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EFFECT OF ALLOYING HEAT-RESISTANT PACKING COATINGS ON THEIR TRIBOTECHNICAL, PHYSICAL AND MECHANICAL PROPERTIES

Purpose. To determine the effect of alloying nickel-based packing coatings on friction, wear and microhardness to ensure predictable performance properties at the temperatures of about 1100 °C.

Methodology. The friction coefficient and the energy rate of wear were determined regarding the results of applying methods for modeling the thermo-mechanical loading using small-sized samples in the heating chamber that was additionally installed on the СМЦ-2 friction machine. The microhardness of the samples having different structural states was determined according to GOST 9450-76 on the LECO AMH 43 USA microhardness tester. The evaluation of the nature and microgeometry of the wear debris was carried out using PEM-106I electronic focused-beam microscope. To solve the stated problem, the nickel-based packing coating used at MOTOR SICH JSC, an aircraft manufacturing enterprise of Ukraine, was chosen.

Findings. Based on the study on the microhardness and tribotechnical characteristics, the coating composition which best fits the combination of the examined mechanical properties providing reliable performance of the coatings was selected.

Originality. Graphic patterns of the friction coefficient changes when the coatings interact with the flanges of the rotating disc at different heating stages of the media and the average energy rate of mass wear of their materials were obtained. Based on the study on microgeometry and distribution of the elements in the chemical composition of wear debris, probable areas of destruction of the examined coatings were identified for each composition, which in turn can determine their ability to accumulate stress. It was found out that coating of Composition 3 alloyed with an integrated yttrium-containing Co–Ni–Cr–Al–Y master alloy and Composition 2 with a monoyttrium master alloy have the tendency to form a satisfactory packing contour when modeling the thermo-mechanical load of the frictional contact. It was observed that depending on the nature of the thermal effect, there occurs hardening of the surface layers of the coating and of the base metal while increasing the duration of exposure, which is more likely to be attributed to the developing balancing diffusion of alloying elements from the transition zone of coatings.

Practical value. The application of the suggested coating will enable to improve the engine efficiency by reducing the leakage of gases while maintaining the size of the radial clearances, and reduce the fuel consumption per hour.

Keywords: *friction coefficient, energy rate of wear, packing coating, nickel alloy, yttrium, microhardness, small-sized sample*

Introduction. The efficiency of gas turbine engines (GTE) is determined by the parameters of the working process in its main parts: the compressor, the combustion chamber, and the turbine. One of the factors characterizing the efficiency of a GTE is gas temperature before the turbine. Temperature rise causes the increase in the engine load factor, and accordingly the decrease in the engine mass-to-power ratio [1].

Temperature rise before the turbine with simultaneous increase in the overall pressure ratio enables to achieve not only high specific thrust of the engine, but also low specific loss of fuel [2]. Therefore, to increase the engine efficiency is possible due to the increase in the fuel combustion completeness, i. e. to the rise in the operational temperature of the combustion chamber. Thus, temperature rise by 50 °C leads to the efficiency increase by 12.5 % [3]. However, in its turn, it results in sharp decrease in the operating durability of the turbine parts.

One of the main directions for the improvement of GTE design aimed at lowering the gas flow consumption and optimizing fuel consumption rate is the decrease in the radial clearance in the rotor-stator part of the GTE turbine using various packing materials. Solving the problem of creating reliable packing materials will enable efficient operation of the GTE with a substantial reduction of specific fuel consumption. It is attributed to minimizing the clearance between the stator and rotor parts.

Literature review. Preventing inefficient blow-by of gas and cooling air via gas dynamic packing of the GTE rotor parts is one of the main tasks when designing a turbine. That is why, there are packing materials allowed for in the engine design in order to reduce the blow-by of gases in the turbine. Study [4] notes that leaking of 1 % of the cooling air into the flow channel results in the increase in the specific fuel consumption by 0.3 %.

Researchers [5] point out the prospects of using alloys based on such churlish elements as Nb, Mo, and especially alloys of Nb–Al and Nb–Si systems that are respectively hardened by Nb_3Al and Nb_3Si compounds [6].

However, such elements do not meet the requirements because of inadequate resistance to oxidation. Moreover, obtaining these alloys by powder metallurgy methods is rather expensive and time-consuming and is under development now. Oxide-based materials differ by low reliability because of their low impact hardness and ductility. We should mention the development of diamond-like coatings alloyed with silicon and molybdenum that are used to increase the resources of the friction couples. Studies [7] show the formation of nano-sized carbide phase inclusions in the coatings. However, usage of diamond-like coatings in tribology in our country is at the stage of theoretical research and experiments. In addition, one should note the prospects of applying 'smart materials' when coatings are multilayered structures and have a unique ability to restore. Still, at the moment, the range of their application is rather limited. In study [8], there are various structures of 'adaptive coatings' on diamond-like matrix that include solid tungsten carbide particles, greased with tungsten and molybdenum disulphide on aurum and ceramics matrix (YSZ). The authors consider this direction in research to be promising, but such a coating technology is complicated and experimental.

It is noted that usage of heat-resistant alloys on heat-resistant chrome-based alloys was feasible for the coatings used at the temperatures lower than 1100–1200 °C. However, they are characterized by high brittleness at the temperatures of 300–350 °C. Still, in the process of long heating at high temperatures, heat-resistant chrome alloys tend to absorb nitrogen, which has a negative effect on their low-temperature ductility. What is more, for the stated temperatures, one can use WC-Co–Cr type coatings with high hardness and low friction coefficient. High wear resistance is ensured by combining of WC as a hard constituent and cobalt as a ductile alloy. However, such coatings are brittle and hard to wear in. Coatings of ZrO_2 and Y_2O_3 types, which are applied to the Ni–(Al, Cr) and Ni–Co–Cr–Al–Y transition layer, are promising. Such coatings are used up to the temperature of 1100 °C. The outer layer has low heat conductivity, the metal layer is thermostable, heat resistant. Such a combination provides a gradual decrease in metal temperature. However, such kind of coatings is inappropriate as a big number of layers made adjusting the clearance difficult. The coatings of SiC–SiO_2 system that is sprayed on the alloy fibers of Fe–Cr–Al–Y system are characterized by wear-in, wear, adequate erosion resistance, but the values of heat resistance are not satisfactory enough.

Thus, to create heat resistant coatings, Ni–Cr–Al-based alloys are often used. High heat resistance of these alloys is determined by the formation of the film of stable Cr_2O_3 and Al_2O_3 oxides [9]. In study [10], the coating based on the alloy of Ni, 20 % Cr, 13 % Al, 0.5 %Y sprayed on ЖС6У alloy is considered. After spraying, there is an ultra fine-grained structure in the alloy. Such a structure provides the formation of microduplex structure, which in its turn is highly ductile and stable under a high temperature. Authors of the studies [11] note the prospects of using rare-earth metals in heat resistant coatings. To get the coatings, complex alloying with rare-earth metals, yttrium, lanthanum, cerium, neodymium, scandium, etc., is used. When melting the microadditive, the grain is ground and modified, harmful impurities (sulphur, phosphorus, and others) are extracted out of the melt, grain borders and phases combining them into finely dispersed compounds. It is also noted that lanthanum has a positive effect on the structure during crystallization, namely it contributes to grounding of dendrites. The stability of the structure with lanthanum is higher because there is less change in the ratio of γ'-phase particles area to their perimeter. The research studies show that when 0.1 % of lanthanum is added to the Ni–Cr–Al-based alloy, γ–phase disappears, lanthanoids appear, γ'-phase volume ratio decreases, secondary γ'II –phase appears.

It is significant to note that in addition to heat and corrosion resistance, packing coatings in the process of exploitation must wear in well.

In study [12], Ni–C– and Ni–Cr–Al-based packing coatings sprayed onto BN carrying base are examined. Obtained coatings are very hard, and according to [13], the harder the coating is, the higher erosion resistance is. What is more, high heat resistance and resistance of these alloys to high temperature corrosion are caused by the formation of the film of exclusively stable Cr_2O_3 and Al_2O_3 oxides. Thus, the research studies have revealed that Ni–Cr–Al coating has a high friction coefficient and self-lubricating properties.

Results of the tribological tests [14] show that the coating with Ni–C couple on the Ti–6Al–4V alloy softens later than the base material, which leads to the destruction of the part, in contrast to Ni–Cr–Al-based coating with hardening phases distributed evenly [15]. Similar tests on the Co–Ni–Cr–Al–Y system alloy which were also sprayed onto BN, show that adding yttrium improves the hardness and also contributes to higher adhesion of the coating to the carrying base [16]. Therefore, one should note that rare-earth metals have a positive effect onto the structural stability of alloys and of coatings themselves, prevent the formation of harmful structural components (topologically densely packed phases, σ-phases, μ-phases, and so on).

Taking into account the aforesaid, one can formulate the following requirements to the packing coatings: satisfactory wear-in at the initial stage and ability to increase wear resistance at fixed operating modes of the engine, high indicators of adhesive hardness and heat resistance at the operating temperatures of 1000–1100 °C, a tendency to increase friction coefficient and decrease the time of its stabilization between the contacting surfaces of the friction couple when they wear in.

In order to design a reasonable composition of the packing coating, in this study, the tribological tests were carried out, the microhardness was examined, the nature and microgeometry of the particles of coatings that were alloyed with yttrium-containing alloys were studied.

Materials and methodology of research. KHA serial coating, which is nowadays used in the aircraft engines produced by Motor Sich JSC, was chosen as the base material for the research. This coating contains Ni (base), Cr, Si, Al and solid oils (graphite and BN). Such a composition ensures the sulphide corrosion resistance of the material and contributes to the formation of the oxide film with high protective properties and satisfactory adhesive interaction with the material.

The following compositions of the master alloy were examined: Composition 1 – KHA-82 + NiY; Composition 2 – KHA-82+Y; Composition 3 – KHA-82+CoNiCrAlY; Composition 4 – KHA; Composition 5 – KHA-82. KHA-82 is KHA coating as a base with BKHA powder (ТУ 14-1-1790-76), composition of the furnace charge: Nickel base, 15.0–19.0 % BN, 1.0–3.0 % Al, 1.4–2.5 % Si, 1.5–2.0 % C.

The coating, which is 3 mm thick, was applied by gas-flame method onto the chocks made of heat resistant nickel alloy that contains the components (Al and Cr), with the dimensions of 15 × 15 × 20 mm.

After the coatings were formed, the samples were mechanically processed to achieve the necessary geometry.

Five samples of chocks representing each coating composition were studied. Discs with four flanges of trapezoid profile and the outer diameter of $D = 50$ mm were also produced from a heat resistant nickel-based alloy. Thus, the given elements of appropriate geometric sizes formed a model 'a rotating disc with flanges – a fixed chock'.

As the packing coatings are used under the conditions of high temperature gas medium, it was also necessary to study the behavior of the material under the long-lasting temperature impact. That is why the tests of the samples with the coating were carried out in the initial state and after a long-lasting exposition under the temperature of 1100 °C for 50 and 100 hours.

Modeling the tribotechnical contact of the elements of the labyrinth packing was carried out on СМЦ-2 machine under the conditions of heated gases flow according to the methodology presented in study [17] with further improvement of the methods to evaluate the properties of the heat resistant coatings presented in study [18].

The average energy rate of wear taking into account determining the impact of the friction forces at each stage of the modeled interaction (first zone *A* is not heated; second zone *B* is heated; third zone *C* is a fixed mode, Figs. 1–5) was found out according to the formula

$$I_m = \frac{3\cdot\Delta m}{N\cdot l_1\cdot\bar{\mu}_1 + N\cdot l_2\cdot\bar{\mu}_2 + N\cdot l_3\cdot\bar{\mu}_3} \approx \frac{3\cdot\Delta m}{N\cdot\sum_{i=1}^{3} l_i\mu_j}, \quad (1)$$

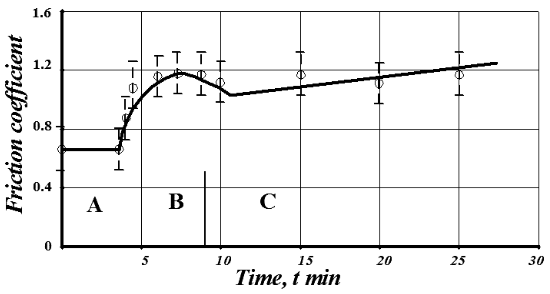

Fig. 1. Dependence of the friction coefficient on the time of tribotechnical test of the coating Composition 1 – KHA-82 + NiY:

A – without heating; B – heating; C – fixed mode

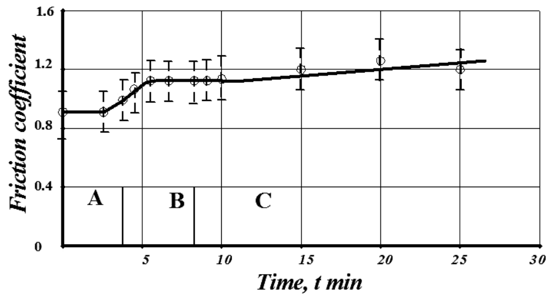

Fig. 2. Dependence of the friction coefficient on the time of tribotechnical test of Composition 2 – KHA-82 + Y:

A – without heating; B – heating; C – fixed mode

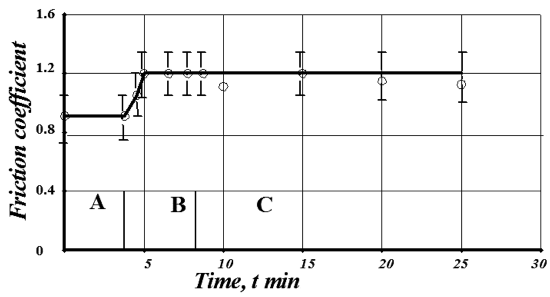

Fig. 3. Dependence of the friction coefficient on the time of tribotechnical test of Composition 3 – KHA 82+CoNiCrAlY:

A – without heating; B – heating; C – fixed mode

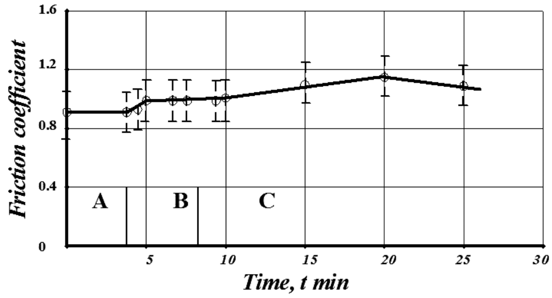

Fig. 4. Dependence of the friction coefficient on the time of tribotechnical test of Composition 4 – KHA:

A – without heating; B – heating; C – fixed mode

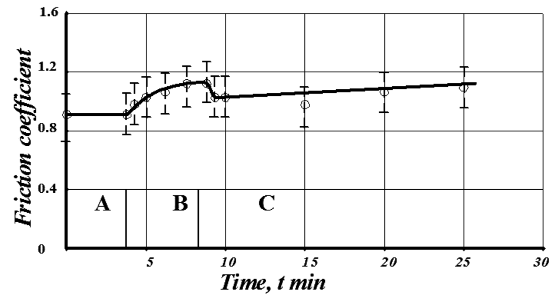

Fig. 5. Dependence of the friction coefficient on the time of tribotechnical test of Composition 5 – KHA–82:

A – without heating; B – heating; C – fixed mode

where Δm is the average mass wear of the coating, mg; μ_j is the average current value of the friction coefficient at the corresponding stages of the cycle; li is the average rubbing path where friction coefficient μ_j becomes apparent, m; *N* is the pressing force of the sample, N.

The value of the pressing force is determined regarding the wear nature of the coatings of the relevant compositions and possibility to register the moment of friction resistance according to the data presented in study [18]. The pressing force was $N = 17.4$ N.

The estimated rubbing path at Stage 1 was $l_1 = 141.3$ m. At Stage 2, the rubbing path was $l_2 = 306.15$ m. At Stage 3, the rubbing path l3 for the sample coatings of Composition 1 was 1097,4 m; it was 1130,4 m for the ones of Composition 2; 1097,4 m – for the ones of Composition 3; 1059,8 m – for the ones of Composition 4; 1125,7 m – for the ones of Composition 5.

The friction coefficient was calculated according to the formula

$$\mu = \frac{M_{t_i}}{N\cdot r}, \quad (2)$$

where M_t is the moment of friction, N · m; *r* is the radius of friction, m. $r = D/2 = 0.025$ m.

In the study, a cycle of tribological tests was used. It models the initial and fixed stages of mechanical interaction of full-size surfaces that form the packing contour. The cycle includes the following stages:

Stage 1: contact interaction of the surfaces of small-sized samples without heating (time $t_1 = 3$ min);

Stage 2: heating up to the average temperature (600–680 °C) for the fixed testing mode (time $t_2 = 5.5$–6 min);

Stage 3: contact interaction of the surfaces of small-sized samples at a fixed temperature mode (time $t_3 = 19.5$–20 min).

At Stages 2 and 3, there were combustion products of INTERTOOL GS-0022 isobutane liquefied gas fed into the chamber with the samples. In order to simulate the rotation of the GTE rotor, the rotation frequency of the sample disc was

$n = 300\ \mathrm{min}^{-1}$, taking into account the feasibility of the СМЦ-2 friction machine.

The average temperature of the fixed mode (Stage 3) was:

Composition 1 $T = 615–640$ °C;

Composition 2 $T = 649–671$ °C;

Composition 3 $T = 620–638$ °C;

Composition 4 $T = 620–636$ °C;

Composition 5 $T = 649–671$ °C.

The evaluation of the coating microhardness was carried out on the LECO AMH 43 USA microhardness tester according to the requirements of GOST 9450-76. The load was 10 g.

Results. ***Tribotechnical tests.*** The properties and operability of the nickel-based coatings in terms of wear resistance are greatly dependent on forming in the coating a certain structure with difficult to solve dispersed particles, oxides, nitrides and intermetallides that can greatly increase operating temperature and erosion resistance of the parts working under the conditions of high temperature gas medium. In the process of gas-flame application of the coatings that differ in their composition, intermetallides of various kinds formed. Theoretically, they have different wear resistance. Lack of precise data about the impact of the formed phases on the high temperature wear resistance of the coatings caused the necessity to find out the peculiarities of tribotechinical properties of the coating compositions under consideration under the operating modes of the friction units.

Analysis of the distribution of the friction coefficient enabled to find out its average value within the time of particular stages of testing and graphically approximate functional dependences $\mu = f(t)$ for each composition presented in Figs. 1–5.

As it can be seen in Figs. 1–5, at Stage 1 of testing the friction coefficient for all alloys was quite high and fixed for 3 minutes, and it was as follows: for the coatings of Composition 1 – 0.7; Composition 2 – 0.85; Composition 3 – 0.9; Composition 4 – 0.8; Composition 5 – 0.82. It indicates high values of friction forces in the zone of frictional interaction, which determines, on the one hand, density of the contact between the surfaces of the rubbing paths of coatings and disc flanges and, on the other hand, causes accumulation of stress in its volume. We should also note that, in our opinion, under the frictional interaction, mainly the molecular (adhesive) component of the friction force becomes apparent. In this case, Composition 3 had the highest value of the friction coefficient (0.9), while Composition 1 had the lowest value.

To Compositions 1 and 5 (Figs. 1, 5), at Stage 2, formation of clearly defined maximums of friction coefficient with its almost equal values of 1.1 was specific. However, the general wear process differed in its nature of tribotechnical interaction at Stages 1 and 3 of the tests.

Sharp changes in the friction coefficient indicate the accumulation of stress in the friction zones of the coatings of Composition 1, 2 and 4 (Figs. 1, 2, 4), which is likely to be the result of peculiar morphology and topography of coating components distribution that were characterized by forming the structures with massive conglomerates of particles connected by cohesion. In its turn, the location of the pores was nondiscrete, voids of quite a large volume were observed in the material.

Formation of a certain microstructure results in flanges contacting with quite large groups of coating particles when cutting the surface. This causes a relatively quick accumulation of stress on the surface of the frictional interaction with further immediate contact release while the flanges of the disc immerge into the large-volume voids.

Formation of a more favorable microstructure of the coatings of Compositions 3 and 5 with a higher dispersion and even distribution of particles of gas-thermal coating causes a monotonous decrease in the friction coefficient values (Figs. 3, 5); a stable character of wear overall due to less duration of frictional interaction of the counterbody with the coating, and, accordingly, a lower level of general accumulated cold hardening. In this case, one can observe quick wear-in of the coating of Composition 3 (less than 5 min). Afterwards, the friction coefficient remains 1.2 steadily. The duration of wear-in of the coating of Composition 5 is longer (≈ 9 min), but the friction coefficient in the fixed mode is 1.05.

Nonmonotonic nature of the change in the friction coefficient of the coatings of Compositions 1 and 5 with the formation of precise maxima is likely to be the result of emergent additional resistance of the movement to the disc flanges that is the effect of gradual accumulation of stress in the friction zones because of the solid particles of oxide, nitride, and intermetallide compounds.

The most beneficial wear in terms of the reliability of the frictional contact was observed in the coating of Composition 3. It was characterized by a smooth increase in the friction coefficient from 0.9 minimum to 1.2 final. This is the evidence of a more even distribution of stress on the layers of materials in the course of time and formation of tight frictional bonds with lower stress.

Value $\mu \geq 1$ of the friction coefficient shows that there take place volume and surface destructions of the material. These processes are caused by immediate accumulation of fatigue in the cohesive bonds of the coating fragments with simultaneous formation of the packing areas in the zone of stable frictional contact. It happens while the material deforms when the variable cross-sections of disc flanges are submerged at certain depths. The formation of packed sliding path occurs alongside with the decrease in the specific pressure onto the coating material.

The fixed temperature of interaction in the course of time enabled to determine the nature of tribological state of the studied materials compositions. It was found out that:

- Compositions 4, 3, 5, have steadily stable friction characteristics with the friction coefficients of 1.11; 1.2; 1.05 respectively. It shows the formation of an energetically profitable stable structure of loaded layers of material;
- Compositions 1, 2 are distinguished by further processes of structural transformation according to the conditions of interaction. It should be noted that Composition 2 does that with a bit higher intensity, more inner stress and friction.

Thus, smooth increase in the friction coefficient with explicit stability at the end of the interaction stage is due to the absence of significant stress in the contact layers, which is characteristic to Compositions 3, 4, 5 (the sequence is given in the order of decreasing compliance with the stated requirements to the friction coefficient).

The mass of the wear debris, which is related to the work unit of friction, according to the common beliefs, should be minimal. It is determined, in the first place, by the requirements of the necessary sufficient depth of cutting in and minimal clearance between the surfaces that form the packing contour. In its turn, there should be the effect of borderline frictional contact along the surface in the zone of maximum approximation of the surfaces of the packing contour.

Energy intensity of mass wear is a quantitative characteristic of the evaluation of frictional behavior of the material that should be as low as possible because in this case mass losses will be minimal. However, it is impossible to form an effective contour without losing the material when cutting in and provide tight contact of the surfaces with the required depth of cutting in. Therefore, at this stage, it is suggested taking into account its minimal value. Composition 3 complies with this requirement most closely (Table 1).

As for the values of energy rate of wear, the lowest values were characteristic to the coating of Composition 3 with 10.95 $\mu g \cdot J^{-1}$, which is by 20–25 % lower than that for Compositions 2, 5 (Table 1). The highest values were registered for the coating of Composition 1 and amounted to 16.05 $\mu g \cdot J^{-1}$. Average values of this mass are typical of the coatings of Compositions 2, 5, 4.

Table 1

Summary data of tribotechnical tests

Composition	Properties of friction and wear of the coating material				
	Mass wear, Δm, mg	Friction coefficient			I_m, mkg · J^{-1}
		$\bar{\mu}_1$	$\bar{\mu}_2$	$\bar{\mu}_3$	
KHA-82+NiY	0.146 ± 0.007	0.69	1.06	1.04	16.05
KHA-82+Y	0.135 ± 0.015	0.86	1.05	1.17	13.13
KHA82+ CoNiCrAlY	0.114 ± 0.006	0.9	1.10	1.2	10.95
KHA	0.124 ± 0.013	0.83	0.97	1.06	13.63
KHA-82	0.129 ± 0.008	0.86	1.05	1.05	13.66

Taking into account the data given above, we can conclude that the most optimal values of friction and wear characteristics are typical of the coating of Composition 3.

Measuring the microhardness. According to the results of the previous research studies, it was found out that in the initial state, the microhardness of the coatings under consideration amounts to 170 MPa, which is attributed to their high porosity, peculiarities of cohesive interaction of the particles and a low content of hardening phases.

A significant increase in the microhardness up to 1000 MPa after a long thermal treatment in the oxidizing medium at 1100 °C for 50 and 100 hours is attributed to the increase in oxide and intermetallide phases in the structure.

In terms of exploitation of packing coatings, such a character of the change is the most beneficial because, in the beginning of exploiting when interacting with the labyrinth packing or turbine blade, the coating should be mild enough to ensure easy wear-in of the frictional surfaces, and in the course of further exploitation it should strengthen for efficient corrosion and mechanical wear resistance to ensure fixed clearance and fuel economy.

Evaluation of the distribution of chemical elements in the wear debris. In the course of contact interaction of the friction elements under consideration, wear debris formed. They fall onto heat resistant carrying base. After each research was finished, the wear debris were collected for the next X-ray spectrometry and microstructure analysis. All the wear debris of the coatings under consideration contain particles of different sizes and fractions – from the tiniest to quite large ones – that have the form close to globules.

Approximate correlation of large and small particles is 30 to 70 %. X-ray spectrometry of the particles on the electronic focused-beam microscope revealed heterogeneous distribution of chemical elements (Table 2) and difference in the forms and sizes of particles (Fig. 6).

Analysis of wear debris overall shows changes in the sizes and forms of the particles depending on the coating composition.

The following distinctive features of the wear debris particles were found out:

Coating 1 – flat forms of the majority of fractions from 2 to 8 μm;

Coating 2 – presence of both round and elongated acicular fractions from 4 to 12 μm;

Coating 3 – presence of larger particles with pointed edges of 10 μm and small inclusions from 2 to 4 μm;

Coating 4 – presence of particles with pointed edges of (15–25) μm and larger;

Coating 5 – presence of large particles of above 20 μm with smooth rounded edges.

Taking into account the data obtained, one can identify likely areas of destruction of the studied coatings:

- for coatings of Compositions 1 and 2 inside volumetric coating fragments;

- for coatings of Composition 3 and KHA along the edges of the formations and partially inside them;

Table 2

Average content of chemical elements in the wear debris samples

Composition number	% – content of chemical elements				
	B	Al	Si	Cr	Ni
1	1.17 (43.3)	3.59 (36.2)	2.08 (17.9)	1.15 (29.3)	88.67 (0.7)
2	1.06 (11.3)	2.24 (29.2)	2.47 (13.6)	0.23	92.09 (0.5)
3	1.56 (25.8)	2.18 (10.6)	2.85 (32.7)	0.25 (66.6)	70.81 (3.5)
4	1.33 (35.08)	1.02 (17.3)	2.41 (7.6)	0.013 (51.3)	90.24 (2.3)
5	4.02 (13.7)	1.94 (19.6)	2.46 (10.2)	0.16 (60.4)	82.33 (7.8)

Note. Percentage divergence of values is given in brackets

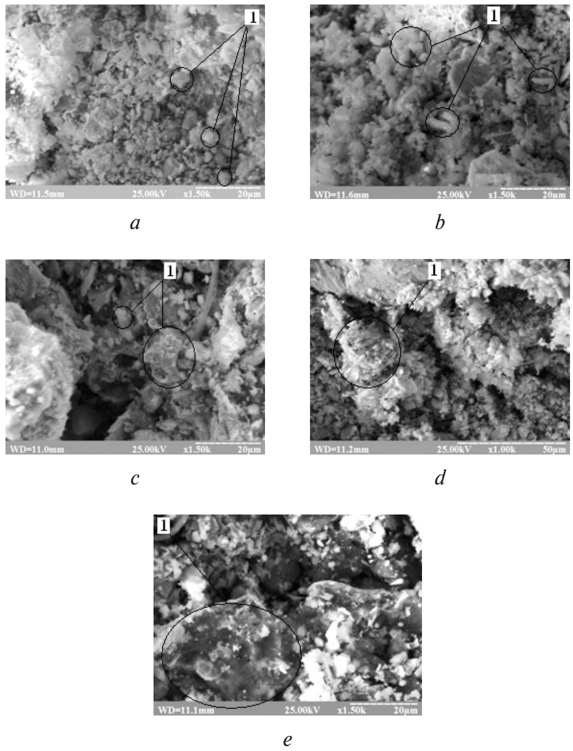

Fig. 6. Microstructure of wear debris:

1 – a separate particle of wear debris; a – Coating 1; b – Coating 2; c – Coating 3; d – Coating 4; e – Coating 5

- for coatings of Composition 5 mainly along the edges of the fragments.

Conclusion. The effect of alloying nickel-based packing coatings on their tribotechnical characteristics, microhardness, nature, and microgeometry of the wear debris fragments was examined in the study. Based on the results of the carried out research, we should note that coating of Composition 3 alloyed with integrated CoNiCrAlY master alloy best meets the combination of physical and mechanical properties that should ensure stability of clearances of rotor-stator turbine elements. What is more, the composition is characterized by smooth increase in the friction coefficient with the quickest stabilization of the maximum value.

At the same time, coating of Composition 2 with monoyttrium master alloy is most likely to form packing edge under the conditions of modeling the thermomechanical loading of the frictional contact that will be characterized by the following features:

- demonstration of increased friction with the prevailing molecular component that affects cohesive bonds in the surface-volume structures of the material, which determine a large area of contour interaction of surfaces;

- relatively higher wear resistance that will cause saving microprofiles of the worn in areas of friction interaction that will inversely restore along wearing with a higher tendency to accumulate fixed deformations.

Thus, taking into account the fact that coating of Compositions 3 and 2 with the overall satisfactory frictional wear resistance compete with one another in certain advantages of tribotechnical characteristics and physical and mechanical properties, further prospects of research aimed at improving the chemical composition of coatings should be related to namely these base materials. Coatings of Compositions 1, 4, 5 meet the operating requirements the least.

References.

1. Campos-Silva, I., Contla-Pacheco, A.D., Figueroa-López, U., & Martínez-Trinidad, J. (2019). Sliding wear resistance of nickel boride layers on an Inconel 718 superalloy. *Surface and Coatings Technology*, (378), 124862. https://doi.org/10.1016/j.surfcoat.2019.06.099.

2. Kablov, E.N., Ospennikova, O.G., & Petrushin, N.V. (2015). A new single-crystalline intermetallic heat-resistant alloy on the basis of γ′-phase for GTE. *Aviatsionnyie materialyi i tehnologii*, (1), 34-40. https://doi.org/10.18577/2071-9140-2015-0-1-34-40.

3. Aleksandrov, D.A., & Artemenko, N.I. (2016). Wear-resistant coatings for protecting friction parts of modern gas turbine engines. *Trudy VIAM, 10*(46), 65-72. https://doi.org/10.18577/2307-6046-2016-0-10-6-6.

4. Hassanzadeh, M., Saremi, M., Valefi, Z., & Pakseresht, A.H. (2018). Investigation on Improved-Durability Thermal Barrier Coatings: An Overview of Nanostructured, Multilayered, and Self-Healing TBCs. *Production, Properties, and Applications of High Temperature Coatings*, 60-78. https://doi.org/10.4018/978-1-5225-4194-3.ch003.

5. Loghman-Estarki, M.R., Nejati, M., Edris, H., Razavi, R.S., Jamali, H., & Pakseresht, A.H. (2015). Evaluation of hot corrosion behavior of plasma sprayed scandia and yttria co-stabilized nanostructured thermal barrier coatings in the presence of molten sulfate and vanadate salt. *Journal of the European Ceramic Society*, *35*(2), 693-702. https://doi.org/10.1016/j.jeurceramsoc.2014.08.029.

6. Liu, Y., Sun, J., Pei, Z.L., Li, W., Liu, J.H., & Gong, J. (2020). Oxidation and hot corrosion behavior of NiCrAlYSi + NiAl/cBN abrasive coating. *Corrosion Science*, (167), 108486. https://doi.org/10.1016/j.corsci.2020.108486.

7. Keshavamurthy, R., Naveena, B.E., & Sekhar, N. (2018). Thermal Spray Coatings for Erosion-Corrosion Protection. *Production, Properties, and Applications of High Temperature Coatings*, 246-267. https://doi.org/10.4018/978-1-5225-4194-3.ch010.

8. Korzhov, V.P. (2015). Structure and mechanical properties of laminated niobium composite with carbide reinforcement obtained through diffusion welding. *Deformatsiya i razrushenie materialov*, (7), 22-29.

9. Hruschov, M.M. (2018). Chrome-carbon coatings based on chrome and detonation nanodiamonds: preparation by magnetron spraying, peculiarities of the phase composition and tribological properties. *Problemyi mashinostroeniya i nadezhnosti mashin*, (2), 44-53.

10. Sadri, E., & Ashrafizadeh, F. (2018). High Temperature Nanocomposite Coatings by Plasma Spraying for Friction and Wear Applications. *Production, Properties, and Applications of High Temperature Coatings*, 216-245. https://doi.org/10.4018/978-1-5225-4194-3.ch009.

11. He, Y., Wang, S.C., & Walsh, F.C. (2015). The monitoring of coating health by in situ luminescent layers. *RSCAdvances, 5*(53), 42965-42970. https://doi.org/10.1039/c5ra04475h.

12. Greshta, V., Tkach, D., Sotnikov, Ye., Lehovitser, Z., Klimov, A., & Fasol, Ye. (2018). Peculiarities of selecting ligatures to improve the operational properties of sealing coatings for the parts of the turbine of gas-turbine engines. *Novi materIali i tehnologiyi v metalurgiyi ta mashinobuduvanni*, (1), 25-31. https://doi.org/10.15588/1607-6885-2018-1-4.

13. Zhao, Y., Wang, Y., Yu, Z., Planche, M.P., Peyraut, F., Liao, H., & Montavon, G. (2018). Microstructural, mechanical and tribological properties of suspension plasma sprayed YSZ/h-BN composite coating. *Journal of the European Ceramic Society*, *38*(13), 4512-4522. https://doi.org/10.1016/j.jeurceramsoc.2018.06.007.

15. Greshta, V., Tkach, D., Sotnikov, Ye., Lehovitser, Z., & Klimov, A. (2015). Development of a thermal barrier coating for details turbine engine, workers at high temperatures *Aviatsionno-kosmicheskaya tehnika i tehnologiya*, (10), 6-10.

16. Gao, S., Xue, W.I., Duan, D., & Li, Sh. (2016). Tribological behaviors of turbofan seal couples from friction heat perspective under high-speed rubbing condition. *Friction, 4*(2), 176-219. https://doi.org/10.1007/s40544-016-0114-x.

17. Greshta, V.L., & Kubich, V.I. (2019). Methodology of tribotechnical testing of metal materials in terms of thermomechanical loading on SMC-2 machine. *Problems rubbing that znoshuvannya in cars, 4*(85), 18-22. https://doi.org/10.18372/0370-2197.4(85).13867.

18. Boguslaev, V.O., Greshta, V.L., Tkach, D.V., Kubich, V.I., Sotnikov, E.G., Lekhovitser, Z.V., & Klymov, O.V. (2019). Evaluation of the Tribotechnical Characteristics of Therma-Barrier Sealing Coatings under Critical Loads. *Journal of Friction and Wear*, *40*(1), 80-87. https://doi.org/10.3103/S1068366619010033.

Вплив легування жаростійких ущільнювальних покриттів на їх триботехнічні та фізико-механічні властивості

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Мета. Визначення впливу легування ущільнювальних покриттів на нікелевій основі на прояв характеристик тертя, зношування й мікротвердості для забезпечення прогнозованих експлуатаційних властивостей за температур порядку 1100 °С.

Методика. Коефіцієнт тертя та енергетична інтенсивність зношування визначалися за результатами використання методики моделювання термомеханічного навантаження з використанням малогабаритних зразків у нагрівальній камері, що додатково встановлювалась на машині тертя СМЦ-2. Мікротвердість зразків з різним структурним станом визначали відповідно до вимог ГОСТ 9450-76 на мікротвердомірі LECO AMH 43 USA. Оцінка природи й мікрогеометрії продуктів зношування проводилась за допомогою електронного растрового мікроскопу РЕМ-106І. Для вирішення поставленої задачі було обрано ущільнювальне покриття на основі нікелю, яке застосовується на авіадвигунобудівному підприємстві України ПАТ «МОТОР СІЧ».

Результати. За результатами проведених досліджень мікротвердості та триботехнічних характеристик було обрано склад покриття, що найкраще відповідає поєднанню досліджених механічних властивостей, які забезпечують надійну працездатність покриттів.

Наукова новизна. Отримані графічні закономірності зміни коефіцієнта тертя при взаємодії покриттів із гребінцями диска на різних стадіях розігріву середовища, що обертається, та середньостатистичної енергетичної інтенсивності зношування покриттів за масою. За результатами дослідження мікрогеометрії й розподілу елементів хімічного складу продуктів зношування, для кожного складу встановлені ймовірні місця руйнувань розглянутих покриттів, що, у свою чергу, може визначати їх здатність до накопичення напружень. Встановлено, що покриття складу № 3 – леговане комплексною ітрійвмісною лігатурою Co–Ni–Cr–Al–Y та складу № 2 із моноітрієвою лігатурою мають схильність до формування задовільного ущільнювального контуру в умовах моделювання термомеханічного навантаження фрикційного контакту. Визначено, що в залежності від характеру термічного впливу спостерігається явище зміцнення поверхневих шарів покриття та основного металу по мірі підвищення тривалості витримки, що, скоріше, є наслідком розвитку процесу вирівнювальної дифузії легувальних елементів із перехідної зони покриттів.

Практична значимість. Застосування запропонованого покриття дозволить підвищити коефіцієнт корисної дії двигуна завдяки зменшенню витоку газів, при збереженні розміру радіальних зазорів, та знизити витрати палива за годину.

Ключові слова: *коефіцієнт тертя, енергетична інтенсивність зношування, ущільнювальне покриття, нікелевий сплав, ітрій, мікротвердість, малогабаритний зразок*

Влияние легирования жаростойких уплотнительных покрытий на их триботехнические и физико-механические свойства

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Цель. Определение влияния легирования уплотнительных покрытий на никелевой основе на проявление характеристик трения, износа и микротвердости для обеспечения прогнозируемых эксплуатационных свойств при температурах порядка 1100 °С.

Методика. Коэффициент трения и энергетическую интенсивность изнашивания определяли по результатам использования методики моделирования термомеханической нагрузки с использованием малогабаритных образцов в нагревательной камере, которая дополнительно устанавливалась на машине трения СМЦ-2. Микротвердость образцов с различным структурным состоянием определяли согласно требований ГОСТ 9450-76 на микротвердомере LECO AMH 43 USA. Оценка природы и микрогеометрии продуктов износа проводилась с помощью электронного растрового микроскопа РЭМ-106I. Для решения поставленной задачи было выбрано уплотнительное покрытие на основе никеля, которое применяется на авиадвигателестроительном предприятии Украины ПАО «МОТОР СИЧ».

Результаты. По результатам проведенных исследований микротвердости и триботехнических характеристик был выбран состав покрытия, который лучше всего соответствует сочетанию исследованных механических свойств, обеспечивающих надежную работоспособность покрытий.

Научная новизна. Получены графические закономерности изменения коэффициента трения на стадиях разогрева среды взаимодействия покрытий с гребешками вращающегося диска и среднестатистической энергетической интенсивности их изнашивания по массе. По результатам исследования микрогеометрии и распределения элементов химического состава продуктов износа, для каждого состава установлены вероятные места разрушений рассмотренных покрытий, что в свою очередь может определять их способность к накоплению напряжений. Установлено, что покрытие состава № 3 – легировано комплексной иттрийсодержащей лигатурой Co-Ni–Cr–Al–Y и состав № 2 с моноиттриевой лигатурой имеют склонность к формированию удовлетворительного уплотнительного контура в условиях моделирования термомеханической нагрузки фрикционного контакта. Определено, что в зависимости от характера термического влияния наблюдается явление упрочнения поверхностных слоев покрытия и основного металла по мере повышения продолжительности выдержки, что, скорее, является следствием развития процесса выравнивающей диффузии легирующих элементов из переходной зоны покрытий.

Практическая значимость. Применение предлагаемого покрытия позволит повысить коэффициент полезного действия двигателя благодаря уменьшению утечки газов, при сохранении размера радиальных зазоров, и снизить расход топлива.

Ключевые слова: *коэффициент трения, энергетическая интенсивность изнашивания, уплотнительное покрытие, никелевый сплав, иттрий, микротвердость, малогабаритный образец*

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