Article

Tribological Characteristics of Nitrided in Plasma Glow Discharge Samples Made from Titanium Alloy VT5 in Pairs with Different Materials

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Abstract: One of the modern methods of improving operating characteristics of titanium and titanium-based alloys under conditions of friction and increased contact loads is the method of ion-plasma nitriding. The effect of nitriding of VT5 alloy (Al 4,5-6,7 %, V to 1,2 %, Mo to 0,8 % – analogue 3.7115) in the plasma of a glow discharge excited in a hollow cathode on its tribological characteristics in pairs with different materials in T-1 fuel and under dry friction conditions has been studied. For research and tribological tests, samples of VT5 alloy were nitrided in the plasma of a glow discharge excited in a hollow cathode at a temperature of 975 ± 15°C and a pressure of 58 ± 2 PA in a nitrogen-argon gas mixture with a nitrogen content of 78 %. Studies of samples of VT5 alloy after nitriding showed that the surface roughness Ra was in the range of 0.58-0.64, and the surface hardness HV5 was 525 ± 20 kgf/mm^2 at a base hardness of 325 ± 15 kgf/mm^2. Tribological tests were performed on a friction machine 2070 SMT-1 according to the scheme "cube - roller". Tests under conditions of friction with oil were performed at a load of 200 N. The sliding speed during the tests was 1.3 m/s, the test time was 75 sec. The test under dry friction conditions was carried out at a load of 100 N and a sliding speed of 0.785 m/s, the test time was 30 minutes. Low wear ability in relation to the nitrided titanium alloy VT5 (<2.4x10^{-4} mm^3/s), as well as friction coefficients at the level of 0.08 to 0.12 in the order of their growth had bronze VB-23NTS (Pd 18–22 %, Ni 3–4 %, Zn 3–4 %, Sb 3–4 %, P 0.15–0.3) r.O10C2N3, VB-24 (Sb 4.7–6, 2 %, P 0.4–0.9), steel 1.3505, cast iron GGG80, cemented steel 20Cr3MoWV.

Keywords: titanium alloys; nitriding; tribological characteristics; friction; wear resistance

1. Introduction

Titanium alloys have a number of certain properties, such as high specific strength, fatigue properties, corrosion resistance and some others. which determine the expansion of their use in various fields of application, in particular, in the production of aerospace equipment [1, 2]. The introduction of titanium and titanium-based alloys is one of the urgent tasks in aircraft engineering. However, the tendency to grip during sliding friction and other low tribological properties limit the possibility of their wider use in aerospace units and assemblies. The application of titanium alloys can be significantly expanded if their surface is modified by different methods of processing or coating, increasing their wear resistance, antifriction and other properties [3-6]. The demand for application of titanium alloys and alloys on its base in friction units in units and equipment is caused both by the general tendency to decrease weight of aerospace products and by the need to replace aluminum-based alloys if it is necessary to ensure operation of corresponding units at temperatures above 130°C [1]. Among the enterprises working in this direction is, in particular, FED JSC (Ukraine) [7]. When determining the possibility of using a particular titanium alloy, first of all, of course, its physical and mechanical properties are taken into account, but its price and availability are also important. In this respect, low-alloyed, with

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average strength level, single-phase α-alloy of titanium BT5, the close analogue of which is the titanium alloy Grade 6, could be considered as quite suitable for use in friction pairs with relatively low load level and operating temperatures up to 400°C. after modifying its surface by methods used to improve the tribological properties of titanium-based alloys. In addition, it is a single-phase α-alloy and, unlike the stronger and higher-temperature two-phase α+β titanium alloys, it has such important properties as thermal aging resistance, low creep, stability of mechanical characteristics during long-term operation and some others [8].

2. Analysis of literary sources and the state of the problem

One of the modern methods to improve the performance characteristics of titanium and titanium-based alloys under friction conditions is the method of ion-plasma nitriding [9-11]. Thus, work [9] shows that after the ionic nitriding of VT6 alloy, the microhardness of the HV surface increases by 3-4 times compared to the initial state, depending on the nitriding conditions. Measurements of wear of the samples nitrided in different modes, carried out on the Nanovea tribometer according to the scheme "ball on disk" at a load of 4N showed that its value can differ by 4 times, that is, it depends significantly on the conditions of nitriding the samples. In work [10] the tribological characteristics of the titanium alloy (Ti-6Al-4V), which is an analogue of the domestic alloy VT6, were studied. The wear value and friction coefficient were measured with a CSM tribometer (Switzerland) in the unidirectional sliding mode with a Si3N4 ball at a load of 3 N. The studies showed that the coefficient of friction could have a value of ≈ 0.6 to 1.0 depending on the mode of ion nitriding and the presence of texture of the sample surface layer, as well as the wear value, which was in the range from 0.025 mm to 0.3 mm3. In [11] the tribological studies of the VT8 titanium alloy nitrided in different modes were conducted on a universal friction machine UMF 2168 under the "disk-finger" scheme in the conditions of dry friction with a loading of about 20 N. The counterbody was hardened steel 45 (HRC-45). It was found that the friction coefficient of nitrided titanium samples at such test conditions decreased by a factor of 2-3 times as compared to the test of nonnitrided samples and could range from 0.2 to 0.4 depending on the nitriding modes, and the wear rate decreased by ~ 70 - 40 times respectively.

The results of the effect of ion-plasma nitriding on the tribological characteristics of titanium and its alloys when working with those or other materials, which are given above, indicate the high efficiency of such treatment to improve the tribological characteristics of titanium-based alloys, although they may differ significantly even for identical materials. friction pairs due to the mismatch of conditions of their manufacture, methods and conditions of investigation of their characteristics.

Therefore, it is possible to correctly compare the tribological characteristics of friction pairs made of nitrided titanium-based alloys with different materials on the basis of literature data only if the conditions of their manufacture, nitriding, methods and conditions of testing. Find information in the literature about the possibility of using the alloy VT5 in friction pairs with metallic materials and its tribological characteristics after modifying its surface by ion-plasma nitriding was not possible. These circumstances prompted the authors of this work to conduct a study to find out the effect of plasma nitriding of the VT5 alloy on its tribological characteristics in friction pairs with different materials.

3. Problem statement

The materials of the article contain the following issues: equipment, research methods and materials.

The aim of this research is to study the effect of nitriding of the VT5 alloy in a glow discharge plasma excited in a hollow cathode on its tribological characteristics in pairs with various materials under dry friction conditions and in fuel TS-1.

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4. Equipment, research methods and materials

For research and testing, samples were made of VT5 alloy in the form of cubes with a side of 10 mm with a roughness of Ra 0.63. Before making the samples, the alloy was annealed at 850°C for one hour in a vacuum furnace at residual gas pressure ≤ 1.3x10^{-2} Pa. Nitriding of the samples was carried out in a glow discharge plasma excited in a hollow cathode in the form of a cube with dimensions of 100x100x100 mm^3 at a temperature of 975±15°C and a pressure of P=58±2 Pa for 4 hours in a nitrogen-argon gas mixture containing nitrogen. Fig. 1 shows a photo of a glow discharge in a hollow cathode during sample nitriding.

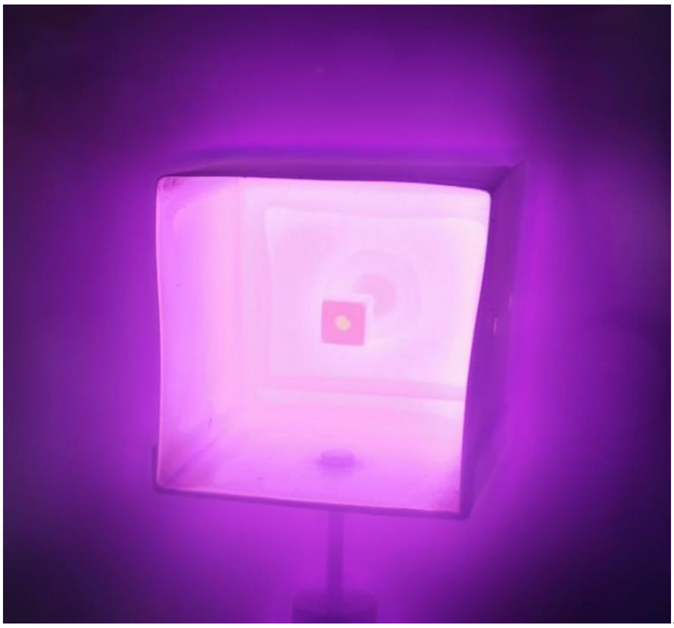.

Figure 1. Photograph of a glow discharge in a hollow cathode during nitriding of a sample located in the center of the cathode.

The temperature of the samples during nitriding was controlled with a Luch pyrometer (Ukraine), the composition of the gas mixture was set using FG201 flowmeters from Bronkhorst (Netherlands), and the pressure was measured with a KPDR900 vacuum gauge from Kurt J. Lesker (USA). The hardness of the nitrided surface of the samples was determined using a QNESS Q60M hardness tester manufactured by CHEMIKA (Austria) at a load of 5 kg; the roughness of the coatings was determined using a JENOPTIK nanoscan 855 profilometer (Germany). The surface topography before and after tribological tests was studied using an Altami MET-1C optical microscope with a digital camera.

Tribological tests were performed on a modernized 2070 SMT-1 friction machine according to the “cube-roller” scheme under conditions of dry sliding friction and friction with lubrication. Lubrication was carried out by immersing the movable counterbody in a bath with TS-1 fuel, GOST 10227-86. Cubic specimens were used as a fixed specimen "shoe". The "shoe" specimen during the tests was fixed in a special mandrel with the possibility of "self-installation" on prismatic supports. This made misalignments during loading impossible and allowed (taking into account the shape of the specimens) to minimize the scatter of data during testing. The movable specimen "roller" was used as standard samples with a diameter of 50 mm and a height of 12 mm, made of various materials that can be used in various branches of mechanical engineering and aircraft building (Steel 1.4878, steel 1.3505, cemented steel 20Cr3MoWV, nitrided steel 20Cr3MoWV, cast iron GGG80, bronze Br.O10C2N3, VB-23NTS (Pd 18–22 %, Ni 3–4 %, Zn 3–4 %, Sb 3–4 %, P 0.15–0.3), VB-24 (Sb 4.7–6, 2 %, P 0.4–0.9). The conditions of tribological tests are given in Table 1.

Table 1. Conditions for conducting tribological tests.

Load,N	lubricant	Sliding speed, m/sec	Test time, sec
200	+	1,3	75
100	–	0,785	1800

The amount of wear was determined by weight method. Weighed samples before and after tests (after thorough washing) on analytical scales with the accuracy of 1x10-4 G. Average arithmetic values of the test results of each mating material were calculated from the data of 2 parallel experiments. Instrumental errors of friction coefficients determination at tests with 100 N overloading were 2 - 10 %, at tests with 200 N overloading the errors were 1.85 - 12 %. The smallest values of percent errors refer to large values of friction coefficients.

5. Results

Studies of specimens from the VT5 alloy after nitriding showed that the surface roughness Ra was in the range of 0.58-0.64, and the hardness of the HV5 surface was 525±20 kgf/mm² with a base hardness of 325±15 kgf/mm². Fig. 2 shows the structure of the digestive in a mixture of hydrofluoric and nitric acids of a cross section of a nitrided layer. In the structure of the nitrided layer, there is a thin, 3-4 μm thick, dark outer layer, then a light uniform continuous layer 25-30 μm thick, behind which there is an intermediate layer between the base and the solid light layer. The intermediate layer has a mixed structure of light-colored fragments, similar to a continuous layer, interspersed in a field with a base structure. Such a three-layer structure of the surface nitrided layer is formed during the nitriding of titanium and α-alloys in a certain temperature range above the temperature of the $\alpha \rightarrow \beta$ phase transition, which for the VT5 alloy, according to various literature data [12,16], is in the temperature range (940 ÷ 990)°C. The outer layer is titanium nitride TiNx, then the layer in which the transition from the β phase to the α phase occurred due to its saturation with nitrogen to a concentration sufficient for such a transition at the nitriding temperature. In the intermediate layer, only in some fragments of its structure, a nitrogen concentration was reached that was sufficient for the formation of the -phase at the nitriding temperature in the -phase layer. On cooling, these fragments, having the same color as the overlying layer, did not experience a polymorphic transformation, while the base and the rest of the intermediate layer experienced a $\beta \rightarrow \alpha$ transformation on cooling. The core structure of the nitrided sample did not change compared to the alloy structure it had after annealing at 850°C.

The results of tests of nitrided samples in contact with different materials under lubricated friction conditions are presented in Table 2. They can be conditionally divided into two groups. One group of materials is friction pairs that have shown satisfactory results in terms of wear and friction coefficient for these test conditions, which include all types of tested bronzes, cast iron, cemented steel 20Cr3MoWV and steel 1.3505. Another group of tested materials in friction pairs, which included nitrided steel 20Cr3MoWV and steel 1.4878, had high values of both the coefficient of friction and the amount of wear of the contacting materials.

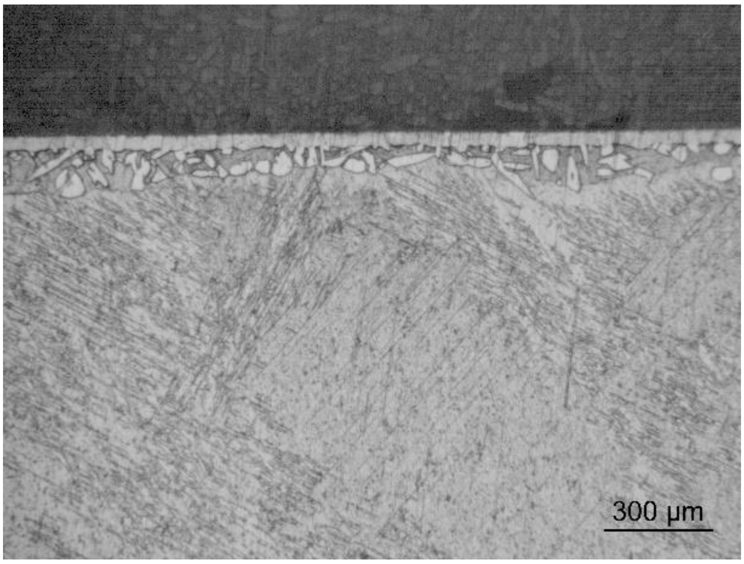

Figure 2. The structure of the digestive in a mixture of hydrofluoric and nitric acids of the transverse section of the nitrided layer of the sample from the VT5 alloy.

In the first group of materials, the lowest friction coefficient was recorded in the friction pair of nitrided titanium with bronze VB-23NTS, Br.O10C2N3, VB-24, steel 1.3505, cast iron GGG80, as well as 20Cr3MoWV cemented steel, had a minimum wear capacity with respect to nitrided titanium (2.4x10^{-4} mm^3/s), in a pair after testing even some increase. Friction tracks with this group of materials are hardly noticeable on the surface of nitrided samples during visual inspection and practically did not change in the surface structure compared to the original one (Fig. 3). Another group of materials tested in friction pairs, which included nitrided steel 20Cr3MoWV and steel 1.4878, had high values of both the friction coefficient and the amount of wear of the contacting materials. A higher wear capacity in relation to nitrided titanium, as well as the value of intrinsic wear, had nitrided steel 20Cr3MoWV. The friction coefficient of this group of materials turned out to be the same and had a value of 0.54. Fig. 4 shows a view of the friction track after tribological tests of a nitrided titanium sample paired with nitrided steel 20Cr3MoWV

Table 2. Test results of friction and wear pairs lubricated with TS-1 fuel.

№	Counterbody material	"Pad" wear, g	Counterbody wear, g	Friction coefficient	Pad wear rate mm^3/Nм	Counterbody wear rate mm^3/Nм
1	bronze VB 23NTS	0,0000	0,0030	0,08	<1,13x10^{-6}	1,81x10^{-5}
2	bronze Br.O10C2N3	0,0001	0,0010	0,10	1,13x10^{-6}	6,25x10^{-6}
3	bronze VB 24	0,0000	0,0002	0,10	<1,13x10^{-6}	1,21x10^{-6}
4	cast iron GGG80	0,0000	0,0016	0,11	<1,13x10^{-6}	1,14x10^{-5}
7	steel 1.3505	0,0002	0,0011	0, 10	2,26x10^{-6}	7,22x10^{-6}
8	steel 20Cr3MoWV cemented	+0,0002	0,0003	0,12	Increase 2,26x10^{-6}	1,97x10^{-6}
9	steel 20Cr3MoWV nitrided	0,0020	0,0090	0,54	2,26x10^{-5}	5,92x10^{-5}
10	steel 1.4878	0,0014	0,0031	0,54	1,58x10^{-5}	2,42x10-5

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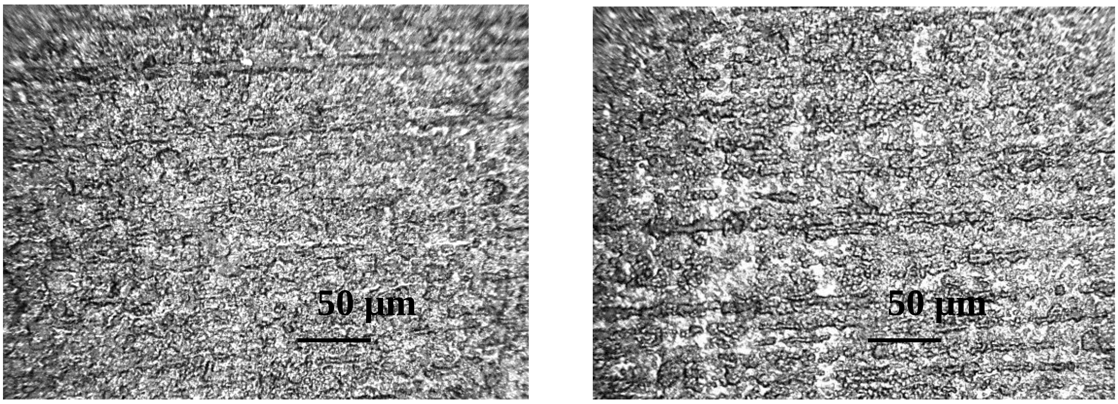

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Figure 3. Structure of the surface of a nitrided sample before and after tribological tests in a pair with cemented steel 20Cr3MoWV with lubrication in the fuel, respectively a) and b) (x200).

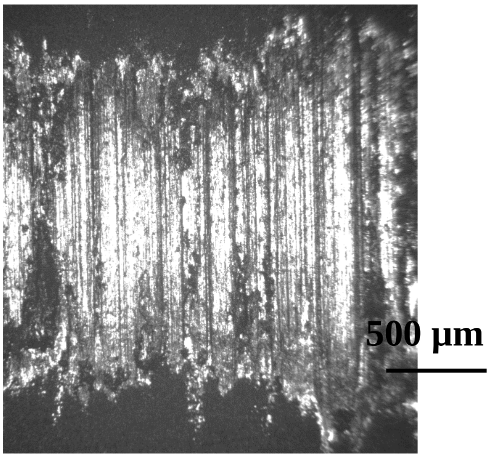

Figure 4. Friction paths of a nitrided titanium sample after tribological tests paired with nitrided 20Cr3MoWV steel lubricated in T-1 (x15) fuel.

The track has contours with torn edges, and its surface is a rough striped relief with differences in the depth of furrows of tens of microns (Fig. 5) at a maximum average track depth of ≈40 µm.

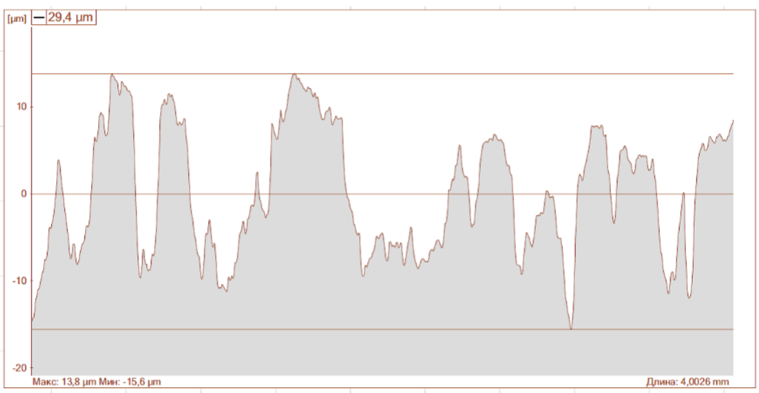

Figure 5. Profilogram in the region of the maximum depth of the surface of the friction track of a nitrided titanium sample after tribological tests in a pair with nitrided steel 20Cr3MoWV with lubrication in T-1 fuel.

The friction track after tribological tests paired with steel 1.4878 has a similar appearance at a somewhat shallower depth. With such a depth of the friction track, wear in the

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area of contact of the nitrided sample with the counterbody must be completely subjected to the upper layer of titanium nitride, the continuous nitrided layer and partially the intermediate layer between the nitrided layer and the base material of the titanium alloy, shown in Fig. 1.Fig. 6 shows the structure of transverse sections of titanium samples with a nitrided layer in the area of friction tracks with nitrided steel 20Cr3MoWV and steel 1.4878.

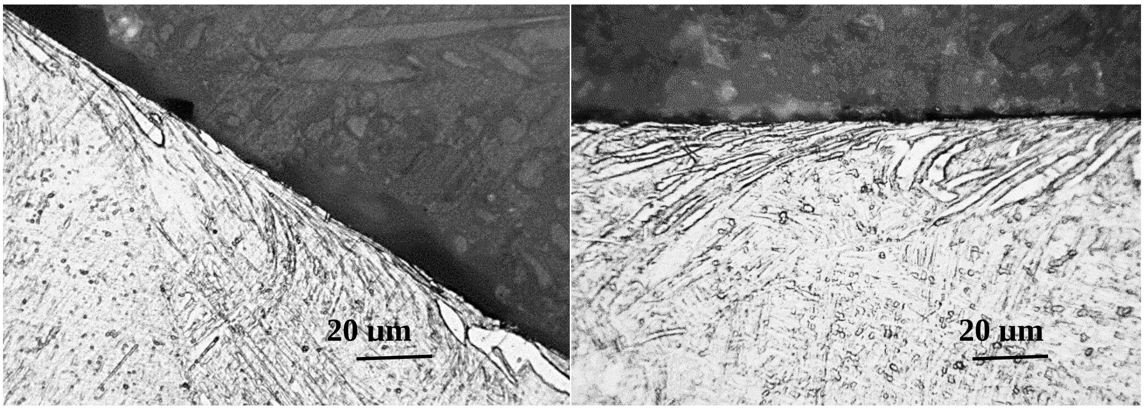

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Figure 6. The structure of a transverse section of a nitrided titanium sample in the region of the maximum depth of the friction track after tribological tests (x500): a) paired with nitrided steel 20Cr3MoWV; b) paired with steel 1.4878.

It can be seen from Fig. 6 that in the region of the maximum depth of the friction track after tribological tests with nitrided steel 20Cr3MoWV and steel 1.4878, the wear limit of the titanium sample material is in the region of the intermediate nitrided layer, not reaching the base material. Deformation distortions in the structure of the intermediate layer are also clearly visible, caused by the influence of the friction force between the rotating roller and the surface of the test sample.

Sufficiently good tribological properties of cast irons in friction pairs with various materials are primarily associated with a high content of carbon in them, which, upon contact of rubbing surfaces, participates in the formation of surface films that provide sliding with a low coefficient of friction. From these positions, it is possible to explain why the results of tribological tests in friction pairs with nitrided and cemented, steel 20Cr3MoWV differ so much, in which, according to [14], the surface concentration of carbon, depending on the carburizing modes, can range from 2.14 % to 5 .7 %, but at a distance of 0.2 mm from the surface, the carbon concentration can be from 0.95 % to 1.45 %.

At operation of different friction pairs with grease in conditions of limiting friction the coefficient of friction has value at level 0,08 - 0,15, occupying intermediate values between values, characteristic for liquid friction conditions and conditions of dry friction. Exactly in this range there is value of coefficient of friction for the first group of friction pairs. In the second group of friction pairs, the obtained value for the friction coefficient indicates a significant contribution of adhesive interaction between materials, despite the presence of a lubricating liquid, which leads to seizure and formation of scuffs in some parts of the contacting surfaces in the friction pair. This is evidenced by the type of friction paths of these groups of materials.

In order to predict the behavior of units and mechanisms under conditions of insufficient lubrication or interruptions in its supply, it is necessary to know the characteristics of the selected tribopair also in dry friction conditions. Besides, for many friction units the use of lubricating oils according to the conditions of their operation is simply unacceptable. Cemented steel 20X3MVF is widely used in the production of various units. Therefore, it was interesting to determine the tribological characteristics of nitrided alloy VT5 when working under dry friction conditions, which showed an increase in pad weight rather than wear when tested with lubrication in pair with this material. Given the nonlubricated friction pair operating conditions used in the units produced, the tests were conducted at a load of 100N. The tests showed that at the initial point during the next 75 seconds of testing, the coefficient of friction had an almost constant value of 0.34. After this period of time the coefficient of friction became inconsistent and lower with values fluctuating first from 0.32 to 0.2 and increasing until the end of the test to values from 0.26 to 0.52. Table. 3 shows the results of measuring the wear of the studied samples in this experiment.

Table 3. The results of tests without oil of the friction pair "nitrided alloy VT5-cemented steel 20Cr3MoWV".

path, m	"Pad" wear, g	Counterbody wear, g	Friction coefficient	Pad wear rate mm³/Nм	Counterbody wear rate mm³/Nм
1413	Increase +0,0005	0,0046	0, 2 ÷0,52	Increase 6,51x10^{-7}	4,46x10^{-6}

After testing without oil the friction pair "nitrided alloy VT5 - cemented steel 20X3MVF" the shoe added weight, as well as after testing such a pair with grease. But if, after testing such a steam with lubrication, the surface of the nitrided titanium alloy in the area of contact with the counterbody did not undergo significant changes, then in this case a friction track was formed, which, as measurements showed, had a depth of about 13 µm. With such a track depth from the counterbody Ø 50 mm, the calculated weight drop should have been at least 0.0006 g. The discrepancy between the calculated change in the block weight and the actually measured one indicates that during the sliding of this pair, material is transferred from the roller. Fig. 7 shows a photo of the friction track on the pad with material enveloping on the edge of the roller exit with the surface of the pad and numerous areas with the products of interaction of rubbing materials on the surface of the friction track.

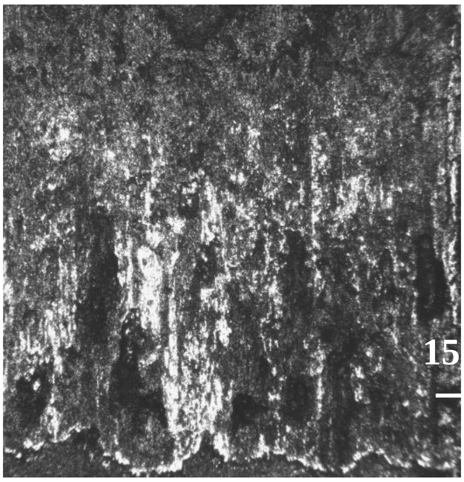

Figure 7. Friction track of a nitrided titanium sample after tribological tests in a pair with a sample of cemented steel 20Cr3MoWV without lubrication (X40).

The change in the value of the friction coefficient during testing can be explained by a change in the composition of the contacting material of the pad surface during its wear. The initial period, apparently, corresponds to the time during which the sliding was carried out over the titanium nitride layer, during which the adhesive interaction with the roller material was constant and, therefore, the friction coefficient did not change. With a further increase in the depth of the development of the area of contact with the roller, the adhesive interaction of the material of the roller is enhanced due to the appearance of contact with the titanium alloy, the sliding of which is accompanied by the process of

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transferring the material of the roller and acts of local setting of the contacting materials. This leads to instability of the value of the friction coefficient and an increase in the amplitude of its fluctuations as a result of an increase in the contact area of the counterbody with the titanium alloy with subsequent wear of the nitrided layer. A similar character of the change in the friction coefficient was also observed in [5] when testing according to the “disk-ball” scheme of the nitrided VT6 alloy paired with a ceramic ball without lubrication.

The studies carried out in this work have shown that, depending on the material contacting in the friction pair with the nitrided alloy VT5, it is possible to provide sliding with sufficiently low values of the friction coefficient and wear of the tribopair materials under the test conditions chosen in this work. The presence of titanium nitride layer on the surface of titanium nitrided alloys ensures their high wear resistance. The reduction of adhesion interaction and tendency to adhesion with contacting materials during sliding is also associated with the presence of a nitride layer on the surface of nitrided alloys. The processes of transferring the counterbody material to the nitrided surface of titanium alloys may play an important role. Based on these positions, an explanation of the results in this work, obtained by testing the friction pair "nitrided alloy VT5 - cemented steel 20Cr3MoWV " without lubrication, is proposed.

6. Conclusion

Tribological tests of materials from steel 12X18H10T, steel ШХ-15, nitrided steel 20Х3МВФ, cemented steel 20Cr3MoWV, high-strength cast iron ВЧ2169-2 - analogue of ВЧ80-2, bronze BrSu3N3Ts3S20F0 have established

- Low wear ability in relation to nitrided titanium (2,4x10-4 mm3/sec) under tests in the conditions of lubrication in fuel T-1 and friction coefficients at the level from 0,08 to 0,12 had bronzes BrSu3N3Ts3S20F0, 2, BrO10C2NZ, BrSu6F0,9, steel ШХ-15, cast iron ВЧ2169-2, cemented steel 20Cr3MoWV in order of their increase

- Low values of wear and values of coefficient of friction of steel ШХ-15, cast iron ВЧ2169-2, cemented steel 20Cr3MoWV in the pair of friction with nitrided alloy VT5 can be explained by the high content of carbon in them, which plays the role of solid lubricant during sliding and participation of process of alloy VT5.

- The results of the conducted tests of the nitrided alloy VT5 should be considered as preliminary when considering the possibility of their use in the friction pairs of units and units of aerospace and other equipment, which may serve as an impetus for further research in this direction.

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