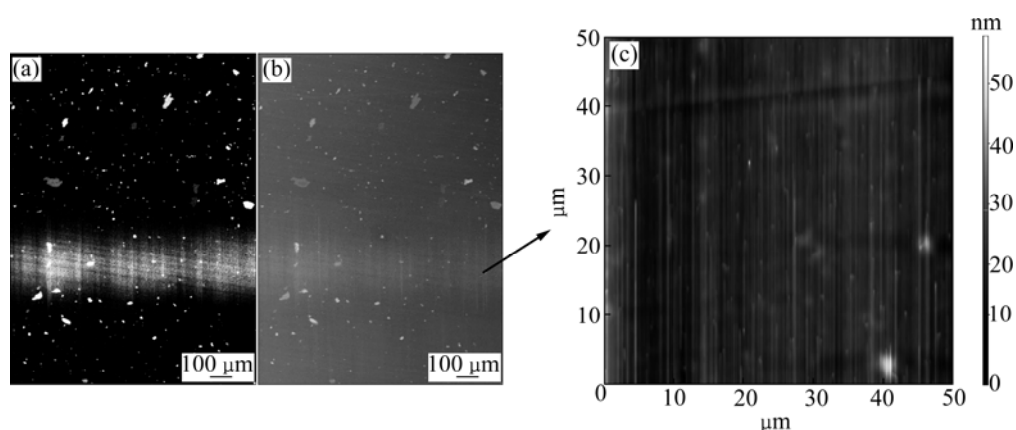


Fig.2 Backscattered electron (a) and secondary electron (b) SEM images of wear track of DLC film on WC-Co and AFM topography of worn path (c)

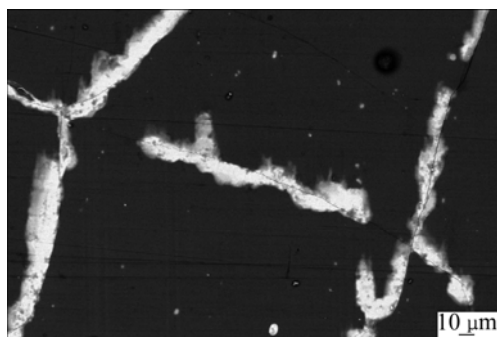


Fig.3 SEM image of block coated with chromium and DLC after testing in deionised water

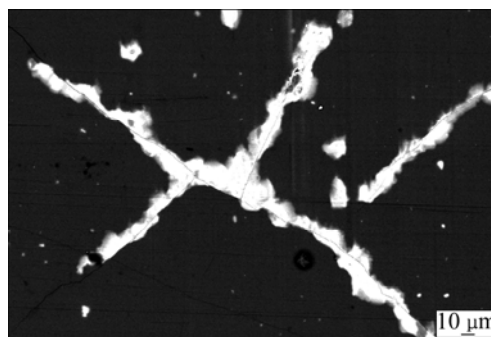


Fig.4 SEM image of block coated with chromium and DLC after testing in deionised water with dispersed alumina

Probably chromium microcracks promote a self-sustaining mechanism for DLC detachment, which starts with DLC fracture by buckling around the cracks and propagates through the compressive action of the counter-body asperities against the free edges of the DLC film. The deposition of a chromium layer with low density of microcracks could be beneficial for saving the integrity of the DLC coating. A low density of microcracks can be achieved through the electrodeposition of chromium in hexavalent chromium based electrolytes with low content of chromium and at low deposition temperatures. At high temperatures, up to 75 °C, in electrolytes with high chromium content, a crack free chromium electrodeposit could in case be obtained.

When alumina particles are dispersed in water, the failure mechanism is quite similar, as demonstrated by the same detachment pattern and the same correspondence with chromium microcracks (Fig.4). However, the presence of dispersed alumina results in a higher wear rate (Table 1).

Alumina particles can activate a three-body wear mechanism, which may strongly increase the wear rate of the mating surfaces. For comparison, the wear tests were

repeated on Cr-plated blocks, without the DLC coating. In this case, the wear rate increased by a factor of 6.3 after the addition of alumina to water. Therefore, it appears that the high hardness of the DLC coating is beneficial to reducing the wear enhancement induced by the dispersed ceramic powder.

These tests probably create wear conditions more severe than those existing in the drilling hammer, because alumina particles are harder than stone chips, but this choice leads to a conservative estimation of the wear resistance of the tested coatings.

No evidence of corrosion products was found by SEM analysis of the Cr-plated blocks, after many cycles of soaking and drying. On the contrary, rust is visible on the uncoated low-carbon steel after soaking in water for short time. The expected protective action of the chromium layer is then confirmed.

The values of the friction coefficient are in agreement with those reported for DLC coatings deposited by other techniques[1–2, 6].

The duplex coating (Cr plus DLC) exhibits a favorable tribological behavior, although it does not attain the highest wear resistance. However, the wear rate of the duplex coating would correspond to an acceptable

duration of the hammer life, under typical operating conditions. The selection of hard metal as a substrate would actually provide the highest wear resistance, but important drawbacks exist: low fracture toughness, difficult machining and high cost. On the contrary, Cr-plating enables the employment of low-alloy steels, which ensure high toughness and are easily manufactured.

4 Conclusions

The tribological behavior of DLC coating in water was evaluated for the development of an innovative water-powered drilling hammer. The failure mechanism of the DLC coating was found to depend on the properties of the base material.

A soft substrate can suffer large deformation, thus inducing coating fracture and delamination. On a hard substrate, the DLC coating exhibits higher wear resistance, resulting from the existence of an abrasive wear mechanism. Microcracks in the substrate can promote local detachment of the DLC film.

A duplex coating, consisting of electroplated chromium covered by a DLC layer, combines beneficial tribological properties with corrosion protection, even in water containing hard abrasive particles. This surface treatment enables the use of a ductile and tough substrate.

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