Tribological behaviour of VT22 titanium alloy after surface hardened treatments

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Abstract. In this research the tribological behaviour of VT22 titanium alloy (Ti–5Al–5Mo–5V–1,5Cu–Fe) after various surface hardened treatments (cold surface plastic deformation (ball burnishing), subsequent thermo-chemical treatment (gas nitriding) and their combination) in a pair with bronze was investigated. According to the results of the tribological test, SEM and EDX analyses of the wear surfaces, wear mechanisms (or processes) those of tribo-pairs in the conditions of boundary lubrication were established. It is shown that combined treatment (previous ball burnishing and subsequent gas nitriding) of titanium alloy provided higher tribotechnical parameters (wear resistance, friction coefficient and temperature near the friction zone) of investigated tribo-pairs compared to ball burnishing or gas nitriding. It was established that the combined treatment increases the wear resistance of VT22 titanium alloy in tribo-pair with bronze (Cu–10Al–4Fe–4Ni) twice and reduces the friction coefficient by 30% compared to nitriding without surface pre-deformation.

1. Introduction

The aircraft operation experience and analysis of the exploitative destruction of details manufactured from titanium alloys shows that the predominant failure of aggregates can be divided into three main types: fatigue and wear failures, fretting [1].

The fatigue failures are characteristic for highly loaded aircraft details operating under dynamic alternating loads. Currently there are the reliable methodological tools for calculating fatigue resistance of constructions, therefore the appearance of the operational fatigue failures indicates a miscalculation of the designer and it is considered as structural defect, or it is caused by the influence if unaccounted external factors. The last ones include manufacturing and technological violations, the influence of the combination of external factors (unaccounted loads, environmental influence, extraordinary overloads, etc.). To prevent the fatigue failures, it is performed «strengthening» of details by increasing strength, size or rigidity in order to reduce the existing loads below the threshold for material. The preliminary assessment of the fatigue strength of particularly responsible aggregates is carried out on the base of results of bench tests that simulate the external influences on the investigated object [1–5].

Unlike fatigue failures, the wear failures and fretting of construction units cannot be calculated previously. The bench and laboratory tests give an approximate result due to the multi-factorial of external factors, so only exploitation determines the durability of friction units. The importance of the reliability of friction units is confirmed by the following facts: more than 50% of failures of units and aggregates of the aircraft is associated with wear of hinge joints, 90% of repaired parts – the result of wear of friction units. The friction units in the aircraft are subjected to significant vibration loads, the influence of external factors (dust, significant temperature differences from -60 to 100ºC, etc.). In this regard, it is almost impossible to find the universal way to protect the elements of constructions from wear, and therefore it requires an individual approach to each friction unit [1–5].

Titanium alloys have poor tribotechnical characteristics. If we consider the constructions manufactured from VT22 alloy, that operate due to the movement of their elements (aircraft control system, landing gear, hydraulic system, etc.), then it becomes clear how important ensuring their reliable operation. It is connected with the fact that increased wear of details in friction pairs in some cases violates the tightness of the working space, in other cases – the normal mode of lubrication, in others – leads to loss of the kinematic accuracy of the mechanism that impairs control and reduces flight safety. Also, the wear and damage of surfaces reduce the fatigue resistance of details and can cause their destruction even at low stress concentrators and too low rated loads. The increased wear disrupts the normal interaction of details in the units, can cause significant additional loads, shocks in the joints and vibrations, sudden damage. Seizing of details can lead to an accident [3].

For example, in the construction of the control mechanism of the flaps of the aircraft An-124 «Ruslan» the rails were manufactured from VT22 titanium alloy unlike previous constructions manufactured from high-strength steel. It increased significantly the resource and eliminated the corrosion and chipping of the chrome coating that is characteristic of steel details. However, after ~ 6,000 flights (more than intended resource of aircraft), in the areas of the carriage during takeoff, landing and cruise phase it was found the unacceptable wear holes because of the rollers of the carriage [5].

The various methods of surface engineering are used to increase the wear resistance of titanium alloys, including VT22 titanium alloy. It is well known that the deformed surface layer with increased density of point and linear defects is formed during rolling by diamond ball. It can intensify the diffusion of nitrogen during gas nitriding, and reduce the time and temperature parameters of thermo-diffusion saturation by nitrogen and ensure the regulated surface and volume characteristics of the alloy, and, consequently, the appropriate wear resistance.

Therefore, the purpose of this work is to investigate the influence of combination of cold surface plastic deformation (diamond ball burnishing) and thermo-chemical treatment (gas nitriding) on the tribotechnical behaviour of titanium alloy.

2. Methodology

In this work, VT22 titanium alloy (Table 1), which is widely used in «An» aircraft, was investigated.

Table 1. Chemical composition and mechanical properties of VT22 titanium alloy. Chemical composition according to GOST 19807-74

Element	Alloying element					Impurity, not more					Matrix
	Al	Mo	V	Cr	Fe	Si	C	O	N	H	Ti
Content, wt.%	4.4…5.7	4.0…5.5	4.0…5.5	0.5…2.0	0.5…1.5	0.15	0.1	0.2	0.05	0.015	rest

Mechanical properties according to GOST 26492-85				
Heat treatment	$\sigma_в$, MPa	δ, %	ψ, %	KCU, kJ/m^2
Annealing	1080…1280	7…10	17…30	250…300
Quenching+aging	1280	6…7	16…18	180…200

From the whole range of methods of cold surface plastic deformation, the methods based on rolling friction can be used for treatment of titanium alloys. It is caused by the fact that titanium alloys during cold surface plastic deformation have a tendency to contact seizing and sticking on tools. Therefore, in this work, we chose the method of diamond ball burnishing, which has lower sliding friction and, as a consequence, less probability to form defects on the treated surface. The ball with a diameter of 5 mm was made of diamond polycrystalline composite material of the C–Co–34Ni system. The regime of ball burnishing (*Regime 1*): load 300 N; number of passes – 11; the feed rate and rotation frequency were constant: 0.07 mm/rpm and 200 rpm, respectively. The cold surface plastic deformation was performed at Bakul Institute for Superhard Materials of the NAS of Ukraine.

Gas nitriding was carried out using equipment that allows to saturate both under static conditions at atmospheric pressure and in a rarefied dynamic atmosphere of nitrogen, as well as to reproduce the technological regulations of heat treatment of alloys (cyclic changes in temperature, heating and cooling rates) and provide gas-dynamic, time and temperature regimes of nitriding in one technological cycle. Gaseous nitrogen of commercially purity was used for nitriding, which before supplying into the furnace reactive space was freed from oxygen, filtering it out using a silica gel and titanium chips pre-heated up to 50°C above the saturation temperature. We combined gas nitriding with strengthening heat treatment of VT22 alloy, that allows to form the wear-resistant strengthened nitride layer and volume strengthening of VT22 alloy in one technological cycle according to the following regime (*Regime 2*): heating to 840°C, exposure of 10 h, cooling with furnace to temperature of 750°C, exposure of 3 h; cooling to 450ºC at a rate of 5ºC/min; 600°C, exposure 4 h, cooling with furnace. Nitriding was performed at atmospheric pressure of nitrogen. Nitrogen was supplied at temperature of 840°C.

Combined treatment (*Regime 3*): consists of pre-rolling by diamond ball (Regime 1) and subsequent gas nitriding (Regime 2).

The tribotechnical characteristics of the treated samples of VT22 titanium alloy were investigated under conditions of ultimate lubrication using SMT-2 friction machine on the base of 1000 m at specific load of 0.6 MPa with sliding speed of 0.6 m/s. As a lubricant we used hydrofluid AMG-10 (aviation hydraulic oil, GOST 6794-53), which is used in the hydraulic systems of domestic aircraft Counterbody were made from deformable bronze (Cu–10Al–4Fe –4Ni). The friction scheme – «disc-block». The wear resistance of the investigated friction pairs was evaluated by weight change by weighing before and after friction interaction using Voyager analytical balances with an accuracy of ±0.1 mg. The temperature near the friction zone was determined using chromel-alumel thermocouple. The frictional moment was measured by non-contact inductive controller of equipment. Using software, the data is converted into a digital format, and then is converted automatically into the friction coefficient. The measurement error of the frictional moment is not more than 5%. The graphs of the dependences of friction coefficient and temperature changes on the test time were built. The wear mechanisms were determined by analyzing worn surfaces of the friction pairs using scanning electron microscope EVO-40XVP.

3. Results and discussion

According to previous studies [6, 7] combined treatment of titanium alloy provided an increase of the level of surface strengthening compared to nitriding without previous surface deformation, which will influences on the tribotechnical characteristics of VT22 titanium alloy. The efficiency of combined treatment for titanium alloy in friction pair with bronze was investigated comparing with tribotechnical characteristics (wear intensity, friction coefficient, temperature near the friction zone) of analogical friction pairs, where titanium alloy was used in initial state and after, ball burnishing and gas nitriding. It should be noted that instead of the alloy in the initial state we chose the alloy after strengthening heat treatment.

The analysis of the kinetics of change of the friction coefficient showed that at the initial stage of the friction tests the friction coefficient is high. By increasing time exposure it decreases due to grinding of friction pair surfaces. After some time it stabilizes for all friction pairs. It should be noted that for the alloy in initial state and after and ball burnishing we fix zones of short-term oscillations (jumps) of the friction coefficient that indicates the seizing in these friction pairs. The lowest values of the friction coefficient are fixed for the friction pair, where titanium alloy was hardened by combined treatment. Carrying out of the surface deformation before nitriding of titanium alloy allows reducing the friction coefficient of the investigated friction pair by 30% compared to gas nitriding (Figure 1).

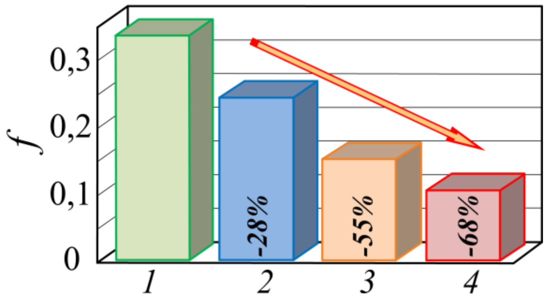

Figure 1. Average value of friction coefficient of tribo-pairs, where titanium alloy in initial state (*1*) and after ball burnishing (*2*), gas nitriding (*3*), combined treatment (*4*).

We also determined the temperature near the friction zone, that indicates qualitatively the course of frictional interaction in general, and affects it. The values of the temperature near the friction zone correlate well with the values of the friction coefficient. Thus, for friction pair, where the titanium alloy was in initial state or after ball burnishing, we fixed significant increase of the temperature near the friction zone. It indicates qualitatively the increased intensity of the course of plastic deformation and diffusion processes, for example return deformation as one of the stages of surface plastic deformation and mutual diffusion dissolution of the elements in the surface friction layer. It leads to the seizing of the contact surfaces, that is unacceptable during friction. For a more detailed explanation Kostecki [8] proposed the dislocation-vacancy hypothesis of creation of metal bonds, according to which an activation during friction of surface layers of metal as a result of intense plastic deformation is the main factor of the seizing. During frictional interaction the work of the friction force is spent on creating heat in the contact zone and energy absorption by the surface layer. These two parameters of external friction process are the main factors that determine the triboactivation of the surface layers of the metal. Such energy absorption during plastic deformation of the alloy determines the kinetics of accumulation of structural defects. The activated surface is gradually saturated by vacancies, and in the process of seizing there is a mutual diffusion of atoms of contacting materials into vacancies. As a result, structures with strong metallic bonds are formed at the points of actual contact where diffusion processes occur. The more metal is prone to the formation of vacancies, the more energy will be absorbed during plastic deformation and, accordingly, more wear will be occurred due to seizing. This explains the fact that the temperature near the friction zone is high due to low thermal conductivity and high chemical activity of titanium alloy. It will accelerate the diffusion processes of microwelding (seizing) of surfaces. Instead, nitriding or deformation-diffusion treatment due to formation of chemically inert nitride film reduces the tendency to seizing of contact surfaces. It reduces the temperature near the friction zone and the wear intensity of the friction pair. The lowest values of the temperature near the friction zone were fixed for friction pair, where titanium alloy was hardened by combined treatment compered to ball burnishing and gas nitriding (25°C compered to 40 and 30°C, respectively).

According to the gravimetric analysis of the samples after tribological tests, it was found that the wear intensity of the counterbody (bronze) is twice higher than the wear intensity of titanium alloy discs, regardless of their surface treatment (Figure 2). The highest values of the wear intensity are fixed for friction pair, where titanium alloy was strengthened by strengthening heat treatment. Surface deformation treatment provides an increase of the wear resistance by about 2 times, and gas nitriding or combined treatment increases by an order of magnitude compered to initial state. Combined treatment of titanium alloy provides the lowest values of the wear intensity of the friction pair compared to the alloy after other hardened treatments (Figure 2). It should be noted that titanium alloy hardened by combined treatment in the whole range of tests does not wear out practically, which is evidence of high level of antifriction properties of its surface, which is obviously due to higher surface hardness of the alloy after treatment [6, 7].

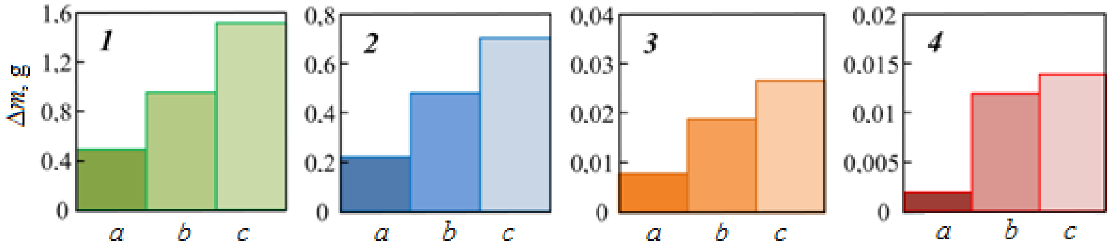

Figure 2. Wear intensity of body (*a*), counterbody (*b*) and friction pair (*c*), where titanium alloy was in initial state (1) and after ball burnishing (*2*), gas nitriding (*3*), combined treatment (*4*).

The wear mechanisms of friction pairs were also determined in the work. Thus, the topography of the worn surfaces of titanium alloy in initial state and after ball burnishing is characteristic of the mechanisms of adhesive (seizing) and fatigue (delamination) wear, which agrees well with the assumptions obtained after analysis of the friction coefficient and temperature near the friction zone. On the surface we fix the characteristic peculiarities of these mechanisms: areas of adhesion transfer and adhesive craters that correspond to the mechanism of adhesive wear, and areas of delamination and cracks – fatigue wear [9, 10].

Such wear mechanisms describe the interaction of friction surfaces that is accompanied by the intense plastic deformation of thin surface layers under the loads exceeding yield strength of materials. However, the nature of mechanisms of the adhesive and fatigue wear are slightly different, namely:

The mechanism of the adhesive wear [9] describes the wear, where in the process of frictional interaction the natural protective oxide film on the surface of titanium alloy is destroyed. The plastic deformation in the contact zone contributes to the maximum convergence of the friction surfaces and formation of the texture of extreme deformed grains located in the direction of the relative motion of friction pairs. During friction at an interatomic distance the seizing (micro-welding) of contact surfaces occurs. It is accompanied by the energy release. When the molecular interaction between microwelded surfaces is greater than the tensile strength of the materials, and the bodies continue to move mutually, softer material is pulled out of the surface. As a result, chaotically located adhesive craters are formed on the contact surface of samples with lower material hardness (bronze) and adhesion transfer (sticking) occurs on samples with higher hardness (titanium alloy). This is confirmed by micro-X-ray spectral analysis of the worn surfaces: the counterbody material (copper) was fixed on the surface of titanium samples. Such areas of sticking are located chaotically. They are directed by sharp edges towards the frictional flow of the material.

The mechanism of the fatigue wear [10] describes the wear, where in the process of frictional interaction the fatigue cracking, chipping and delamination of the surface layers of titanium alloy are occurred. As a result of high cyclic loads during friction, it is occurred the grain refinement, change and appearance of new dislocation structures and stress in the surface layer. It leads to surface strengthening (work hardening) and re-strengthening of titanium alloy, which begins with the appearance of wide sliding bands. As a result, insignificant cracks are formed. They arise in zone of maximum tangential stress at some depth below the surface and spread to surface. Cracks can also arise on the surface and spread into the deep of metal. The crack opening occurs under the action of pulsating oil pressure. At later stage, the crack, reaching base of the antifriction layer, changes its direction, spreading at the junction between the antifriction layer and the base. As a result, individual areas of the surface layer are detached from the surface and then chipped. Chipping is characterized by the formation of pits on the friction surface as a result of the detachment of wear particles of material during fatigue wear. The formed pits with a diameter of several micrometers increase in the process of operation of the friction unit, and peeling (delamination) of friction surface occur.

It should be noted that after friction on the surface and in the surface layer of titanium alloy in initial state we fix smaller in volume and size characteristic peculiarities of these mechanisms (areas of delamination, cracks, sticking), that indicates higher wear resistance of such hardened surface.

Instead, nitride film, which has high chemical inertness and hardness, formed on the surface of titanium alloy after gas nitriding and combined treatment, changes the wear mechanism of friction pairs to abrasive one. It describes the wear of surface as a result of its interaction with hard particles (abrasive) at relative motion [11, 12]. The topography of the worn surface of titanium alloy strengthened by nitriding or deformation-diffusion treatment is unchanged practically. The worn surface of bronze has groove micro-relief characteristic of the mechanism of abrasive wear. This is due to the fact that during nitriding or deformation-diffusion treatment the micro-relief is formed on the surface of titanium alloy, where during friction the highest and hardest micro-asperities of the surface profile (nitride phases) are the actual contact spots. During friction these micro-asperities like an abrasive furrow (plastically deform) softer surface of the counterbody and create grooves. The number and nature of such grooves after frictional interaction with the alloy, strengthened by different ways, are different. The smaller number of grooves and their moderate depth on the bronze surface paired with the combined treated titanium alloy indicate higher wear resistance of the friction pair compared to nitrided titanium alloy.

The higher tribotechnical characteristics of the friction pair, where titanium alloy was strengthened by deformation-diffusion treatment, can be explained by its better surface quality. Since the ability of abrasive (nitride micro-asperities) to penetrate into bronze surface depends not only on the ratio of their surface micro-hardness, but also on the geometric shape. The abrasive with larger size and sharp shape can be pressed into the metal of counterbody deeper and increase its wear by several times [13]. Obviously, smaller values of roughness (Table 2) of the surface of titanium alloy after deformation-diffusion treatment due to pre-burnishing provide the formation of surface micro-relief with low micro-asperities. It provides less wear of the bronze block (counterbody). Instead, nitride layer with higher surface roughness (higher high points of the micro-relief) is formed during gas nitriding. It is confirmed by the formation of wider and deeper grooves on the worn surface of the bronze block (counterbody). Obviously, it causes higher wear intensity of the bronze block and, as a result, we obtain lower tribotechnical characteristics of the friction pair than that where the titanium alloy was hardened by combined treatment.

Table 2. Parameter of surface roughness Ra (μm) of friction pairs before and after friction

Regime	Before friction		After friction	
	Disc	Block	Disc	Block
R0	0.12	0.90	1.25	1.49
R1	0.15	0.90	0.95	1.23
R2	0.24	0.90	0.15	0.25
R3	0.19	0.90	0.10	0.18

Conclusions

1. It was determined that at the stage of stable wear the lowest values of the friction coefficient and temperature near the friction zone were fixed for friction pair, where titanium alloy was hardened by combined treatment. Carrying out of surface deformation before nitriding of titanium alloy allows reducing the friction coefficient of the investigated friction pair by 30% and temperature near the friction zone by 20% compared to the pair where the titanium alloy was hardened by gas nitriding.

2. It was shown that the friction pair where titanium alloy was hardened by combined treatment provides the highest wear resistance. It is one order of magnitude higher than for friction pair, where the titanium alloy was in initial state and after ball burnishing, and twice as high as where the alloy was hardened by gas nitriding.

3. It was established that the wear of titanium alloy in initial state and after ball burnishing corresponds to mechanisms of the adhesive and fatigue wear. The formation of nitride film on titanium

alloy surface after gas nitriding and combined treatment changes the wear mechanism to abrasive wear that explains the decrease of the wear intensity of these friction pairs by one order of magnitude.

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