Tribological Properties of Multilayered Vacuum Coating

Aleksandr Rogachou, Aleksandr Popov, Dmitri Piliptsov, Maksim Yarmolenko, Aleksandr Rogachev, Nikolai Fedosenko

Abstract:

The results of studies show the deposition conditions of the titanium-nitride based coatings and their structure influence on the tribological characteristics of the dry friction and in the diesel fuel. Tribological characteristics of multilayered systems on the basis of diamond-like coatings (DLC) have been studied. The deposition of the systems onto small-size cutting tools is found efficient for improving their service characteristics. When depositing the coatings to the cutting tool surface the microrelief of edges is not distorted and the service life increases 1.3 - 1.5 times. The morphology and tribological behaviour of composite and multi-layer polymer coatings based on polytetrafluoroethylene (PTFE) and polyurethane (PU) are studied after deposition by means the method of electron beam dispersion. It is shown possibility to produce fine-film systems based on polyurethane with polytetrafluoroethylene as filler that possess high tribological performance.

Keywords: *diamond-like coatings, polytetrafluoroethylene, polyurethane, friction.*

1. Introduction

Deposition of thin hard coatings from the gaseous phase onto friction surfaces is an effective method of improving their wear resistance and reducing the friction coefficient [1]. Vacuum coatings from polymers, carbides, nitrides and oxides of transition metals are the most promising and their structure and tribological characteristics have been studied sufficiently well [1], [2]. Yet, their performance varies within a broad range and is a function of the coating structure and thickness, sliding velocity, and magnitude of stress in the contact zone [1]. This demands the development and use of multilayered coatings in friction units. Each layer of such coatings fulfils a definite function and their combination produces integrity of high performance characteristics. Hence, it is essential to investigate the tribological behaviour of the coatings and effects of deposition conditions in order to identify the optimal performance and the most effective parameters of the thin film, for solving tribological problems, such as hardening and recovery of precision friction units.

2. Experimental

Flat substrates made from hardened ball bearing steel 100 CR 6 with hardness ≈7.9 GPa were used as tribotest specimens. First they were polished to roughness R_a = 0.063 m and then multilayered coatings were deposited. Titanium nitride coatings (TiN) were produced by condensation at ion bombardment with or without magnetic separation of the drop phase at nitrogen pressure $6{\cdot}10^{-2}$ Pa. The authors have studied DLC, carbon coatings alloyed with titanium (Ti+C), titanium nitride (TiN) coatings obtained using the magnetic separation of the plasma flow, and laminated coatings (Ti-DLC) consisting of alternating titanium and DLC layers. Titanium-alloyed carbon coatings were formed by the simultaneous deposition of carbon and titanium onto the tool surface. As a rule, the layers were deposited during one cycle. Copper coatings were deposited by arc evaporation with the arc current 90 A. Solid lubricant layers from polymerized products of electron beam dispersion of PTFE, PU were obtained using the methods described in [3], the conditions were the following: the energy of electrons - 1.5 keV, the rate of coating deposition - 0.8 m/min, the surface temperature was equal to the ambient temperature. Before the deposition of the multilayered coating the surface of the specimen was bombarded with titanium ions having the energy 1.5 keV.

A multiple wave microinterferometer MII-11 served to evaluate the coating thickness by measuring the height of the step on the reference specimen and also by gravimetry. The thickness and the rate of deposition of PTFE, PU coatings were registered with a quartz resonator directly during the layer depositing.

The ball reciprocated on the flat without lubrication and in the diesel fuel during tribotests. The sliding velocity in the centre of the friction track was 0.01 m/s. A ball of 6 mm in diameter made of 100 CR 6 steel served as a counterbody, in some cases it was also coated. The friction coefficient was recorded during the dynamic contact; the wear rates of the counterbody and the coating were registered after each test.

3. Results and discussion

The properties of the coatings produced by CIB, including their tribological characteristics, are known to depend strongly on the concentration of the drop phase in the flux governing the coating surface morphology.

The accomplished tribological studies of the multilayered titanium-nitride coatings with a total thickness up to 2 μm, when produced under optimal process conditions, have shown sufficiently low friction coefficient against 100 CR 6 steel and high wear resistance (Figure 1, Table 1).

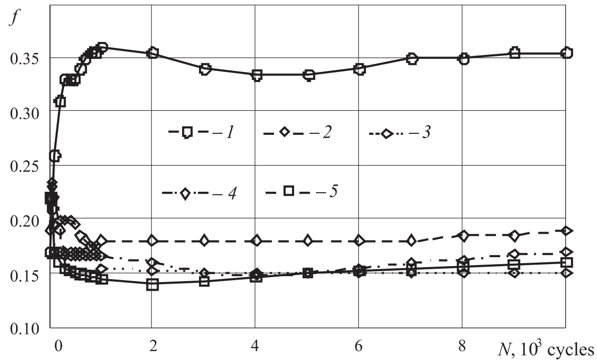

Figure 1. Friction coefficient as a function of number of cycles in diesel fuel for specimens with different coatings: 1 - original specimen from 100 CR 6 steel; 2 - TiN; 3 - TiN + PTFE; 4 - TiN + Cu; 5 - TiN + Cu + PTFE.

Table 1. Tribological Characteristics of Friction Pairs with Multi-Layered Coatings at Friction in Diesel Fuel.

Coating composition	Counterbody wear rate I [10^{-9}]	Pressure in contact zone p [MPa]	Counterbody linear wear Δh [µm]
100 CR 6	26.60	10.19	5.20
TiN*	73.50	3.60	14.70
TiN* + Cu	66.50	3.97	13.30
TiN* + Cu + PTFE	58.50	4.52	11.70
TiN	4.15	63.70	0.83
TiN + PTFE	6.50	40.70	1.30
TiN + Cu	3.00	88.10	0.60
TiN + Cu + PTFE	2.60	99.50	0.53

Figure 1 shows that the friction coefficient of the original uncoated specimen stabilizes after 300 cycles at a level 0.34–0.36. The friction coefficient of the specimen with the TiN coating 0.21 m thick is 0.18, provided it is produced under optimal process conditions. Table 1 shows that the wear rate of the counterbody (100 CR 6 steel ball) is strongly determined by the presence of the drop phase in the TiN coating. When drops are 10–20 µm in size the wear of the counterbody almost triples compared with the original specimen. When the plasma flux is separated magnetically (dimensions of the drops in the coating are 4 m) the wear of the counterbody decreases three times compared with the wear in a steel–steel friction pair.

When a two-layer coating is produced by consecutive deposition of TiN and Cu layers within one process cycle (Cu coating has the thickness d = 0.074 µm), the friction coefficient decreases after 700 cycles still more and the wear rate of the counterbody diminishes 2.1 times. In the case of a two-layer TiN + PTFE coating (d = 0.41 µm for the PTFE coating) the friction coefficient stays below the friction coefficient of the specimen coated with TiN, the wear rate of the counterbody is 1.6 times lower. When the fluoropolymer coating is 0.1–0.5 µm thick, its wear resistance is maximal, besides it is transferred to the counterbody relieving local stresses at the real contact spots. Coating with three layers (TiN, copper, and PTFE) reduces the friction coefficient still more and wear rate 2.5 times compared with the one-layer TiN coating. The wear of the counterbody is approximately 10 times less than that of the original 100 Cr 6 steel specimens.

The results of the tribotests given in the table 2 show that the layered coating consisting of alternating titanium and carbon layers has the best wear resistance. In this case the wear rate is < $0.006 \cdot 10^{-11}$ m^3/m and during the one-hour operation of the machine under a contact pressure of 276 MPa stable friction coefficient of 0.36 and contact resistance of 50 mOhm are kept. A higher wear resistance of the coatings compared, for example, to the multilayer coatings based on DLC and TiN is evidently explained by carbide synthesis occurring in interphase layers. The authors of [4] [5] pointed out the probability of such reactions.

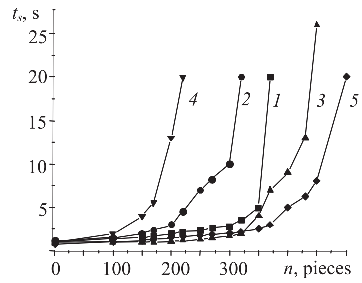

Fig. 2. Hole drilling time ts as a function of number of drillings n, drill diameter d and number of layers: a - d = 0.8 mm; 1 - uncoated; 2 - TiN; 3 DLC; 4 - (C+Ti); 5 - 4 layers (TiDLC).

The TiN-coating adjacent to the substrate is seen to have the granular structure with the grain size ≈ 0.07 µm. The titanium and DLC layers have the fine structure with pronounced blurred phase boundaries of diffusion nature.

Good tribological behaviour of the multilayer coatings is confirmed by the life tests of the coated drills (Fig. 2). It is seen from the curves in Figure 2 that when depositing TiN-coatings by the common technique the drilling time increases more rapidly compared to the uncoated drill. It results apparently from the fact that the cutting edges damaged in the arc spraying of the titanium nitride coating get blunt fast.

Table 2. Tribological Characteristics of Coatings.

Coating	Number of layers k	h [µm]	f	I_v [10^{-11} m^3/m]
No	–	–	0.52	1.4
TiN	1	1.1	0.59	0.75
Ti–DLC	11	0.1–0.2	0.22	<0.2
TiN–(DLC–TiN)	1(4)	0.8–(0.05–0.05)	0.18	0.2
TiN–(Ti–DLC)	1(7)	0.8–(0.01–0.05)	0.36	<0.006

The morphology and tribological behaviour of composite and multi-layer polymer coatings based on polytetrafluoroethylene and polyurethane are studied after deposition by the method of electron beam dispersion. The analysis of the results proves that the coatings produced by concurrent dispersion of the mixture of the polymers (curves 5) have a rather low and stable (what is essential) friction coefficient (its variations during repeated tests did not exceed 25%) compared to other thin films. It has been observed that PTFE in the multi-layer coatings produced by consecutive application of PU and PTFE is practically fully removed from the friction zone after 80 friction cycles. This is the reason why the monolayer PTFE coatings have a relatively short service life. Yet the friction coefficient after such modification of the rubbers is rather low, especially at the initial stages of friction. Morphological changes in the coating during friction were determined with scanning electron microscopy. It was established that friction of rubbers protected with composite polymer-polymer coatings is accompanied with smoothing of the coatings, especially of the PU drop formations, resulting in appearance of a system of folds perpendicular to the direction of movement of the indenter. The friction process produces no cracks in the coating and it is an essential feature of wear of such coatings. No wear of the rubber surface layer was detected after 10^3 friction cycles that would always be the case if elastomers modified by application of a PTFE coating alone are worn.

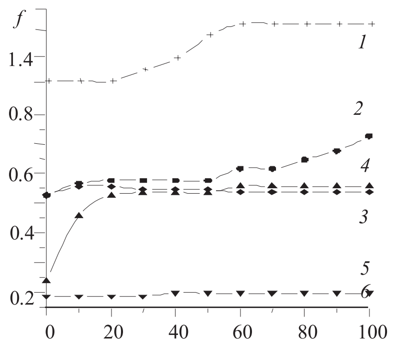

Fig. 4. Dependence of friction coefficient f on number n of cycles of abrasion of modified rubbers. 1 - Rubber unmodified; 2 - Duplex PU coating (layer thickness - 0.25 μm) + PTFE (0.25 μm); 3 - Duplex PU-PTFE coating (ratio between the components - 1:1; 0.25 μm) + PTFE (0.25 μm); 4 - Duplex PU-PTFE coating (2:1; 0.25 μm) + PTFE (0.25 μm); 5 - Monolayered PUPTFE coating (2:1; 0.5 μm).

4. Conclusion

It is demonstrated that the friction pairs, whose components have multi-layered TiN + Cu, TiN + Cu + PTFE coatings demonstrate the best tribological characteristics when the coatings are deposited under optimal conditions with account for the temperature criterion and the concentration of the drop phase. Tribotests of the coatings have shown that the friction coefficient remains stable in the range ≈ 0.14–0.18. The wear of the counterbody is minimal in the diesel fuel.

The deposition of the diamond-like coatings and multilayer systems on their basis onto small-size cutting tools is shown to be highly efficient for improving their performance. The multilayer DLC - and titanium-based systems have the highest wear resistance. Their deposition does not lead to the damage of the cutting edges that provides increase 1.35–1.47 times in the life.

Our study determined the main morphological features of deposition of composite PTFE- and PU-based coatings. It was established that binary polymer-polymer coatings structured as a PU-matrix containing PTFE particles have the best tribological characteristics. Multi-layer coatings have a higher friction coefficient and fail more intensively in the process of dynamic contact as compared to composite coatings.

AUTHORS

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References

[1] Matsevityi V.M., Lyubchenko A.P., Kazak I.B., *Journal of Friction and Wear*, vol. 4, no. 17, 1996, pp. 93-96. (in Russian)

[2] Rogachev A.V., Yarmolenko M.A., Tszyan Syao Hun, Lude Lu, *Journal of Friction and Wear,* no. 2, vol. 25, 2004, pp. 74-77. (in Russian)

[3] Rogachev A.V., Kazachenko V.P., Schebrov A.V., *Collection of Papers: Polycom-98*, Gomel, 1998, pp. 59-65. (in Russian)

[4] Popov A.N., Rogachev A.V., Kazachenko V.P., *Abstracts of Intern. Scientific Conf. "Materials and Technologies - 2000"*, Gomel, 2000, pp. 79-80. (in Russian)

[5] Rogachev A.V., Popov, Kazachenko V.P., Sidorskii S.S., *Materials, Technologies and Tools*, no. 2, vol. 5, 2001, pp. 77-80. (in Russian)