Structural-morphological features and fretting resistance of nanostructured topocomposites formed by ion-plasma modification

D N Korotaev¹, K N Poleschenko², E N Eremin³, G A Vershinin⁴, E E Tarasov⁵ and E V Ivanova⁶

¹Siberian State Automobile and Highway University, 5, Mira ave., Omsk, 644080, Russia
²Omsk Research Institute of Process and Engine Manufacture (RIPEM), 283, street of B. Khmelnytskyi, Omsk, 644021, Russia
³Omsk State Technical University, 11, Mira ave., Omsk, 644050, Russia
⁴Dostoevsky Omsk State University, 55A, Mira ave., Omsk, 644077, Russia
⁵FGUP Federal Research and Development Centre “Progress”, 4, 5th Kordnaya street, Omsk, 644018, Russia
⁶Omsk Tank-Automotive Engineering Institute, 119, 14th military town, Omsk, 644098, Russia

E-mail: korotaevd99@mail.ru

Abstract. The article proposes an approach to solving the problem of increasing fretting resistance of lock joints of blades for gas turbine engines through the creation of nanostructured topocomposites with the surface layers in a metastable state having a low shear stability in terms of vibrofriction. The authors implement the method of vacuum combined ion-plasma processing, which allows forming the surface layers of the material with mixed amorphous-nanocrystal structure and purposeful controlling the surface morphology. They show that the proposed flow diagram allows developing the required morphology from the arrays of nano-sized conglomerates of the “asperity – cavity” type on the surface. A comparative study of fretting resistance of nanostructured topocomposites in terms of vibrofriction is carried out. It is established that the specificity of their wear is to reduce the wear rate at the initial stage.

1. Introduction
Improving the performance of parts of structural elements of gas turbine engines (GTE) remains one of the key problems of power engineering industry. Loss of performance of GTE parts due to fretting wear exceeds more than sixty percent of all types of wear [1]. Fretting is a wear process of lock joints of blades for compressors (LJBC) occurs in hard conditions of vibrofriction with no lubricant. Already in the initial period due to the wear rate of the contact surfaces, the destruction of the lock joints can occur. Currently, to improve the fretting resistance of parts, various methods are used to prevent the relative displacement of the contacting surfaces, protect the surface from fretting processes and develop materials with a low tendency to hardening [2 - 6]. Researches in the field of development of the
combined methods of the modifying processing matching up ion-beam, ion-plasma and radiation-chemical processing [7, 8] are conducted. Recently, the development of methods to improve the resistance of parts of the GTE, based on structural and technological solutions, including the formation of friction surfaces and the application of wear-resistant coatings [9, 10] is conducted. One of the promising directions of materials modification in relation to solving the problems of increasing the fretting resistance of structural elements on their basis is the formation of superhard nanocomposite coatings [11, 12].

2. Problem statement
As a rule, in studies on the production of nanostructured coatings, the main attention is focused on the development of superhard coatings with a stable nanostructure by vacuum ion-plasma processing [11, 12]. On the contrary, the authors develop the concept based on the idea of developing nanostructured topocomposites (NSTPC) with metastable gradient layers possessing low shear stability [13 - 15]. The main task of improving the performance of the GTE lock joints is to develop a method for obtaining NSTPC, which provides the development of working surfaces with high plasticity under vibrofriction at repeated variable loads and resistance to oxidative processes under high temperatures.

This problem was solved by developing a method of vacuum combined ion-plasma processing using a cascade cross-effect [16], which allows obtaining titanium-based topocomposites with low shear stability, contributing to the development of rotational plasticity [17] in the operation of one-piece lock joints of the gas turbine engine blades. The aim of this work is an experimental study of structural and morphological features and fretting resistance of nanostructured topocomposites formed by the combined ion-plasma processing.

3. Materials and methods
To achieve this goal, a three-cathode system with an ion reflector¹ was developed, which is installed on the upgraded NNB-6.6 installation, allowing surface processing of materials and products using one, two or simultaneously three cathodes located at different angles relative to the processing surface. The constructive scheme of the three-cathode system and its description are presented in [10]. Ion-plasma processing was carried out in several stages. At the first stage, the samples were cleared in the glow discharge. At the second stage, in order to form a sublayer of the TiN coating, the alloy VT8 was processed with ions Ti and N in a pulsed mode using a single cathode. The amplitude of the voltage pulses was about 5 kV, the pulse duration was about 50...60 µs, the frequency was 15...25 kHz at a constant negative voltage of 1000 V. Then nanocoatings of about 30 nm thick of the brand INTOM 20² were applied on the samples based on the Ti – Al system.

To initiate the cross-effect using three cathodes, the substrate is supplied with high-voltage pulses of voltage with the amplitude of about 20 kV, the duration of 10...20 µs and the frequency of 10...15 kHz at the voltage of 1000 V. The reflector is necessary to obtain multicharged ions in the plasma of clusters. The pressure in the chamber was 7 · 10⁻⁶ mm Hg. The final stage was carried out by ion-plasma processing with the use of two cathodes located at the angle of 45° relative to the processing surface under the above-mentioned regimes. The template was used for selective processing of local surface areas and the formation of the required nanocluster morphology of coatings.

The phase composition of the surface layer of the coating was investigated by the method of transmission electron diffraction microscopy of thin foils using the microscope of the brand EMV-100L. The foils were made from the plates cut parallel to the processed surface by their subsequent electrolytic thinning. The morphology of the modified surfaces was studied using an atomic force microscope MFP-3D SA (Asylum Research) in a semi-contact mode in the open air (the humidity of 65%). The cantilevers of the series TipsNano, with a resonance frequency of 240 kHz and a probe bending radius of 10 nm were used in the work.

¹ The cathodic system is developed in Omsk Scientific Research Institute of Process and Engine Manufacture.
² Coating INTOM - 20 (INTOM series) is developed in Omsk Scientific Research Institute of Process and Engine Manufacture.
Obtaining kinetic dependencies of wear of nanostructured topocomposites was carried out on a vibration stand under the following conditions: the pressure $P$ was varied from 4 to 6 MPa; the range of displacement speed $V$ was from 1 to 4 m/s; the test period $t$ varied from 60 to 120 min; the oscillation frequency remained constant $f = 10$ Hz, the displacement amplitude $A_P = 0.2$ mm.

4. Results and discussion

In figure 1 the results of electron-microscopic studies of the transition layer of titanium nitride after ion-plasma processing under the cascade cross-effect are shown.

![Figure 1](image)

**Figure 1.** Electron microscopic light-field and dark-field images of areas of the coating structure TiN (x200000).

From the analysis of the above-cited data, it follows that the ion-plasma processing under the conditions of the cascade cross-effect contributes to the formation of a mixed amorphous-nanocrystal structure of the coating. For figure 1, a dark speckles represent the $\text{Ti}_2\text{N}$ crystallites of the nanometer range phase, and the light layers separating them correspond to the amorphous component of the structure. Images of a polycrystalline aggregate with crystallite sizes of 10...20 nm are shown in figure 1, b. These crystallites have almost an equiaxial shape (fig. 1, c, d). The indication of microelectronograms (fig. 1, f) suggests that the structure under consideration has a single-phase structure represented by $\text{Ti}_2\text{N}$.

The observed structural changes appear to be due to the cascade overlapping in the interaction of multidirectional atom flows, which contribute to the formation of thermal peaks. During the formation of thermal peaks, the energy released in the cascades of atomic collisions during their existence ($\sim 10...12$ s) does not have time to dissipate from the region of propagation of cascades of size $r_0 \sim 50$ Å. It leads to a sharp increase in the temperature ($\sim 10^9$ K/s) [18], under which favorable conditions for solid-phase chemical reactions with the formation of nanocrystal phases and amorphous structures are created.

As is known, amorphous metal alloys have high corrosion resistance, because they do not have grain boundaries. Obtaining gradient compositions consisting of amorphous structures and alloying elements are prone to self-passivation, is a positive factor contributing to the increase of nanostructured topocomposites in terms of fretting-wear.

Figure 2 presents images illustrating the change in the morphology of the Ti-Al based coating depending on the conditions and time of ion-plasma exposure.
Figure 2. Image of surface morphology of nanostructured topocomposites depending on the conditions and the time of the ion-plasma processing. Designations: a) - processing using a template, processing time is 1 min; b) - processing using three cathodes, processing time is 3 min; c) - processing using three cathodes, processing time is 5 min; d) - processing using two cathodes located at angles of 45°, processing time is 10 min.

Analysis of the data obtained allows us to note that under the formation of coatings (fig. 2, b, c) there is no prevailing mechanism of embryo development. However, when using cathodes at the angle of 45° counter flows of atoms along the surface are developed. This leads to the formation of explicit nanocluster formations with a specific surface morphology of the "asperity – cavity" type (shown with the arrows in Figure 2, d, respectively, 1 and 2). This type of surface structures is a favorable factor for reducing the level of internal stresses in the area of tribocontact zones and energy dissipation due to the development of deformation under the “shift + turn” scheme [17]. At the same time,
according to the provisions of physical mesomechanics, the presence of amorphous structures will contribute to the fact that plastic shifts in nanozones will be accompanied by the rotation of grains as a whole [19, 21].

These statements are confirmed by the results of the study of wear kinetics of nanostructured topocomposites shown in figure 3. The data obtained indicate that the variant with the coating formed by the type "asperity – cavity ", is characterized as the lowest intensity of wear at the stage of running in and lower wear rate at the stage of normal wear and tear. The study of the surface failure features of the samples showed that the signs of destruction of nanostructured samples as a result of the formation of brittle fracture nucules and the formation of cross cracks are absent.

Figure 3. Kinetic dependences of the wear of nanostructured topocomposites. Conditions of vibrofriction: the pressure P = 4 MPa; the displacement speed V = 1 m/s; the test time t = 60 min; the oscillation frequency f = 10 Hz, the amplitude of the displacement AP = 0.2 mm. Designations: 1 – the sample of the structure type, shown in figure 2, b; 2 – the sample of the structure type shown in figure 2, c; 3- the sample of the structure type shown in figure 2, d.

The study of worn surfaces of the samples did not reveal any signs of destruction in the area of the boundary between the "base-coating". The decrease in the wear rate of nanostructured topocomposites may be due to the formation of secondary dissipative structures because of the coordinated development of deformation processes occurring at different scale levels [21].

5. Conclusion

1. Based on the conducted researches, it is established that the formation of nanostructured titanium-based topocomposites using a combined ion-plasma processing leads to the formation of gradient structures of the mixed amorphous-nanocrystal structure.
2. The use of a special cathode system makes it possible to vary the modes and sequence of the combined ion-plasma impact in a single vacuum cycle and take purposeful control of the surface layers morphology. In particular, it was possible to obtain coatings with the morphology of the "asperity – cavity" type, which provides, along with the gradient structure of the surface layers, increased wear resistance and corrosion resistance of composite materials under fretting wear conditions.

References
[1] Drozdov Yu N, Pavlov V G and Puchkov V N 1986 Friction and wear under extreme conditions (Moscow: Mechanical Engineering) p 223
[2] Petuhov A N 2009 Questions of multicycle fatigue for materials and details of modern GTE Vestnik of Samara State Aerospace University 3(19) pp 172-177
[3] Namjoshi S A, Mall S, Jain V K and Jin O 2002 Fretting fatigue crack initiation mechanism in Ti-6Al-4V J. Strain Analysis 37(6) pp 535-547
[4] Lesnevsky L N, Troshin A E, Tyurin V N, Gavrilov V P and Klopov S G 2008 Possibilities of using Ni[Cg] coatings sprayed by the APS method for protection against fretting wear in production and repair technologies Materials of the 10th anniversary Int. scientific and practical conf. Technology of repair, restoration and strengthening of machine parts, mechanisms, equipment, tools and tooling (St. Petersburg: SPbSTU) pp 193-200
[5] Petuhov A N, Pavlov Yu I and Haing M 2011 Strength of the lock joints of compressor blades under cyclic loading Aviation Industry 3 pp 42-44
[6] Farris T N and Murthy H 2005 Temperature Fretting Fatigue of Single Crystal Nickel Proc. 10th Nation. Turbine Engine HCF Conference (New Orleans: LA) pp 123-134
[7] Povoroznyuk S N, Greenberg P B and Poleschenko K N 2008 Modification of chemical and mechanical properties of titanium alloys by ion-beam and ion-plasma processing Proc. of the VI Int. scientific conf. Radiation-thermal effects and processes in inorganic materials (Tomsk) pp 378-383
[8] Borbat V F, Kozorog I B, Muhin V A and Poleschenko K N 2004 Obtaining gradient compositions of increased corrosion resistance and hardness by ion implantation and chemical modification Vestnik of Omsk University 3(33) pp 60-62
[9] Kovshov A G 2018 Evaluation of efficiency in fretting of reinforcing deformation forming of friction surfaces combined with antiwear coatings Izvestiya of Samara Scientific Center of the Russian Academy of Sciences 20(4) pp 248-254
[10] Korotaev D N, Tarasov E E, Poleschenko K N, Eremin E N and E V Ivanova 2018 Formation of wear resistant nanostructural topocomposite coatings on metal materials by ionic-plasma processing J. Phys.: Conference Series 1050(1) pp 012037
[11] Veprek S, Maritza G J, Veprek-Hejman M G J, Kavankova P and Prochazka J 2005 Different approach to superhard coatings and nanocomposites Thin Solid Films 476 pp 1-29
[12] Pogrebnyak A D, Shpak A P, Azarenkov N A and Beresnev V M 2009 Structures and properties of hard and superhard nanocomposite coatings Successes of physical sciences 2009 179(1) pp 35-64
[13] Grinberg P B, Korotaev D N, Poleschenko K N and Surikov V I 2015 Development and production of nanostructured topocomposites Vestnik SibADI 3(43) pp 39-45
[14] Grinberg P B, Poleschenko K N, Goryunov V N and Tarasov E E 2012 Method of nanostructural topo composites producing for load-bearing improvement of constructional parts of power equipment Vestnik of Omsk University 2 pp 253-258
[15] Poleschenko K N, Korotaev D N and Tarasov E E 2016 Structural and morphological features of nanostructured top composite coatings for tribotechnical purpose Vestnik SibADI 4(50) pp 126-132
[16] Grinberg P B, Korotaev D N, Orlov P V, Vershinin G A, Tarasov E E and Ivanova E V 2018 Obtaining of nanostructured topocomposite coatings based on cross-cascade effect Dynamics of Systems, Mechanisms and Machines 6(2) pp 171-177
[17] Panin V E, Sergeev V P and Panin A V 2008 Nanostructuring of surface layers and application of nanostructured coatings (Tomsk: TPU Publishing House) p 285
[18] Bykovskiy Y A, Nevolim V N and Fominskyi V U 1991 Ionic and laser implantation of metallic materials (Moscow: Energoatomizdat) p 240
[19] Korotaev A D, Tyumtsev A N and Pinzhin Yu P 2007 Synthesis and properties of nanocrystal and substructural materials (Tomsk: Tomsk State University) p 368
[20] Noskova N I 2015 Mechanisms of deformation and fracture of nanocrystal materials according to the results of in situ research Nanotechnology and physics of nanocrystal functional materials 1 (Ekaterinburg: UrO RAN) pp 166-182
[21] Poleschenko K N and Khudyakova O D 2016 Fretting-resistance of nanostructured topocomposites on the titanic basis Strengthening technologies and coatings 11(143) pp 44-48
Acknowledgments
The work was financially supported by the Ministry of education and science of the Russian Federation project № 11.11760.2018/11.12. «Increase in operational properties of heterophase materials on the basis of application of the nanostructured topocomposites ».