Investigation of Tribological Properties of Carbide Coatings Deposited by Electrospark at Piezoelectric Tribocontact

J. Padgurskas[a], A. Žunda[a], R. Rukuiža[a], A. Andriušis[a], V. Mihailov[b], D. Metrikaitė[a]

[a]Institute of Power and Transport Machinery Engineering,
Aleksandras Stulginskis University,
Studentu 15, Akademija LT-53362, Kaunas, Lithuania,
e-mail: juozas.padgurskas@asu.lt , raimundas.rukuiza@asu.lt
[b]Laboratory of Electroerosion for Materials Treatment and Corrosion Protection,
Institute of Applied Physics,
5, Academiei str., Chisinau, MD-2028, Republic of Moldova

Investigations presented in this paper were carried out using an originally designed rotary piezoelectric motor of a standing wave tribotester. Test conditions, such as the normal force value in the friction pair, the rotor stop torque value, and the test duration can be programmed and changed in a desirable mode. The rotating speed, covered distance and loading torque of a piezo actuator were measured. Two different coatings (WC-Co8 and TiC15-Co6) were tested as the rotor friction surface and the wear of friction pairs (rotor, counter body) was evaluated after the tests. Investigations reveal an incidental advantage of output parameters of the piezo actuator with the TiC15-Co6 coating on the friction pair. Besides, high hardness of carbide surfaces requires paying more attention to the wear resistance of the frictional material of the counter body.

Keywords: piezo actuator, friction pair, coating, WC-Co8, TiC15-Co6, wear, rotating speed.

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INTRODUCTION

Piezoelectric actuators are considered to be micro-engines of the 21st century. They are used in precise positioning equipment where high accuracy is required. This property is very important in such application areas as medical technologies, measurement techniques, space engineering, etc. Modern high-tech technologies enable easy automation of small-size and precise details manufacturing. Assemblage of such components is taking place at the scale of microns [1, 2].

Regardless of the application, the efficiency of friction joints depends on the mechanical properties (hardness, brittleness, and elasticity), surface roughness and operation conditions (load, speed, presence of lubrication, etc.). Tribological processes in the friction contacts of such actuators are very important. Their investigation is complicated because of high frequency vibrations – up to 500 kHz and higher, [3] and low amplitude of motion – up to 10 µm [4, 5]. The efficiency of a piezoelectric actuator friction pair is influenced by roughness and hardness of surfaces in contact. The wear of the counter-body is a very important characteristic for the longevity of friction pair because piezoelectric ceramic materials are very hard. When the counter-body is too soft, its roughness reduces significantly and a wear spot appears in the contact zone [6, 7]. Interaction of the friction pair materials in the contact zone is worth studying with the aim of finding efficient solutions of this problem.

Dynamic properties of piezoelectric ultrasonic motors depend on the optimum frictional materials. A piezo-ceramic contact with widely used materials, such as steel, alumina, copper, bronze, cause the surface wear of a softer counter-body [2, 8, 9, 10]. Interaction of such materials requires investigations of tribological processes in the contact zone and finding possible solutions of this problem by using suitable coatings that can strengthen the friction surfaces. The surface roughness and hardness parameters could be controlled by using metal carbides and oxides, ceramic, and other tribo-active materials [2, 8, 9].

Tungsten and titanium carbides, such as WC-Co8 and TiC15-Co6, have unique physical and mechanical properties, which makes them attractive for the manufacturing of electrodes used in the electrospark welding (ESW) for the formation of surface layers of different functional purposes. This process is based on the phenomenon of the polar transport of the anode material (treating electrode) on the cathode surface (workpiece), when the electrical impulse discharges in the gas medium [11]. The ESW is characterized by an opportunity of usage of any conductive material, by easy implementation, low power consumption, high adhesion strength of the deposited layers to the substrate, etc. Comprehensive research was carried out on the processes of formation of coatings, including the use of electrode materials based on alloys of tungsten and titanium carbides with the cobalt binder. Those coatings have high hardness, wear, and abrasion resistance, but they have limited use in friction joints because of a high friction coefficient [12, 13]. However, this disadvantage apparently can be advantageous in circumstances where there is a need for a higher friction coefficient. Such operation surfaces are required in piezoelectric actuators which can efficiently function at a high friction torque and are highly wear resistant.

Tribological properties of rotary piezoelectric motors of a standing wave type were investigated in this study when the friction pair of a piezoelectric actuator consists of the rotor surface with the coatings of titanium (TiC15-Co6) and tungsten (WC-Co8) carbides and that of the counter body – of a composite frictional material.

EXPERIMENTAL DETAILS

Testing equipment and operation

The research was carried out using the originally designed friction bench for investigations of tribological properties of a rotary piezoelectric motor of a standing wave type. A conceptual diagram of the test bench is presented in Fig. 1.

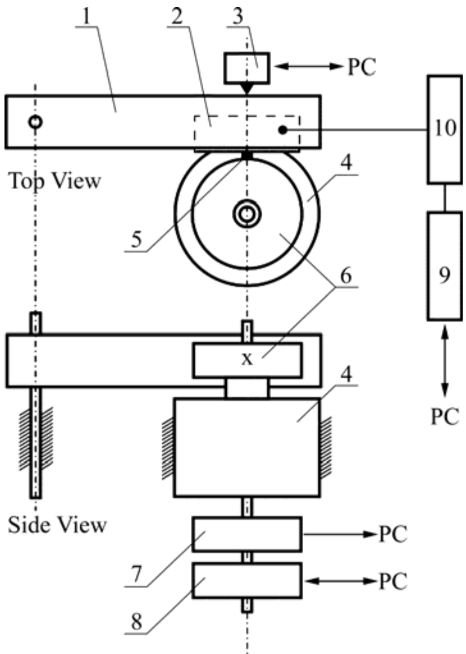


Fig. 1. Principal scheme of ultrasonic piezo actuator test equipment: 1 – stator (holder of piezoelectric element); 2 – piezoelectric element; 3 – pneumatic cylinder with load sensor; 4 – air bearing; 5 – friction material element (counter body); 6 – rotor (roller with special contact surface); 7 – revolution counter; 8 – torque sensor with non-contact break; 9 – frequency generator; 10 – voltage amplifier; PC – personal computer.

The sinusoidal current of the required amplitude and frequency is supplied from the frequency generator *9* through an amplifier *10* to the piezoelectric element *2*, thus exciting there the standing wave effect. So the rotation torque appears in the friction pair between the friction material element *5* and the rotor *6* cylindrical surface.

The optimal excited frequency can be selected semi-automatically according to the maximum rotation speed. To this end, the output of the exciting frequency generator can be regulated using special software by a required step from a selected initial frequency. When the maximum rotating speed is reached, the operation frequency must be adjusted manually by entering a particular value.

The normal load in the friction pair of a piezo contact can be adjusted and sensed automatically as increasing or decreasing by selected steps, as well as continuously during the testing time. The electrical break of a rotor can be switched on/off automatically, so the rotating torque can be measured. The stopping torque can be created by the required steps or continuously, as well as till a deadlock, or in accordance with the adjusted minimal rotating speed. All test modes can be programmed and performed automatically.

Materials of friction pair

The rotors surfaces were covered with two types of carbides – TiC15-Co6 (79% WC + 15% TiC + 6% Co) and WC-Co8 (92% WC + 8% Co) deposited by the ESW. Such coatings are up to 100 μm thick and have a heterogeneous structure. Heterogeneity of the coating structure is accounted for by the peculiarity of the formation process. When electrical pulses are passing between the anode (processing electrode) and the cathode (surface), the material of both the vapor and liquid phases is transferred from the anode to the cathode. It intensively interacts with the cathode material and the environment (nitrogen and oxygen), forming on its surface a coating with the properties and structure different from the material of the anode and the cathode.

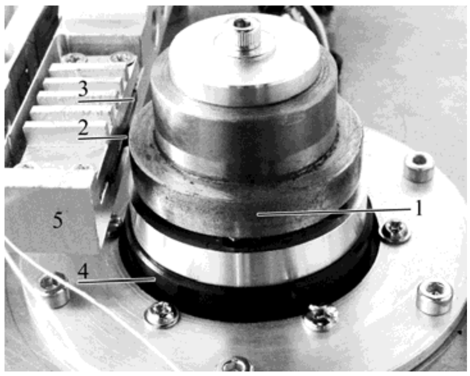


Fig. 2. Tribo-pair: 1 – rotor with coated surface; 2 – counter body; 3 – piezoelectric element; 4 – airbearing; 5 – piezo element holder.

The rotors surfaces were treated mechanically by the diamond flattening after the coating deposition. The Vickers hardness after the processing was 1250 MPa and 932 MPa of WC-Co8 and TiC15-Co6, respectively. The picture of a tribo-pair is presented in Fig. 2.

A prism-shaped counter body *2* was made from a composite frictional material of an automotive brake system M5113. The geometrical dimensions of it were: width – 1.5 mm, length – 2.5 mm and height – 1 mm. The Vickers hardness of the friction material was 145 MPa, the elasticity modulus – 20 GPa.

Test conditions

The tests of a piezo actuator friction pair were performed changing the normal load in a tribo-contact and applying the rotor brake during testing. Two tests on each of the two coatings were made. An initial normal load of 500 mN was applied during every test; after half of the testing time it increased up to 1000 mN. The rotor brake was applied four times with selected intervals and the run time during every load. The aim of the rotor stopping was to measure the maximum torque, which was performed by the piezo actuator, and to evaluate the rotation speed change at the given 2.5 mNm constant stopping torque. Figure 3 illustrates the principal scheme of test conditions.

Input parameters for the piezo actuator were: DC current – 100 V, exciting frequency of piezo element – 134.37 kHz, range of frequency – sinusoidal, 90°.

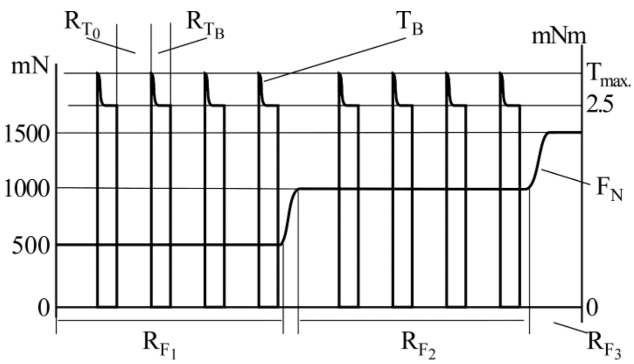


Fig. 3. Principal scheme of test conditions: R_{T0} – idle running interval; R_{TB} – loading torque running interval; R_{F1}, R_{F2}, R_{F3} – running with different normal force intervals; T_B – application of the piezo actuator loading output torque; F_N – curve of application of normal contact force.

During all tests the data on the normal contact force, loading output torque, rotating speed, and covered distance were recorded.

The microscopic surface analysis and hardness tests were performed. Hardness tests were made using a CSM micro hardness-scratch tester. The changes of friction surfaces were evaluated visually using an optical microscope Nicon Eclipse (magnification rate from x50 to x1000).

RESULTS AND DISCUSSION

Output parameters, such as the speed and the loading torque, were measured during the tribological tests of a piezo actuator with different rotors coated by WC-Co8 and TiC15-Co6. The wear of the friction pairs was evaluated after the tests.

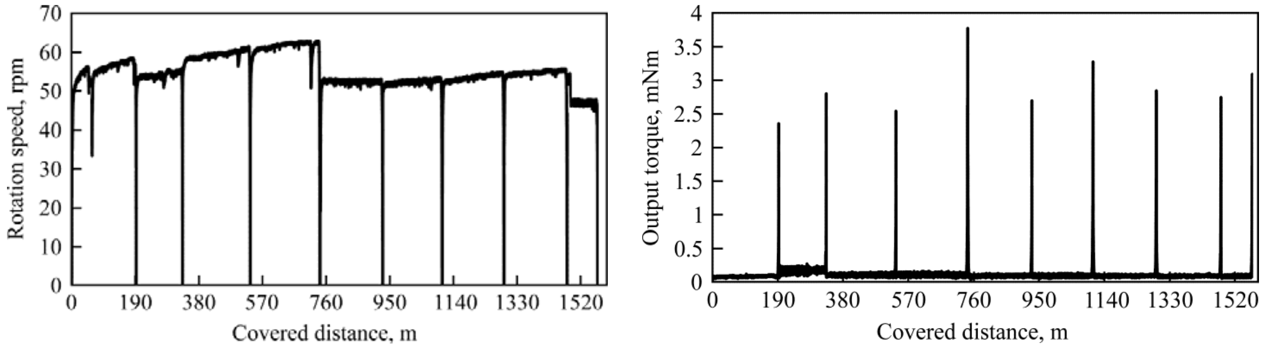
The analysis of the test results shows that the speed and the output torque of a piezo actuator with the rotor coated with the WC-Co8 carbide layer were lower under the same test conditions comparing to those with the TiC15-Co6 coating (Figs. 4 and 5).

The rotation speed was unstable for both coatings under the normal force of the piezo contact F_N = 500 mN. The rotation speed was increasing steadily, up to 63 rpm, during the entire first phase, at F_N = 500 mN, when using the coating WC-Co8 (Fig. 8a, the covered distance up to 760 m). The rotation speed decreased to 54 rpm, when braking with the normal force of F_N = 1000 mN was applied, and later decreased to 48 rpm when the contact force went up to F_N = 1500 mN. The rotation speed has reached the maximal value of 80 rpm after 180 m run of the initial phase, when using TiC15-Co6 coating (Fig. 9a). The rotation speed decreased to an average value of 68–69 rpm after that, but it did not decrease after applying a higher contact force and remained stable at the level of 69–72 rpm. Only after applying the normal force F_N = 1500 mN, the rotation speed decreased to 64 rpm.

In both cases, a gradual increase of the speed up to the maximum value can be explained by the surface running-in phenomenon, which in many cases depends on the initial roughness and the hardness ratio of contacting surfaces. This period takes longer for the harder surface of the WC-Co8 coating (up to 550–700 m covered distance) and shorter for the softer surface of the TiC15-Co6 coating (200 m run). Instability of the rotation speed during separate loading phases could be related to the peculiarities of a rotor with the ESW coatings, which are of high roughness and disparities of the surface. It could also be the cause of the irregularity of the output torque (Figs. 4b and 5b).

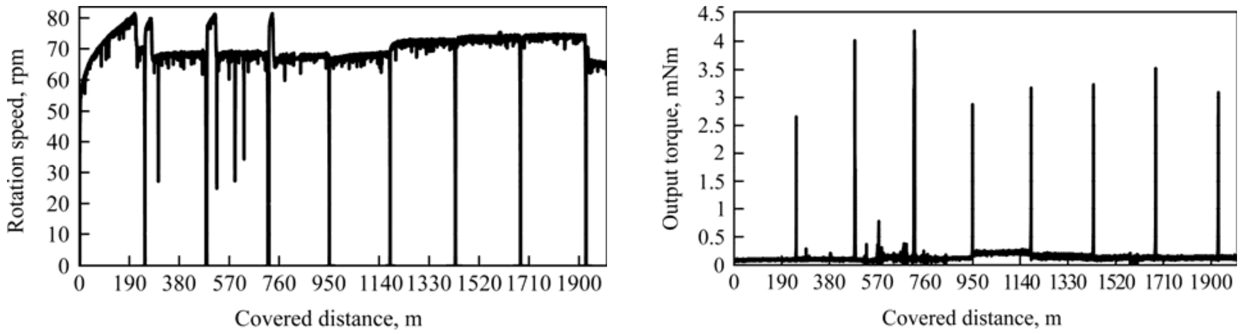
The analysis of the rotor speed variation in Figs. 4 and 5, when a zero or 2.5 mNm constant loading torque of a piezo actuator (according to the test conditions in Fig. 3) is applied, shows that those speed fluctuations were not periodically recurring during one full revolution. Therefore, it is possible to conclude that the speed inequality and complete stop of the piezo actuator is caused not by the parameters of the piezo element but by the mechanical-tribological factors in the friction pair.

This is why it was necessary to analyse the speed/torque dependency curves at the period of the actuation and release under the conditions of loading of the piezo actuator. It contributes to clearing the loading possibilities of a piezo actuator. Figure 6 presents the typical speed/torque curves at the loading of the piezo actuator with the rotor coated by



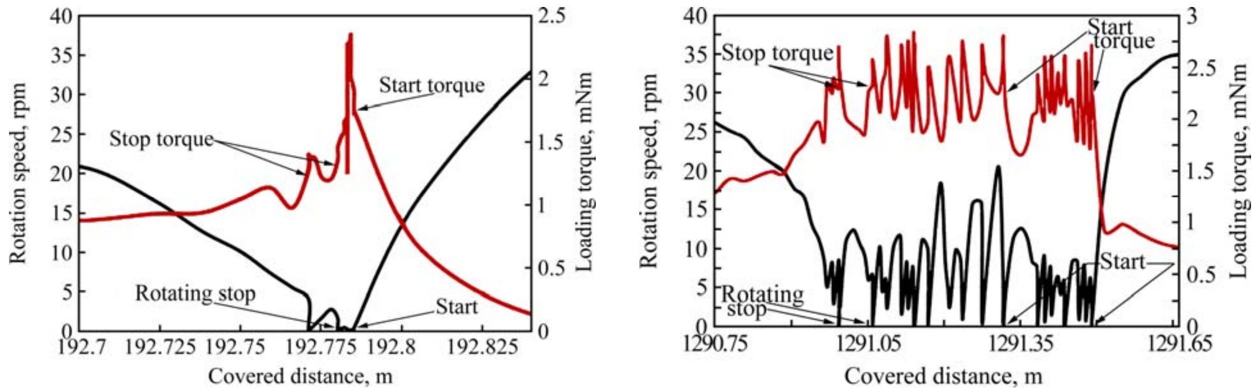
(a) (b)

Fig. 4. Typical curves of piezo actuator operation using rotor surface with WC-Co8 coating: (a) rotation speed; (b) output torque.



(a) (b)

Fig. 5. Typical curves of piezo actuator operation using the rotor surface with TiC15-Co6 coating: (a) rotation speed; (b) output torque.



(a) (b)

Fig. 6. Change of rotating speed and loading torque during test of rotor with WC-Co8 at actuation and release moment of loading at normal contact force of: (a) 500 mN; (b) 1000 mN.

WC-Co8, and Fig. 7 displays the speed/torque curves of the rotor coated by TiC15-Co6.

The loading procedure and its recording are important for understanding of the rotation speed behaviour. At the beginning, loading is applied up to reaching the maximal output torque, which is recorded when the rotation decreases to a minimal value (in this case, up to 18% of the maximum speed). It means that it is not the maximal braking output torque that is recorded, so the rotor should not stop completely. A full stop of the rotor indicates that a constant reliable contact is not assured between the friction surfaces. This is illustrated also by the fact that braking of the output torque has different values (see Figs. 6 and 7).

The tests of the rotor with the WC-Co8 coating show that the piezo actuator begins to slow down and then stops at the ca 1.3 mNm loading torque, when the normal contact force is 500 mN. Releasing the loading, the rotor begins to rotate at the 1.7 mN loading torque value (Fig. 6a). At the 1000 mN normal contact force, the stop and start of the rotation takes place when the output torque values start ranging at about 2.25 mNm (Fig. 6b).

The values of the output braking torque were significantly lower when the rotor with the TiC15-Co6 coating was loaded (Fig. 7). When the normal force of a tribo-contact was 500 mN, the value of the stopped rotor loading torque was 0.9 mNm. After stopping, the rotor began to spin at a higher output torque – on ca 0.7 mNm (Fig. 7a). When the normal contact force is raised up to 1000 mN, the complete stop of the rotor occurs when loading reaches 1.5–2 mNm, and rotation starts at the release of loading up to 1–1.4 mNm (Fig. 6b).

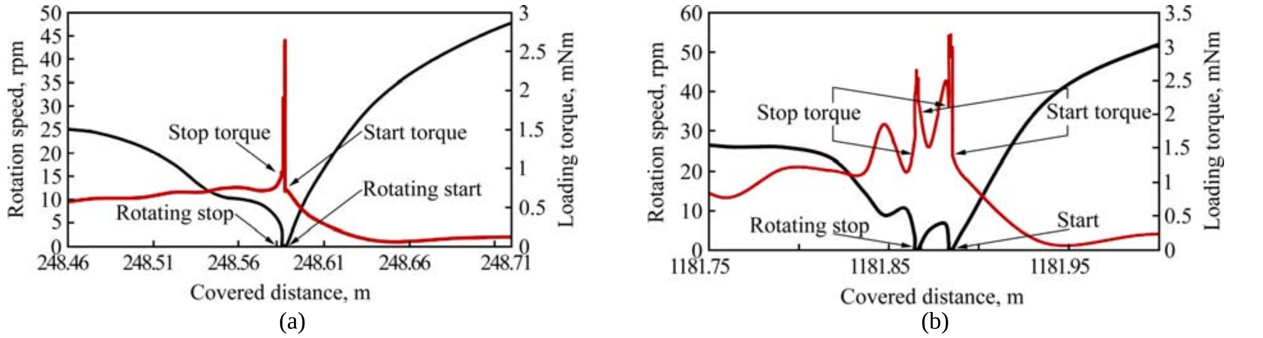


Fig. 7. Change of rotating speed and loading torque during test of rotor with TiC15-Co6 at actuation and release moment of loading when normal contact force is: (a) 500 mN; (b) 1000 mN.

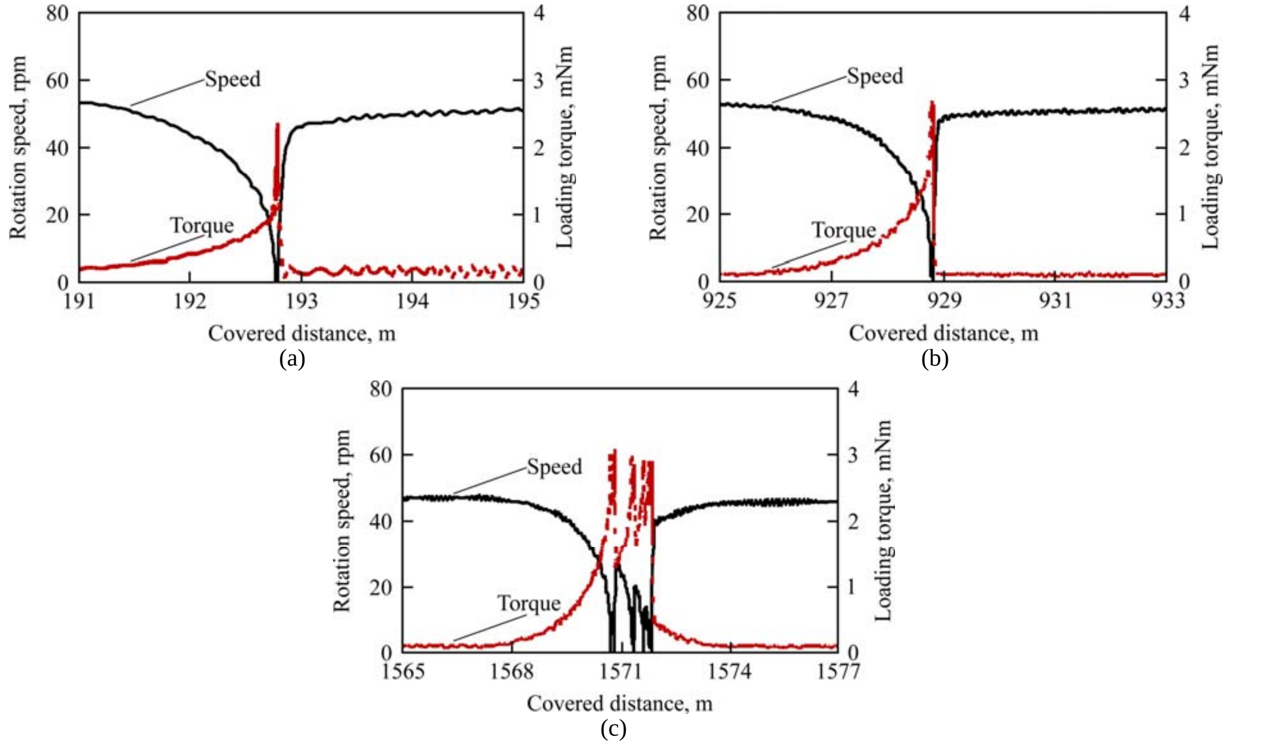


Fig. 8. Correlation of rotation speed and loading torque change during test of the piezo actuator rotor with WC-Co8 coating when normal contact forces are: (a) 500 mN; (b) 1000 mN; (c) 1500 mN.

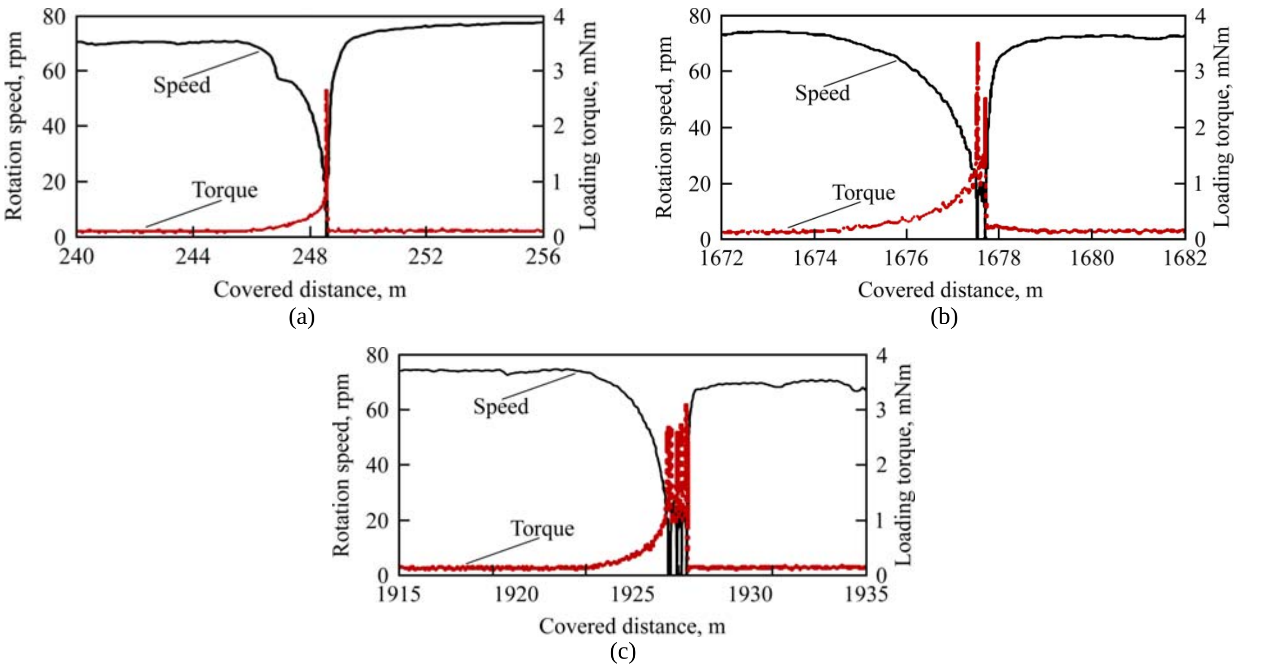


Fig. 9. Correlation of rotation speed and loading torque change during test of the piezo actuator rotor with TiC15-Co6 coating when normal contact force is: (a) 500 mN; (b) 1000 mN; (c) 1500 mN.

The period of a steady rise of the loading and its correlation with the changing speed is an especially important dependency for operation of a piezo actuator. Figures 8 and 9 show that a steady rotation speed does not depend on the applied contact load and it is different for rotors with WC-Co8 and TiC15-Co6 coatings. The unloaded piezo actuators with WC-Co8 coating run at 50–53 rpm, while the speed of the rotors with TiC15-Co6 coating is 70–75 rpm. However, at the increase of the loading there is a limit until the output torque and the rotation speed are stable. This limit is close to the 20 rpm rotation speed for all three versions of the contact loading for both rotor coatings.

The graphs in Fig. 8 tell us that when using the rotor with the WC-Co8 coating, the output loading reaches the value of 0.9 mNm at the 500 mN contact force and the 20 rpm rotation speed. At the ouput loading at 1000 mN it is 1.4–1.6 mNm and at 1500 mN – 1.8–2.0 mNm. It means that it is possible to increase the output torque twice when increasing the contact force from 500 to 1500 mN. Taking into account a higher reference speed, the increase of the output torque is slightly lower, e.g., at 40 rpm the same rise of the contact force causes the 60% higher output torque.

Speed/torque graphs of the rotor with the TiC15-Co6 coating (Fig. 9) demonstrate that at the reference speed of 20 rpm the output loading is 0.6 mNm at the 500 mN contact force. The ouput loading is 1.2 mNm at the 1000 mN contact force, and 13–1.4 mNm at 1500 mN.

The trends of the rotation speed and loading torque show that the unloaded piezo actuator with rotor coated by TiC15-Co6 operates at 10–20% higher rotation speed comparing with WC-Co8 coating rotor. However, the piezo actuator with WC-Co8 coating rotor can be loaded 1.5 times more in the range of the stable speed/torque at 20 rpm.

The analysis of the piezo actuator operation shows that the normal contact force is inversely proportional to the rotation speed. In the loading regime, the output torque is directly proportional to the contact force.

The microscopic analysis of friction surfaces reveals that the surface of the counter body abraded most significantly. Figures 10 and 11 are, in fact, 3D pictures and profiles of the frictional material counter bodies with carbide coating surfaces. The wear scars and riffles (axes pass through the rotation direction of the rotor) are seen on the surface of the frictional material. The profiles show an average 20 μm depth pitting on the surface of the frictional block when it operates with the WC-Co8 coating (Fig. 10). The depth of pits is lower (10 μm) when the block operates with the TiC15 coating (Fig. 11).

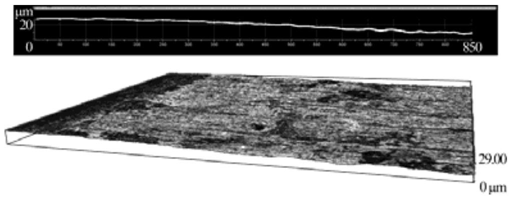


Fig. 10. Surface of counter body after friction test with WC-Co8-coated rotor surface. Rotation direction is left to right.

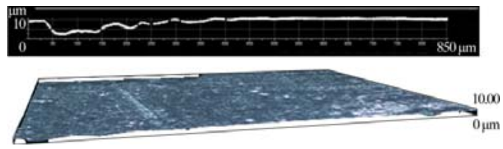


Fig. 11. Surface of counter body after friction test with TiC15-Co6-coated rotor surface. Rotation direction is left to right.

Surface pictures and profiles of WC-Co8 and TiC15-Co6 coatings are displayed in Figs. 12 and 13, respectively. No wear traces were observed on much harder rotor surfaces with the carbide coatings. A common property of the surfaces of both coatings is that they are not smooth. A peculiarity of the ESW is that on the surface the craters are formed that are not smoothened by the diamond flattening of the surface. The craters depths were from 1 to 3 μm and diameters – 10–350 μm.

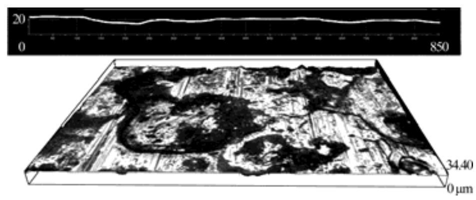


Fig. 12. WC-Co8-coated rotor surface. Sliding direction is from right to left.

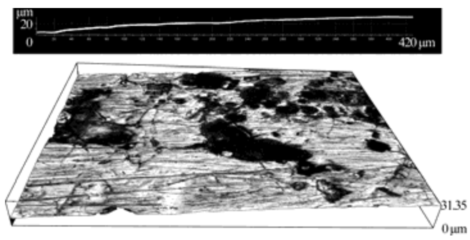


Fig. 13. TiC15-Co6-coated rotor surface. Sliding direction is from right to left.

High asperities and presence of the craters on the coating surface can explain the instability of the rotation speed (Figs. 4a and 5a). The size of craters is similar to the contact area of the counter body. Therefore, the rotor surface was not always contacting equally with the surface of the counter body.

Those coated surface irregularities cause the fluctuations of the rotation speed and of the output torque during the loading of a piezo actuator. The number of craters on the surface of the WC-Co8 coating was higher and they were also wider (Fig. 12). It could be the reason why the rotation speed and the output torque were less stable with the WC-Co8 rotor (Fig. 6) compared to the loading of the rotor with the TiC15-Co6 coating under identical conditions.

Comparison of the operation of differently coated rotors show that the rotor with a harder and rougher WC-Co8 coating ensures a higher output torque of the piezo actuator (Fig. 8). However, such coatings cause higher wear of the counter body (Fig. 9) and instability of both the speed and the torque. Consequently, the rotation speed is decreasing with the covered distance. The TiC15-Co6-coated rotors can achieve a more stable and longer-lasting rotation speed due to lower wear of a counter body, but such piezo actuators have lower loading possibilities.

CONCLUSIONS

An increase in both the speed and the output torque up to their maximum values at the beginning of the tests can be explained by the surface running-in phenomenon, when the surfaces should run-in up to the optimal contact area of the surfaces is formed. It takes longer for harder surfaces (WC-Co8 coating) and shorter for softer surfaces (TiC15-Co6 coating).

An unloaded piezo actuator with the TiC15-Co6-coated rotor operates at a 10–20% higher rotation speed compared with the WC-Co8-coated rotor. The piezo actuator with the latter rotor can be loaded 1.5 times more in the range of a stable speed/torque at 20 rpm. However, the structure of this hard and rough coating causes higher wear of the counter body, instability of the speed and the torque, and, consequently, a decreasing trend of the rotation speed.

Investigations show a promising use of carbide coatings for the friction surface of the rotor of a piezo actuator. In future it is desirable to find best coating materials which could ensure the optimal ratio of the rotation speed and loading possibilities of piezo actuators. In addition, a high hardness of carbide surfaces is worth paying more attention to the frictional material of the counter body, which also should be wear resistant enough.

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Реферат

В работе представлены результаты исследований трибологических характеристик электроискровых карбидных покрытий (WC-Co8, TiC15-Co6) на испытательном стенде оригинальной конструкции, в котором моделировалась работа пьезоэлектрического двигателя стоячей волны. Этот стенд позволял управлять нагрузкой в пьезоконтакте, нагрузкой пьезодвигателя (крутящим моментом), продолжительностью испытаний, а также регистрировать скорость вращения и путь ротора. Из испытанных двух типов карбидных покрытий более высокие трибологические свойства показали покрытия TiC15-Co6.

Ключевые слова: пьезоэлектрическая пара трения, покрытие, WC-Co8, TiC15-Co6, момент нагрузки, скорость вращения.