Effect of coatings on lifetime of composite dampers

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Abstract. A comprehensive study of the mechanical and tribological properties of the carbon composite material of coated and uncoated damping spacers was carried out. Indentation techniques, microscopy, friction tests at different scale levels were used in this study. Previously developed models were used to determine the mechanical properties of coatings. It is shown that the presence of the coating has small effect on the friction coefficient, and the wear rate for coated samples is lower than for uncoated ones. It is obtained that under high loads, which may randomly occur at contact, there is a probability of coating delamination. The influence of the coating thickness on the probability of delamination is calculated and analyzed.

1. Introduction

Ball screw is an electromechanical actuator that transfers rotating motion into a linear one. It has a wide range of applications, for example, it is used in mechanical engineering, robotics, assembly lines, component installers, etc. However, the accuracy of the feed movement during prolonged use is deteriorated due to wear of the ball screw components. This occurs as a result of adhesion (microwelding of plastically deformed microcontacts), abrasion (removal of chips on the surface of components), destruction of surfaces caused by tribochemical reactions \cite{1}. In addition, in order to eliminate gap and ensure the necessary stiffness of the system, the technology of preloaded ball screws is used at most industries. This technique eliminates gap and increases the stiffness of the components, but the friction characteristics vary significantly depending on the preload value. It means that sliding friction increases, the uniformity of movement decreases, wear and heat generation increase. As a result the quality of movement and the service life worsen. In order to overcome the compromise between the stiffness and friction characteristics the following approaches are used in the literature. The ultrasonic nanocrystal surface modification (UNSM) technology was studied to increase the wear resistance and fatigue strength of a steel screw by reducing friction and increasing surface integrity \cite{2}. Also, the new principles of ball screw design were proposed and ceramic balls or PVD coatings were used to reduce friction and improve ball screw performance \cite{3}. Besides a number of researchers have proposed mathematical models for predicting the durability of the system \cite{4–6}. One of the new technical solutions is the using of spacers between adjacent balls, which is described in \cite{7}. The spacer is a damper that minimizes noise, vibration and frictional loss. It has cylindrical shape with an arched recess at the ends and a through central hole to improve the lubricating and cooling effect. The damper is made of carbon-based composite material. As this material is quite compliant and quickly wears out, it is possible to use a coating applied to the contact surface of dampers to increase wear resistance.

The object of this study is dampers whose working surfaces are coated by carbon-based film. There are variety of papers about friction and wear of such coatings, especially diamond-like coatings...
DLCs have excellent mechanical and tribological properties that are comparable to those of crystalline diamond films. They can be made very hard and tough. Previous tribological studies confirm that low friction of such coatings can significantly reduce the sliding friction coefficient both with dry contact and with lubricant [8]. However, their high hardness and high residual stresses often lead to poor adhesion to the substrates. In addition, residual stresses can cause cracking of the coating due to the appearance of cohesive and adhesive cracks during operation, especially at high load values and, therefore, cause an increase in wear rate and friction coefficient. These issues have been successfully addressed by adapting graded intermediate layers between the DLC and the substrate and thus homogenizing the stress distribution [9]. Elements such as Ti, Cr, W are usually used as intermediate layers and as alloying additives for DLC layers [10, 11]. The properties of a multilayer structure with the contents of Cr, CrN, Cr/C as an intermediate layers between the DLC coating and the steel substrate are studied to increase the adhesion and hardness of the coatings [12]. A similar technology was applied to harden the surface of the carbon-based composite material, which is considered in this study. This material is compliant, but carbon coatings were deposited even to more compliant elastomers [13].

The aim of this work is to study the frictional interaction and the mechanisms of fracture of the carbon coating with Ti, used as the alloying component.

2. Materials and methods

2.1. Samples
The object under investigation is full-scale ball screw dampers made of a carbon-based composite material with a carbon coating (with a Ti alloying component) and without coating (figure 1).

![Figure 1. Ball screw dampers.](image)

DLC coatings were deposited on plastic substrate (Titalon 2115AF) using a Closed Field Unbalanced Magnetron Sputtering (CFUBMS) system with a Ti target and three C targets. The target and sample surfaces were cleaned by sputtering with Ar+ ions for 30 min and 10 min, respectively. Prior to the sputtering process, a Ti interlayer was deposited using a Ti target current of 1 A for 10 min. The main DLC coatings deposition process were performed using Ar gas of 18 sccm as working gas and pure N2 gas of 2 sccm and C2H2 of 10 sccm as the reactive gases and a substrate bias of -35 V.

To determine the thickness of the applied coating a section of the sample was prepared and average value of thickness was obtained by means of a scanning electron microscope.

2.2. Indentation methods
Indentation experiments were carried out using a NanoScan-4D nanohardness tester (figure 2a). A corundum spherical indenter with a radius of 65 μm was pressed into the samples surface during testing. The maximum normal load was 5 mN. As a result, average curves of the dependence of the force on the penetration depth were obtained to calculate the elastic modulus of a homogeneous material and coating. For the case of coating, deformation of relatively compliant substrate should be taken into account in calculation of elastic characteristics of coating material [14].
To determine the fracture mechanism wear tests were carried out for coated samples. The tests were carried out under extreme loading conditions in comparison with those realized in ball screw. In this mode, a special table equipped with a tangent force sensor was connected to the nanohardness tester. This test was carried out on the basis of multi-cycle reciprocating sliding with constant normal loads of 5 mN and 10 mN. A corundum spherocical tip with a radius of curvature of 65 μm was chosen as an indenter. The cycle consisted of 50 double passes. In this case, the sliding velocity was 6 μm/s, and the pass length was 1 mm.

2.3. Wear test method
Comparative macro tests to assess the friction coefficient and the fracture mechanism of composite materials with and without coating were carried out on a UMT-2 tribometer according to the pin on disk contact scheme (figure 2b). Polished disk made of “20X13” chromous steel (~ 60 HRC) was used as a counterbody. The tests were carried out with the following parameters: the applied load was 7 N, the friction path was 1 m, and the sliding velocity was 0.01 m/s.

After testing the images of surface were obtained. For these purposes a FEI Quanta-650 scanning electron microscope (SEM) with an attachment of EDAX microanalyzer in low vacuum mode (residual pressure was 50 Pa) was used. Images were obtained in back-scattered electrons. To study the elemental composition of the surface an X-ray spectral analysis was performed.

2.4. Modeling of friction contact
Experimental conditions (Nanoscan-4D) are used as input parameters for the calculation of contact characteristics and internal stresses. Sliding contact of a spherical indenter and a plane coated body is under consideration (figure 3). Contact and internal stresses are obtained from the following boundary conditions at the surface (z = 0):

\[
\begin{align*}
\sigma_z^{(1)}(x, y) &= p(x, y), & \tau_{xz}^{(1)} &= -\mu p(x, y), & (x, y) \in \omega \\
\sigma_z^{(1)} &= 0, & \tau_{xz}^{(1)} &= 0, & (x, y) \notin \omega \\
\tau_{yz}^{(1)} &= 0, & -\infty < x, y < \infty
\end{align*}
\]
Here $p(x, y)$ is unknown contact pressure, $\omega$ is the contact zone with radius $a$. Method of the contact problem solution with such input parameters as coating thickness, geometry of the smooth indenter, load, and elastic properties of coating, substrate, and the indenter is presented in [15].

![Figure 3. Scheme of friction contact.](image)

At the coating-substrate interface the complete adhesion is realized:

$$
\begin{align*}
\omega^{(1)} &= \omega^{(2)}, & \nu_x^{(1)} &= \nu_x^{(2)}, & \nu_y^{(1)} &= \nu_y^{(2)} \\
\sigma_z^{(1)} &= \sigma_z^{(2)}, & \tau_{xz}^{(1)} &= \tau_{xz}^{(2)}, & \tau_{yz}^{(1)} &= \tau_{yz}^{(2)}
\end{align*}
$$

In (1) and (2) $\sigma_z^{(i)}$, $\tau_{xz}^{(i)}$, $\tau_{yz}^{(i)}$, $w^{(i)}$, $\nu_x^{(i)}$, $\nu_y^{(i)}$ are stresses and displacements of elastic coating ($i = 1$) and substrate ($i = 2$).

Boundary element method is used to solve the problem of calculation of stresses in friction contact. The contact zone is considered as a system of squares with size $\Delta s$ with uniform distribution of normal and tangential forces inside each of them. Thus the problem is reduced to calculation of stresses due to uniform load distribution, and it can be solved by method based on double Fourier transforms and superposition [16, 17]. Calculation of stresses in coatings in experimental conditions for different loads in friction contact can be used to determine critical values of stresses, which provide the coating fracture [18].

3. Results
3.1. Determination of coating thickness and indentation results
To determine the thickness of coating a SEM image of the sample section was obtained (figure 4). The coating thickness is 14–22 µm with average value of 19 µm.
Figure 4. Image of a sample section with coating thickness values.

In [19] the three different phases with significantly different values of the reduced Young's modulus were revealed on an uncoated sample. The integral modulus of elasticity is close to the local modulus of a less rigid reinforcing inclusion and is of 400 MPa. For the coated sample the elastic modulus is of 620 MPa. The results were determined by the method proposed in [14], based on the averaged curves of the dependence of force on the penetration depth (figure 5), obtained on a nanohardness tester in the indentation mode.

![Indentation force on the penetration depth for the samples.](image)

Figure 5. Indentation force on the penetration depth for the samples.

3.2. Results of micro tribological tests and stress state calculations
Wear test on a nanohardness tester show that the coating failure has brittle nature. The SEM images (figure 6) demonstrate the fracture process after the tests. An analysis of these images show that with an increase in the normal load, the quantity of fragments with a delaminated coating as well as their size increased.
Concentration of tensile and principal shear stresses often leads to brittle fracture of the coatings. That is the reason we consider here these stress components for the starting values of friction coefficient (0.3) and two loads. The numerical values of tensile-compressive stresses for the surface of the coatings and for coating material at the interface can be analyzed from figure 7.

Maximal tension is realized at the surface due to friction. We can see here, that tension at the interface is almost the same for larger load; and the location of surface and interface maxima one under another may be the reason not only for crack initiation, but for fragmentation and delamination of the coating.

3.3. Results of macro tribological tests
The friction coefficient of coated and uncoated samples was compared. The mechanism of coating wear was also studied. The degree of change in the wear resistance of samples was determined. The UMT-2 tester was applied for this test. As a result of the study (a typical graph is shown in figure 8), it was found that for the macro tests there is no decrease in the friction coefficient (values are ~ 0.31), while the wear rate for samples with coating is lower than for samples without coating. This effect can be observed in SEM images shown in figure 9, where the width of the friction track for a sample with coating is much smaller than for a sample without coating.
Figure 8. Friction coefficient (COF) vs. test time.

Figure 9. SEM images in the back-scattered electrons of the samples after macro tribological test: (a) – with coating, (b) – without coating.

In the selected areas in figure 9 an X-ray spectral analysis was performed. The chemical composition data are presented in table 1.

Table 1. Elemental analysis in the selected areas after tribological tests.

| Selected area | The content of the component, mass. % |
|---------------|---------------------------------------|
|               | C  | N  | O  | F  | Ti |
| 1             | 68.5 | 11.0 | 16.2 | 3.7 | 0.6 |
| 2             | 30.8 | 5.0  | 22.2 | 4.2 | 37.8 |
| 3             | 64.7 | 9.7  | 21.2 | 4.4 | -   |
| 4             | 63.6 | 12.6 | 15.4 | 8.4 | -   |

An analysis of the images show that the fracture character of the coating surface is brittle with separation of coating fragments, as in the micro tribological tests (see figure 6). The elemental composition of the samples surface, presented in the table 1, confirmed that titanium (coating material) is practically absent in the fracture zone. This allows to suggest that at high loads which can randomly occur in ball screws there is a possibility of coating fragments delamination.

4. Conclusions
The elastic modulus for dampers without coating and with carbon coating were calculated (400 and 620 MPa respectively).
According to the results of macro tribological test, there is no decrease in the friction coefficient. The values of this parameter both for samples with and without coating are \( \sim 0.31 \). However the wear rate for samples with coating is less than for samples without coating.

The wear tests show that the fracture of the coating is brittle with separation of coating fragments. At typical loads the presence of coating significantly increases the life of the friction pair.

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References
[1] Fleischera J and Herdera S 2012 *Procedia CIRP* **1** 621–26
[2] Amanov A and Pyun Y 2018 *Tribology International* **123** 105–19
[3] Verl A, Frey S and Heinze T 2014 *CIRP Annals* **63**(1) 361–64
[4] Li F, Jiang Y, Li T and Ehmann K 2018 *Mechatronics* **55** 27–37
[5] Brecher C, Eßer B, Falkner J, Kneer F and Fey M 2018 *CIRP Annals* **67**(1) 409–12
[6] Ni Zhen and Qi An 2018 *International Journal of Mechanical Sciences* **137** 68–76
[7] Chiu Y and Yang P 2003 *United States Patent* No. US 6,561,054 B1
[8] Andersson P, Koskinen J, Varjus S, Kolehmainen J, Tervakangas S and Buss W 2008 *Tribotest* **14** 97–112
[9] Voevodin A A, Walck S D and Zabinski J S 1997 *Wear* **203–204** 516–27
[10] Hongxi L, Yehua J, Rong Z and Baoyin T 2012 *Vacuum* **86** 848–53
[11] Guo C Q, Pei Z L, Fan D, Gong J and Sun C 2015 *Diam. Relat. Mater.* **60** 66–74
[12] Duminica F D, Belchi R, Libralesso L and Mercier D 2018 *Surface & Coatings Technology* **337** 396–403
[13] Thirumalai S, Hausberger A, Lackner J M, Waldhauser W and Schwarz Th 2016 *Surface & Coatings Technology* **302** 244–54
[14] Goryacheva I G, Torskaya E V, Kornev Y V, Kovaleva I N and Myshkin N K 2015 *Journal of Friction and Wear* **36**(3) 262–65
[15] Torskaya E V and Goryacheva I G 2003 *Wear* **254**(5–6) 538–45
[16] Nikishin V S and Shapiro G S 1977 *Space Problems of the Elasticity Theory for Multilayered Media* (Moscow: VTs AN SSSR) p 260
[17] Torskaya E V 2002 *J Friction Wear* **23**(2) 16–23
[18] Kravchuk K S, Useinov A S, Torskaya E V and Frolov N N 2015 *Mechanics of Solids* **50**(1) 52–61
[19] Tsukanov I Yu, Torskaya E V, Lapitskaya V A, Kuznetsova T A, Horng J H and Kao W H 2020 *Journal of Friction and Wear* **41**(2)