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RESEARCH

Increasing the Wear Resistance of Titanium Alloys in Plain Bearings with Galvanic and Vacuum-Arc Coatings

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A B S T R A C T

The aim of the work is to investigate the wear-resistant characteristics of galvanic and vacuum-arc coatings of molybdenum and chromium on X105CrMo17 steel and VT-22 titanium alloy under fretting conditions. The studies were conducted at 20 and 30 MPa, an oscillation frequency of 30 Hz, an amplitude of mutual displacement of the samples of 175 µm, and a number of cycles of 5 x 105. It was found that the vacuum-arc coating of hard chromium under a load of 20 MPa is characterized by wear resistance 2-3 times greater than that of the electrolytic coating: at 30 MPa, signs of seizure appear. High wear resistance of the molybdenum coating applied by the vacuum-arc method was established: at a pressure of 20 and 30 MPa, this coating on the VT-22 alloy is characterized by a decrease in linear wear by 2.6 and 1.2 times, compared to the coating on X105CrMo17 steel. The theoretical aspects of relaxation, hysteresis, and microplastic mechanisms of internal friction under fretting conditions are considered. The use of VT-22 alloy as an inner race with a 70-µm-thick molybdenum coating applied to its surface using a vacuum-arc method is recommended for spherical plain bearings in the aviation industry.

1. INTRODUCTION

The plain bearing design does not have a rolling body. These bearings operate in conditions where there is no circular rotation. This group of bearings is widely used in the aviation industry [1,2]. Plain bearings are designed to transmit radial, axial and combined loads in movable or fixed joints of machines and mechanisms. They are used to compensate for distortions, temperature and elastic deformations that occur during the operation of aircraft [3].

All plain bearings used in the aviation industry [4,5] can be divided into two groups according to the way the working surfaces are lubricated: plain bearings that require lubricant supply and plain bearings without external lubricant. Plain bearings are designed primarily to accept heavy loads of constant direction, at low sliding speeds. They are used in units with increased durability requirements and with limited maintenance. Generally, self-lubricating bearings are made of steel, but there are studies [6] that will allow the use of titanium materials instead of steel in bearings for the aviation industry.

The use of titanium materials in the aviation industry has been relevant for many years. On modern aircraft, almost all steel parts have been replaced with titanium ones, taking into account their features and strength characteristics. But recently there are works [7] that allow the use of titanium materials even in friction units. For example, almost all modern aircraft use titanium alloy landing gear. But there are certain restrictions on the use of titanium alloys in friction nodes due to the high tendency of titanium alloys to setting [8].

Analyzing plain bearings and the experience of leading companies in the production of bearings, it can be argued that the materials of the tribopar used in contact change [9,10]. So, for example, for bearings of the GE…DE, GE…EW-2RS type, they are used for the production of the inner race of hinged bearings of steel grades X105CrMo17. These materials are subject to strict requirements, especially in terms of corrosive effects, which is relevant in the aviation industry. Polished metal-polymer contact is an ideal combination for long-term operation, provided that the composite materials are properly selected. But if zones of corrosive influence of the medium appear on the friction surface, then the surface collapses with a change in roughness. Corrosive ulcers lead to a significant change in the microgeometric characteristics of the surface. And as a result, a change in the profile of the inner cage leads to a catastrophic destruction of the polymer material during the operation of the bearing.

Some manufacturers use a protective coating on metal surfaces in the production of their bearings. Such coatings may include coatings obtained in the process of phosphating, chrome plating, etc., molybdenum disulfide coatings. All these coatings are designed either to increase the corrosion resistance of materials or to increase the wear resistance of friction vapors. For the aviation industry, the issue is relevant both in terms of corrosion resistance and increased wear resistance characteristics of plain bearings.

For example, FLURO uses chrome plating for some series of its plain bearings. It is believed that tribo pair chrome coating-metal-polymer material is the key to reliable operation and increased wear resistance characteristics. Other companies apply ceramic coatings to their bearings [11], which also increases the durability of the plain bearings.

There are also works [12,13], where the authors show the advantages of introducing titanium materials into aircraft structure units due to their unique characteristics (high specific strength, corrosion resistance, wide range of operating temperatures). But attempts to introduce titanium materials for aviation bearings were not used. Titanium materials perform very poorly under sliding friction conditions. In the works [12,14] it is shown that pure titanium material VT-22 works 5 times worse in terms of wear resistance than material X105CrMo17.

Titanium alloys exhibit low wear resistance due to the insufficient strength of titanium alloys at high temperatures and the formation of hard but brittle oxides, nitrides, and carbides due to their high chemical activity with respect to O, N, H, CO, CO2, and atmospheric water vapor [15].

Pin-on-disk wear tests revealed that the formation of TiO2 nanooxide as the main component of tribolayers under sliding friction conditions between titanium alloy Ti–6Al–4V and AISI 52100 steel leads to increased wear of the tribocoupling [16].

[17] demonstrated that the increased wear rate of titanium alloy TC21 is associated with an increase in the alloy's hardness as a result of water quenching of the samples followed by aging, compared to annealed samples. A comparative analysis of wear particles showed that for the TC21 titanium alloy in the annealed state, changes in friction were caused by plastic deformation of the surface layers, while the samples after water quenching and aging showed brittle fracture of the

surfaces, which was caused by the presence of a large number of small α-phase plates precipitated along the grain boundaries, which leads to the formation of a greater number of voids, cracks and delamination.

Thus, it is necessary, on the one hand, to introduce lightweight and durable materials into the aviation industry, and on the other hand, to increase the wear resistance of these materials. Therefore, the current direction in the production of internal races of aircraft plain bearings is the introduction of lightweight and durable materials such as titanium materials (giving lightness of construction), which will be modified with wear-resistant coatings.

In the papers [14,18] it is noted that the use of molybdenum coating increases the wear resistance of friction pairs by 1.5-2 times. The authors conducted a study of the wear resistance of molybdenum and compared it with different materials. It is determined that the thickness of the molybdenum galvanic coating of 0.1 mm is sufficient to ensure the wear resistance of the main materials for the entire service life of the friction pair. The paper [19] shows the positive effect of molybdenum for the restoration of damaged surfaces that were applied by gas-thermal methods.

Therefore, it is necessary to protect titanium alloys with wear-resistant coatings or carry out special treatment of the surface layer.

2. PURPOSE OF THE WORK

The purpose of the work is to determine the wear-resistant characteristics of galvanic and vacuum-arc coatings on titanium alloys and steel surfaces, in order to use them in aviation friction units.

3. TEST METHODOLOGY

For testing titanium alloys with protective wear-resistant coatings, the existing method for testing materials for fretting in accordance with GOST 23.211-80 [20] was chosen. The choice is due to the fact that vibration is one of the main factors influencing aircraft components, due to the catastrophic destruction of parts as a result of fretting.

The performance of research in the field of studying wear under fretting conditions (under conditions of insignificant cyclic displacements of small amplitude at the junctions of the contact surfaces of two solid bodies as a result of the action of vibration loads or deformations) is distinguished by a great variety of methods used, both from the point of view of the load scheme and type of contact, and in assessing surface damage.

The methodology was chosen in accordance with two main requirements:

1. Imitation of fretting (vibration) in laboratory conditions should be as close as possible to the conditions for the occurrence of this type of surface destruction in real structures.
2. The chosen method should be such that it is possible to compare the results obtained with the data of other works.

Due to the specifics of the occurrence of fretting, the following requirements are imposed on test devices:

1. Free from backlash fastening of samples in clamping devices;
2. Torsional rigidity and low deformability of the device;
3. The presence of vibration slipping movement of adjustable frequency and amplitude;
4. The presence of a controlled normal force to create the necessary pressure in the contact;
5. The possibility of supplying lubricant or other medium.

Different types of contact have their advantages and disadvantages. The disadvantages of the plane-plane contact include unequal wear conditions of the working sections of the samples, since their amplitude of displacements with such a scheme is directly proportional to the distance from the axis of rotation. This drawback is eliminated by choosing the optimal geometry of one of the samples. With other types of contact, there is an uneven distribution of pressure in the contact zone, which leads to different wear conditions.

The choice of flat annular contact and rotary-rotational movement of the contact surfaces is due to the need to control the normal load and eliminate the edge effect.

The basis of the adopted method of carrying out the work is a comprehensive study of the qualitative parameters of friction of tribopars. The plane-plane contact scheme was used on the MFK-1 installation, the general view of which is shown in (Figure 1).

Fig. 1. Appearance of the MFK-1 machine for testing the wear of structural materials during fretting.

The installation diagram is shown in (Figure 2). The installation works as follows: the electric motor 2 transmits rotational motion to the eccentric 3 with adjustable eccentricity. The rotational speed and the number of revolutions is recorded by the device 1. The eccentric 3 through the connecting rod 4, connected to the rocker 6 of the shaft 7 of the counter-sample rotary movement drive 8. Amplitude of movement of the counter-sample 8 is regulated by an eccentric 3 and a device 5. A fixed sample 9 is fixed in a centered collet 10 mounted on the shaft of a moving headstock 11. The samples are loaded with a dynamometer 14 and a loading device 15. The value of the axial load on the samples is recorded using a dynamometer of the DOSM-3-0.2 type with a measurement range of 0.2 to 2 KN. Registration of the friction force is carried out by the device 13 through the amplifier 12 using a load bar 11. The number of test cycles was controlled by a meter installed on the front panel of the installation.

The amplitude of oscillations is regulated by changing the eccentricity of the eccentric (roughly) and changing the length of the arm of the horizontal connecting rod (exactly). Coarse amplitude adjustment allows you to change its value from 10 to 1000 microns, accurate - from 5 to 15 microns. The amplitude of relative displacement is defined as the difference in the amplitudes of oscillation of moving and stationary samples. The amplitude measurement is carried out directly on the samples using an optical binocular microscope, using the stroboscopic effect.

The machine for the study of fretting corrosion processes allows testing under the following parameters:

- Loading of samples in the axial direction with forces of 200 – 5500 N;
- Rotary-rotational motion of the counter sample, relative to a stationary sample with a frequency of 3 – 30 Hz and an amplitude of 10 – 500 μm for a standard sample;
- The measuring system of the unit provides continuous recording of the number of cycles of rotary rotational movement of the counter sample with an error of no more than 50 cycles during testing.

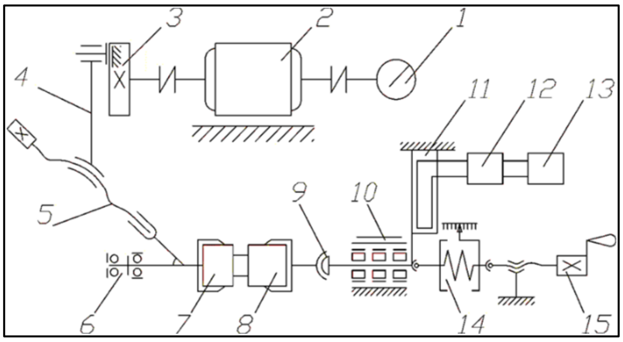


Fig. 2. Diagram of the machine for the study of fretting processes: 1 – revolution counter; 2 - electric motor; 3-eccentric; 4 -vertical connecting rod; 5 –tuning device; 6 -horizontal connecting rod; 7 – movable sample; 8 – stationary sample; 9 – self-orienting collet; 10 –movable headstock; 11 – strain gauge; 12 -amplifier; 13 – recording equipment; 14 –dynamometer; 15 – loading device.

The technique also allows you to measure the coefficient of friction. So, when modernizing the machine for the study of fretting processes, the ability to control the torque is also preserved. Evaluation of the kinetics of friction change allows you to control wear transients. For example, for metal-polymer composite coatings, it is possible to determine the period of operation of each subsequent layer. It is also known that the coefficient of friction in the process of running-in is usually higher than the established coefficient of friction, which characterizes the frictional properties of a particular tribocouple.

Test samples are shown in (Figure 3) the working surface, which is a closed ring with a nominal contact area of 0.5 cm^2, an inner diameter of 11 mm and an outer diameter of 13.6 mm. A certain metal-polymer or polymer is applied or glued to the working surface of the sample, which is tested under vibration conditions.

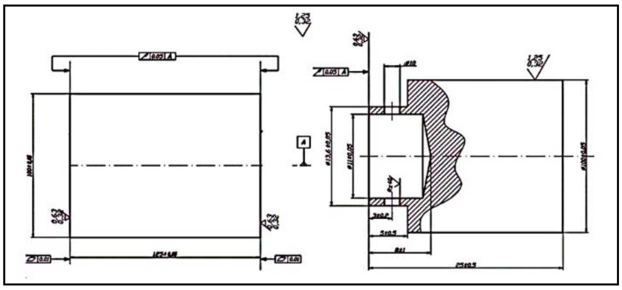


Fig. 3. Samples for testing materials and coatings for vibration load [20].

Measurement of sample wear was carried out using the HANDYSURF 550 profilometer-profilograph according to ISO 17025:2019 [21] by taking profilograms from eight equilateral working surfaces of the sample in the radial direction and was determined according to (Figure 4).

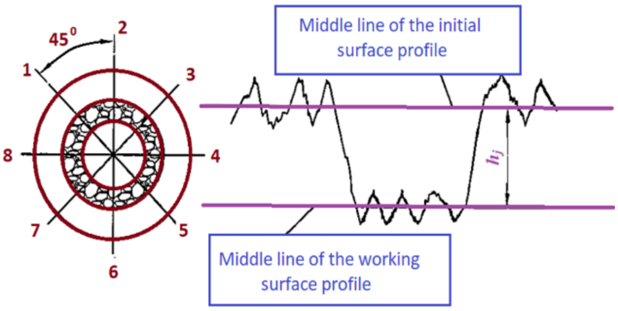


Fig. 4. Scheme for determining the wear of samples during tribostudies under vibration conditions [20].

An important advantage of determining wear by the linear method is that the amount of wear does not depend on the specific gravity of the material and possible changes in the mass of the samples

4. SELECTION OF MATERIALS FOR RESEARCH

Based on the analysis of wear resistance and corrosion resistance of materials, the following materials were selected for tribological studies of materials for inner races of hinge bearings:

1. Molybdenum coating.
2. Chrome-plated.
3. Steel X105CrMo17.
4. Titanium alloy VT-22 (Table 1).

Material X105CrMo17 is the base material that is the basis for GE...DE, GE...EW-2RS type bearings. Titanium alloy VT-22 was chosen as an alternative to steel in order to reduce the weight of the bearing as a whole; for the use of the VT-22 alloy as a triboelement, modification was carried out by strengthening the surface layer with coatings.

Table 1. Chemical composition in % of VT22 material.

Element	% in the alloy	Element	% in the alloy
Ti	79.4 - 86.3	O	< 0.18
Al	4.4 - 5.7	Si	< 0.15
Mo	4 - 5.5	Zr	< 0.3
V	4 - 5.5	C	< 0.1
Fe	0.5 - 1.5	N	< 0.05
Cr	0.5 - 1.5	H	< 0.015

Material X105CrMo17 is the base material that is the basis for GE...DE, GE...EW-2RS type bearings. Titanium alloy VT-22 was chosen as an alternative to steel in order to reduce the weight of the bearing as a whole; for the use of the VT-22 alloy as a triboelement, modification was carried out by strengthening the surface layer with coatings.

To modify the surface layers of the VT-22 alloy, a coating of chromium and molybdenum was chosen. The chromium coating was applied by galvanic and vacuum-arc methods.

Thus, the coatings that were examined for wear resistance are as follows:

1. Electrolytic chromium Cr_{gv} (electrolytic method of application).
2. Hard chromium Cr_h (vacuum-arc method of application).
3. Soft chromium Cr_s (vacuum-arc application method).
4. Molybdenum Mo (vacuum-arc method of application).

Hard chromium and soft chromium differ in the structure of the location of grains on the base material. With hard chromium, the structure of the coating resembles an electrolytic one and the grains are located in a horizontal plane. The soft chromium coating has a vertical arrangement of grains. The thickness range of the test coatings that have been tested is presented in Table 2. The thickness fluctuation is associated with the coating mechanism in the vacuum chamber under the action of an electromagnetic field.

The studies were performed at a constant contact load, corresponding to 20 and 30 MPa. The frequency of oscillations and the amplitude of mutual displacement of the samples remained unchanged and amounted to 30 Hz and 175 μm, respectively. The test base was $5 \cdot 10^5$ cycles. The temperature of the samples during the tests was 20 ºC.

Table 2. Thickness of the coatings studied.

Material Basics	Vacuum arc coatings			Electrolytic chromium
	Hard chromium	Soft chrome	Molybdenum	
VT-22	95-220 μm	115-205 μm	70 μm	12-24 μm
X105CrMo17	95-185 μm	95-180 μm	70 μm	12-24 μm

Steel X105CrMo17 with a hardness of HRC 54-58 was used as a counter sample. The contact surfaces were lubricated with Aero Shell Griess 33. Such conditions are chosen for standard steel-to-steel plain bearings designed to withstand heavy, shock or static loads (e.g. plain bearings in aircraft controls and landing gear assemblies).

The linear wear of a stationary specimen with coatings was measured over a specified number of cycles. To enhance the reliability of the obtained results, at least three tests were used for a single histogram. In the studied friction pair, only the linear wear of the coatings on X105CrMo17 steel and VT-22 titanium alloy was analyzed; wear of the X105CrMo17 steel counterface was insignificant (≪ 0.01 μm). Since the studied materials are intended for maintenance-free bearings, assessing the linear wear of the coatings allows us to predict the change in radial clearance (play) during operation of bearings with a spherical inner ring surface made from the recommended materials. According to DIN ISO 12240-1 [22], standard spherical plain bearings of the ШН30ЮТ and GE30EW-2RS series are manufactured with a nominal clearance of 0.03 to 0.08 mm, and the maximum permissible radial clearance at which the bearing is considered worn out and subject to replacement is 0.2–0.3 mm [23].

5. ANALYSIS OF THE RESEARCH RESULTS

The results of tests of wear resistance of vacuum-arc and electrolytic coatings are shown in (Figure 5, 6) and in Table 3.

Table 3. Linear wear of tested coatings and materials.

Material Basics	Load MPa	Covering	Sample wear, microns
VT-22	20 MPa	-	15.1 μm
		Cr_h	about 0.1 μm
		Cr_s	2.5 μm
		Mo	0.3 μm
		Cr_{gv}	about 0.3 μm
	30 MPa	-	22.9 μm
		Cr_h	1.4 μm
		Cr_s	6.7 μm
		Mo	1.5 μm
		Cr_{gv}	4.1*μm
X105CrMo17	20 MPa	-	1.2 μm
		Cr_h	about 0.6 μm
		Cr_s	5.0 μm
		Mo	0.8 μm
		Cr_{gv}	about 0.5 μm
	30 MPa	-	1.6 μm
		Cr_h	3.0 μm
		Crs	9.7 μm
		Mo	1.8 μm
		Cr_{gv}	7.1** μm

* – actual fretting resistance of 1 μm with breaks up to 20 μm.

** – actual fretting resistance of 1 μm with breaks up to 100 μm.

It should be noted right away that the actual wear of the galvanic coating of chromium during tests of 30 MPa is about 1-2 microns, mainly over the entire contact surface. In the case of the base material of the VT-22 alloy, the linear wear of the chromium coating was 1 μm with tears in several places up to 20 μm deep (Figure 7, a). If there is wear of the galvanic coating of chromium on the titanium alloy VT-22, then the intensity of wear of the material increases sharply due to the increased action of the titanium alloy before setting with the counter-sample (Figure 8).

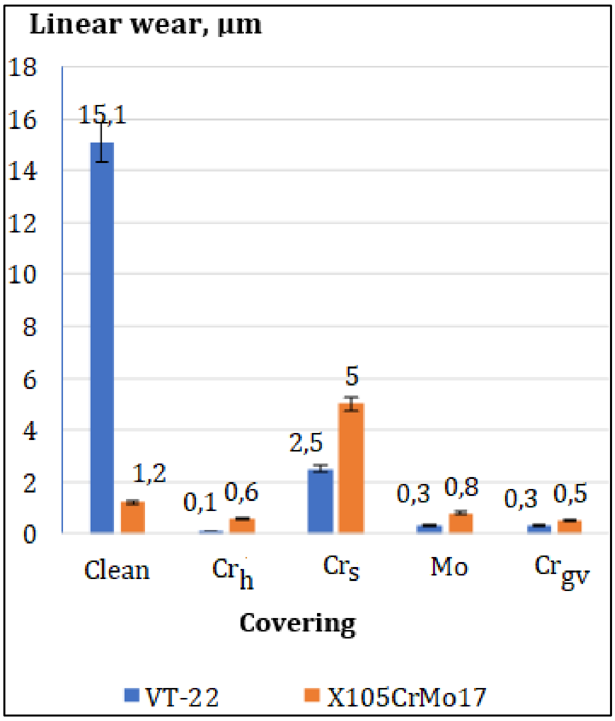


Fig. 5. Dependence of linear wear of vacuum-arc and galvanic coatings at a load of 20 MPa. Test conditions (A – 175 µm, ν – 30 Hz, N – 5·10^5 cycles).

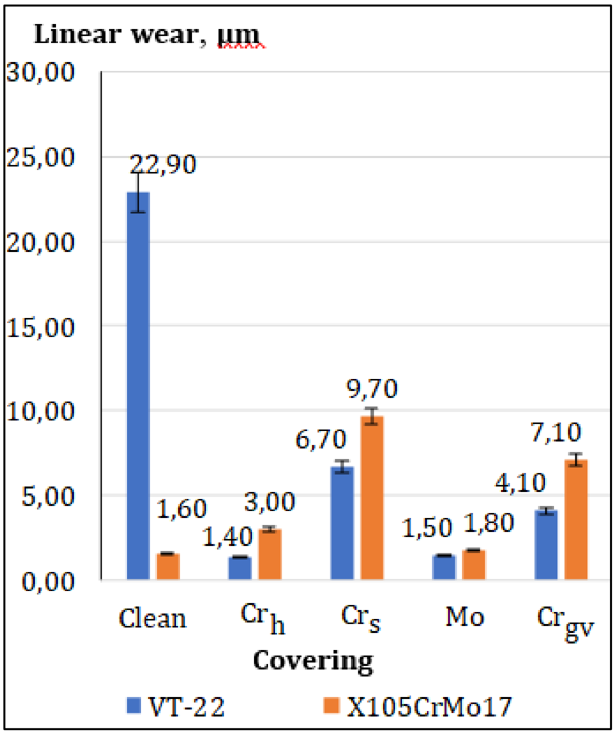
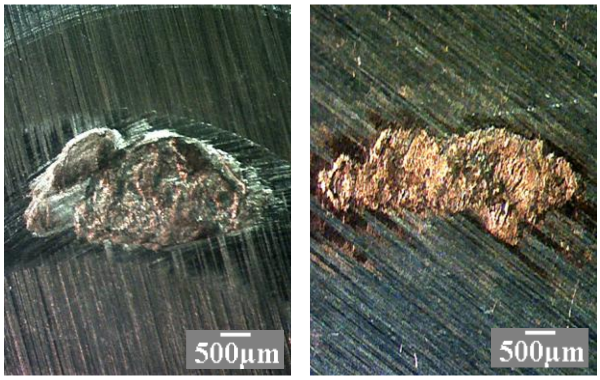


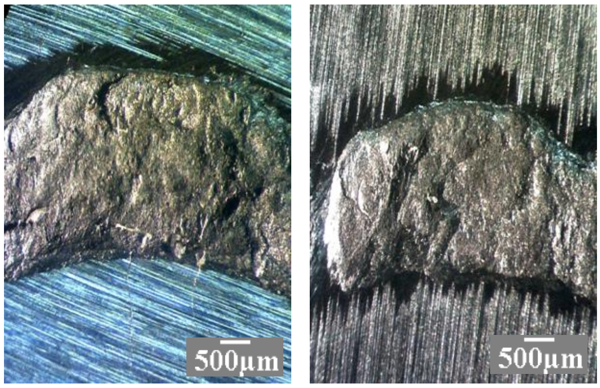
Fig. 6. Dependence of linear wear of vacuum-arc and galvanic coatings at a load of 30 MPa. Test conditions (A – 175 µm, ν – 30 Hz, N – 5·10^5 cycles).

In the case of the base material of the X105CrMo17 steel, the linear wear of the chromium coating was 1-2 µm with tears in several places up to 100 µm deep (Figure 7, b).



(a) (b)

Fig. 7. Breakouts of the galvanic coating of chromium, as a result of setting with X105CrMo17 steel on titanium alloy VT-22 (a) and X105CrMo17 steel (b) at a load of 30 MPa (x56). Test conditions (A – 175 µm, P – 30 MPa, ν – 30 Hz, N – 5·10^5 cycles).

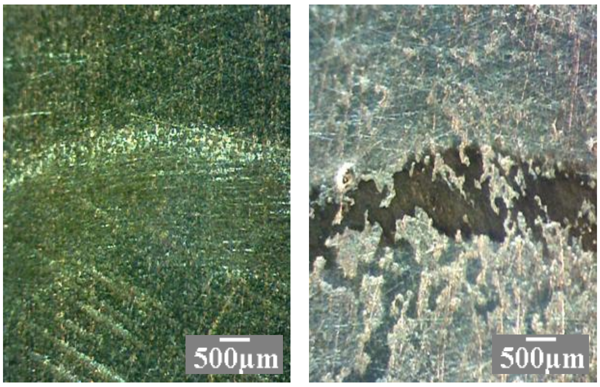


(a) (b)

Fig. 8. Catastrophic destruction of the friction surface of galvanic chromium on the VT-22 alloy with complete wear of the coating (x56). Test conditions (A – 175 µm, P – 30 MPa, ν – 30 Hz, N – 5·10^5 cycles).

Analyzing the wear resistance of coatings based on VT-22 alloy and X105CrMo17 steel under vibration conditions, can say that vacuum-arc coatings of hard chromium and molybdenum showed the most wear-resistant characteristics, both in tests at 20 MPa and at tests at 30 MPa (see Figure 5, 6).

The hard vacuum-arc coating of chromium is characterized by the highest wear resistance compared to other types of coatings of this material. At a load of 20 MPa, the friction surface of hard vacuum-arc chromium on the titanium alloy VT-22 almost did not wear out - the linear wear is 0.1 µm (Figure 9). Only in some places are traces of the coating with X105CrMo17 steel barely noticeable. Hard vacuum-arc coating of chromium on X105CrMo17 steel showed lower parameters in terms of wear resistance (running-in points were larger than on titanium alloy VT-22 (Figure 9), the minimum wear of coatings was 0.6 microns.



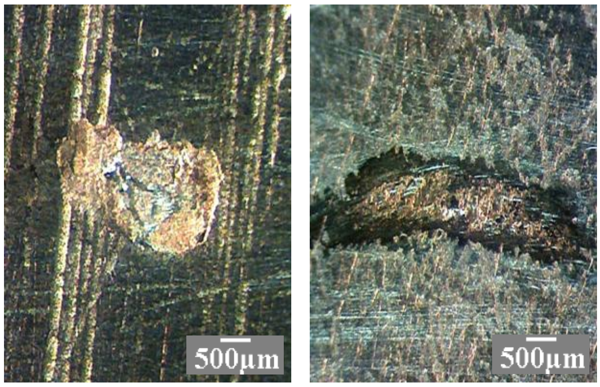
(a) (b)

Fig. 9. Friction tracks of solid vacuum-arc chromium on an alloy of VT-22 and steel X105CrMo17 at a load of 20 MPa (a) and 30MPa (b) (x56). Test conditions (A – 175 µm, ν – 30 Hz, N – 5·10^5 cycles).

At a load of 30 MPa, the wear resistance of the hard vacuum-arc coating of chromium on the VT-22 alloy is almost twice as high as on X105CrMo17 steel. A similar effect is observed when testing other types of vacuum arc coatings. Probably, in the process of friction, coatings applied to a softer titanium base are able to absorb microshocks that occur during vibration and dampen (scatter) them in the VT-22 alloy.

A significant disadvantage of the hard vacuum-arc coating of chromium is the high hardness of this coating. During tests at isolated setting sites, this coating was torn out and transferred to the counter-sample material, which indicates an insufficiently high adhesion strength of the hard vacuum-arc coating of chromium to the surface of the substrate. This pattern was observed both during tests of the coating with a titanium alloy base, and during tests on X105CrMo17 steel (Figure 10). Also on the friction surface, wear of the coating was observed in some places due to setting with the counter sample.

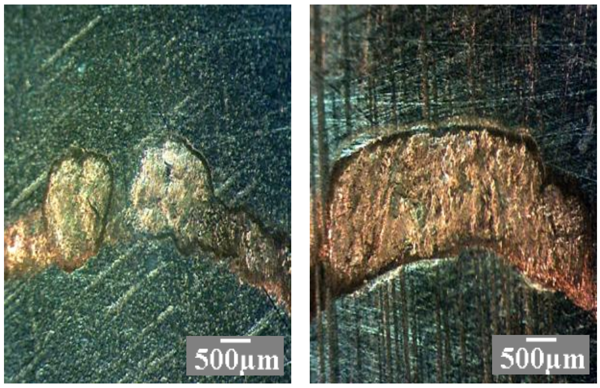
The next coating under study is a soft vacuum-arc coating of chromium. The fretting resistance of this coating is quite low when compared with the coatings listed above. The chromium coating applied to the titanium alloy VT-22 is almost twice more wear-resistant than when applied to X105CrMo17 steel. The soft coating of chromium on X105CrMo17 steel showed the worst results in terms of wear resistance, compared to other coatings, both at a load of 20 MPa and at a load of 30 MPa. At a load of 30 MPa, the soft vacuum-arc coating of chromium is even worse in terms of wear resistance than the base material X105CrMo17.



(a) (b)

Fig. 10. Chips (a) and wear points (b) of a hard vacuum-arc coating of chromium when rubbed in pair with X105CrMo17 at a load of 30 MPa (x56). Loading conditions (A – 175 µm, P – 30 MPa, ν – 30 Hz, N – 5·10^5 cycles).

The friction surface of the soft vacuum-arc coating of chromium applied to the VT-22 alloy differs from the friction surface applied to X105CrMo17 steel. In the case when the base is a titanium alloy, the surface of the coating is smooth with small breakouts on the friction surface (Figure 11, a). In the case when the base is X105CrMo17 steel, the breakouts are more uniform, but there are much more of them (Figure 12. b).



(a) (b)

Fig. 11. Friction surface of soft vacuum-arc coating of chromium on alloy VT-22 (a) and on steel X105CrMo17 (b) with friction with X105CrMo17 (x56). Test conditions (A – 175 µm, P – 30 MPa, ν – 30 Hz, N – 5·10^5 cycles).

The molybdenum vacuum-arc coating showed some of the best results in terms of wear resistance during testing. A similar dependence is observed as on other coatings - on the VT-22 alloy the wear is less than on the X105CrMo17 steel. At a load of 20MPa, the wear resistance of the molybdenum coating on the VT-22 alloy is 2.6

times higher than the wear resistance of this coating on X105CrMo17 steel (see Fig. 5). With an increase in load up to 30 MPa, the wear of the molybdenum coating on the VT-22 alloys and X105CrMo17 steel increases by 5 and 2.25 times. However, even at 30 MPa, the linear wear of this coating on titanium alloy is 1.2 times less than this coating on X105CrMo17 steel.

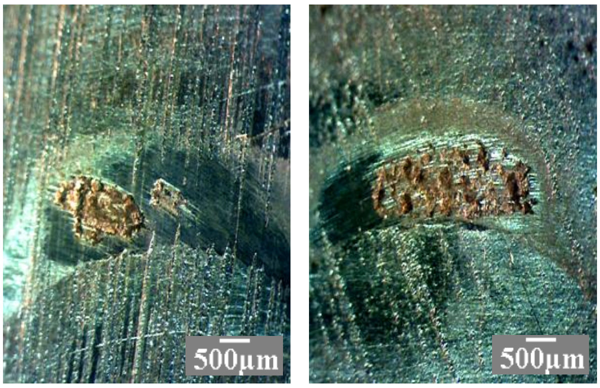


Fig. 12. Places of adhesion of friction surfaces of vacuum-arc coating of molybdenum on steel X105CrMo17 (a) and alloy VT-22 (b) at friction with X105CrMo17 (x56). Test conditions (A – 175 μm, ν – 30 Hz, N – $5\cdot10^5$ cycles).

The nature of the destruction of the molybdenum coating surface is similar to the nature of the destruction of the soft vacuum-arc coating of chromium. At a load of 20 MPa, the nature of surface destruction is uniform. With an increase in the load, the adhesion points of the molybdenum coating to the counter-sample material also increase. There are practically no significant differences in the destruction of the coating surface on titanium alloy VT-22 and on steel X105CrMo17. It should be noted that if the vacuum-arc coating of molybdenum based on titanium alloy VT-22 wears out, then almost immediately, due to the high tendency of the titanium alloy to adhesion and setting, the VT-22 material is transferred to the surface of the counter sample, which entails rapid destruction of the surface. Characteristic places of destruction of the surface of the vacuum-arc coating of molybdenum on various base materials are shown in (Figure 12).

In the work, the materials on which the coating was applied were tested - titanium alloy VT-22, steel X105CrMo17 see (Figure 5, 6). The graphs show that X105CrMo17 steel is 10-15 times more wear-resistant than titanium alloy VT-22. Moreover, the titanium alloy has high linear wear both at a load of 20 MPa and at a load of 30 MPa. Almost four times the VT-22 alloy exceeds the wear of the least wear-resistant coating - vacuum-arc coating of soft chrome.

The friction surface of titanium alloy VT-22 has the same fracture character both at 20 MPa and at 30 MPa. The surface damage is uniform, with small pits in the center of the friction paths, which were formed as a result of the impossibility of removing the friction vapor destruction products due to the specifics of vibration (Figure 13, a). With an increase in the load to 30 MPa, the nature of surface destruction has not changed. The change occurred only in the increase in the depth of destruction of the surface of the titanium alloy.

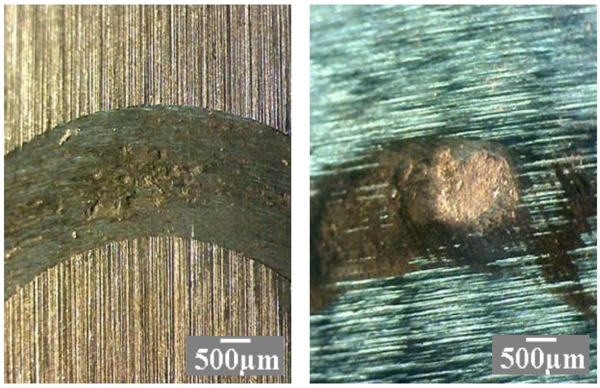


Fig. 13. Friction surface of titanium alloy VT-22 (a) and steel X105CrMo17 (b) with friction with X105CrMo17 at a load of 30 MPa (x56). Test conditions (A – 175 μm, P – 30 MPa, ν – 30 Hz, N – $5\cdot10^5$ cycles).

The wear resistance of X105CrMo17 steel is very high during testing. This indicator exceeds the wear resistance of all vacuum-arc coatings on steel at a load of 30 MPa, and at 20 MPa it exceeds only the vacuum-arc coating of soft chrome in terms of wear resistance.

This effect is explained by the fact that during the tests of X105CrMo17 steel, the material did not set with the surface of the counter-sample made of a similar material. In the case when the coating was tested on X105CrMo17 steel, the tribopara was set with subsequent welding of the coating from the surface. That is, quite deep breakouts were formed, which affected the value of linear wear of vacuum-arc coatings. Only in some places on the surface of X105CrMo17 steel, at a load of 30 MPa, setting points were formed (Figure 13, b).

Thus, in order to increase the wear resistance and durability structures and increase their efficiency of use in the aviation industry, it is proposed to use the VT-22 material as a base with molybdenum coatings applied to the surface. When using plain bearings in large quantities (up to a thousand pieces) in aircraft and the presence of large bearings (20 – 35 mm), replacing steel clips with a strong and lightweight titanium alloy VT-22 will reduce the weight of the aircraft structure and increase its efficiency without losing the reliability of the hinge assemblies.

6. CONCLUSION

1. It was established that chromium coatings formed by electrolytic and vacuum-arc methods and a molybdenum coating applied by the vacuum-arc method exhibit higher fretting resistance at an oscillation frequency of 30 Hz, a mutual displacement amplitude of 175 μm at 20 and 30 MPa on VT-22 titanium alloy, compared to coatings on X105CrMo17 steel.
2. It was determined that the coating of chromium with a thickness of 12-24 μm, applied by the electrolytic method, on an alloy of VT-22 and steel X105CrMo17 under conditions of fretting at 30 MPa, shows a tendency to set. The vacuum-arc coating of hard chromium is characterized by wear resistance under fretting conditions 2-3 times greater than the electrolytic coating, however, at a load of 30 MPa, signs of setting appear.
3. High wear resistance of molybdenum coating (vacuum-arc method) under conditions of fretting is established, at 20 and 30 MPa, this coating on VT-22 alloy is characterized by a decrease in linear wear by 2.6 and 1.2 times, compared to the coating on X105CrMo17 steel.
4. To increase the durability of hinged bearing structures and increase their efficiency of use in the aviation industry, it is proposed to use the VT-22 alloy as an inner cage with the application of a molybdenum coating to its surface by the vacuum-arc method with a thickness of 70 microns. When using plain bearings in large quantities (up to a thousand pieces) in aircraft and the presence of large bearings (20 - 35 mm), the replacement of steel inner races with surface-reinforced lightweight titanium alloy VT-22 will reduce the weight of the aircraft structure and increase its efficiency without losing the reliability of the hinge assemblies.

REFERENCES

[1] R. Kostyunik, O. Mikosianchyk, O. Stelmakh, A. Kushchev, S. Shymchuk, and N. Zaichuk, "An innovative approach to Non-Contact cleaning of Mini-Ball bearings," *Journal of Engineering Sciences*, vol. 12, no. 2, pp. A10–A19, Jan. 2025, doi: 10.21272/jes.2025.12(2).a2.

[2] A. Stelmakh *et al.*, "Improvement of Operational Parameters for PrecisionRolling Bearings by Cleaning Working Surfaces from MicroPollution of Various Nature," *Journal of Engineering Sciences*, vol. 10, no. 1, pp. A31–A40, Jan. 2023, doi: 10.21272/jes.2023.10(1).a5.

[3] N. Kumar and R. Satapathy, "Bearings in Aerospace, Application, Distress, and Life: A review," *Journal of Failure Analysis and Prevention*, vol. 23, no. 3, pp. 915–947, May 2023, doi: 10.1007/s11668-023-01658-z.

[4] S. Kim, S. Byun, and J. Suh, "Effects of tilting pad journal bearing design parameters on the Pad-Pivot friction and nonlinear rotordynamic bifurcations," *Applied Sciences*, vol. 10, no. 16, p. 5406, Aug. 2020, doi: 10.3390/app10165406.

[5] K. Gopinath, K. Raghavendra, M. K. Behera, E. V. S. Rao, M. Umakanth, and S. Gopinath, "Product design aspects for design of accurate mass properties measurement system for aerospace vehicles," *Applied Mechanics and Materials*, vol. 110–116, pp. 4712–4718, Oct. 2011, doi: 10.4028/www.scientific.net/amm.110-116.4712.

[6] E. Khmelnitsky and K. Kogan, "Optimal policies for aggregate production and capacity planning under rapidly changing demand conditions," *International Journal of Production Research*, vol. 34, no. 7, pp. 1929–1941, Jul. 1996, doi: 10.1080/00207549608905005.

[7] M. Khimko, A. Khimko, R. Mnatsakanov, and O. Mikosianchyk, "Resource testing of modified plain bearings for the aviation industry," *PROBLEMS OF TRIBOLOGY*, vol. 29, no. 2/112, pp. 16–22, Jun. 2024, doi: 10.31891/2079-1372-2024-112-2-16-22.

[8] B. A. Lyashenko, Z. A. Stotsko, O. A. Kuzin, M. O. Kuzin, and O. A. Mikosianchyk, "Determination of the optimal parametersof the structure of functional gradientmaterials using mathematical modellingapproaches," *Journal of Achievements of Materials and Manufacturing Engineering*, vol. 1–2, no. 92, pp. 13–18, Jan. 2019, doi: 10.5604/01.3001.0013.3183.

[9] M. Qiu, Z. L. Gao, G. F. Wang, and L. Chen, "Friction and Wear Characteristics of Spherical Plain Bearings with PTFE Woven Liners," *Advanced Materials Research*, vol. 199–200, pp. 763–766, Feb. 2011, doi: 10.4028/www.scientific.net/amr.199-200.763.

[10] T. M. A. Al-Quraan, "Temperature Resistance of the Boundary Lubrication Layers Under Rolling with Slippage Condition," *International Journal of Mechanical Engineering and Applications*, vol. 5, no. 2, p. 78, Jan. 2017, doi: 10.11648/j.ijmea.20170502.12.

[11] Q. J. Wang and Y.-W. Chung, Eds., "Spherical Race Bearings," in *Encyclopedia of Tribology*, Boston, MA: Springer US, 2013, pp. 3225–3225, doi: 10.1007/978-0-387-92897-5_101292.

[12] S. G. Glasunov, "Critical Review Titanium Alloys for Different Branches of Engineering," in *Titanium and Titanium Alloys*, J. C. Williams and A. F. Belov, Eds., Boston, MA: Springer US, 1982, pp. 2087–2091, doi: 10.1007/978-1-4757-1758-7_43.

[13] A. Khimko, V. Kralya, A. Yakobchuk, V. Kostuchik, and A. Sidorenko, "UNITS WEARABILITY OF AIRCRAFT WING LIFT DEVICES," *Problems of Friction and Wear*, vol. 0, no. 55, Jan. 2011, doi: 10.18372/0370-2197.55.3249.

[14] V. Kralya, A. Khimko, V. Borodiy, and A. Yakobchuk, "Facilities for restoration of monorail of mechanization of a wing of aircrafts," *Proceedings of National Aviation University*, vol. 29, no. 3, Mar. 2006, doi: 10.18372/2306-1472.29.1375.

[15] T. P. Penyashki, V. K. Kamburov, G. K. G. Kostadinov, M. K. Kandeva, R. D. Dimitrova, and A. N. Nikolov, "Some ways to increase the wear resistance of titanium alloys," *Journal of the Balkan Tribological Association*, vol. 27, no. 1, pp. 1–20, Jan. 2020.

[16] Q. Y. Zhang, Y. Zhou, X. X. Li, L. Wang, X. H. Cui, and S. Q. Wang, "Accelerated formation of tribo-oxide layer and its effect on sliding wear of a titanium alloy," *Tribology Letters*, vol. 63, no. 1, May 2016, doi: 10.1007/s11249-016-0694-7.

[17] A. Abdelmoneim, R. N. Elshaer, M. El-Shennawy, and A. S. Sobh, "Modeling of wear resistance for TC21 Ti-alloy using response surface methodology," *Scientific Reports*, vol. 13, no. 1, p. 4624, Mar. 2023, doi: 10.1038/s41598-023-31699-1.

[18] S. Chatti, L. Laperrière, G. Reinhart, and T. Tolio, Eds., "Mechanical Micromachining," in *CIRP Encyclopedia of Production Engineering*, Berlin, Heidelberg: Springer Berlin Heidelberg, 2019, pp. 1176–1176, doi: 10.1007/978-3-662-53120-4_300418.

[19] V. V. Shevelya, G. S. Kalda, and Yu. S. Sokolan, "Tribological and Rheological Properties of Thermally Treated Steel under Reverse Friction," *Journal of Friction and Wear*, vol. 40, no. 2, pp. 156–162, Mar. 2019, doi: 10.3103/s1068366619020120.

[20] *GOST 23.211-80*, Products wear resistance assuring. Testing of materials for wear under fretting and fretting-corrosion conditions, pp. 5, 1980.

[21] *ISO/IEC 17025:2019*, General requirements for the competence of testing and calibration laboratories, pp. 22, 2019.

[22] *ISO 12240-1*, Spherical Plain Bearings — Part 1: Radial Spherical Plain Bearings, International organization for standardization, Switzerland, pp.9, 1998.

[23] *Spherical plain bearings and rod ends for heavy-duty applications*, Fluro-Gelenklager GmbH, Catalog Edition, pp.28, 2015.