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RESEARCH

Comparison of High-Temperature Wear Resistance of Gas-Flame and Ion-Plasma Sealing Coatings with 0.1% Yttrium

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A B S T R A C T

Wear-resistant sealing coatings of KNA-82 system with 0.1% yttrium addition for hot parts of gas-turbine engines, applied by gas-flame and ion-plasma methods, are considered. The introduction of yttrium increases the operating temperature from 900°C to 1100°C. The methodology of modeling of processes of contact interaction of engine parts under operating conditions has been developed. Tribotechnical tests modeling the contact of the coating surface with the rotor ridge tops and blade feathers have been carried out, after which linear wear has been measured and the results have been statistically processed. The gas-flame coatings show slower wear reduction at temperatures up to 800 ℃ while both coatings show similar properties at 1100°C. The improved properties are attributed to the formation of phase-like Ni_3Y compound in the grain boundaries.

1. INTRODUCTION

The efficiency factor is one of the main parameters in the design of modern gas turbine engines (GTE). The availability of clearances between the rotor and the stator of the GTE is a determining factor in energy losses. Clearances are inevitable due to the need to ensure the avoidance of contact of parts in conditions of their elastic deformation caused by power and thermal factors under variable operating modes of the GTE.

Various authors aim their research at controlling the range of axial and radial clearances in gas turbine engines, but this problem does not have a final solution to date. Thus studies [1,2] indicate the possibilities of measuring the radial clearance in real time modes as well as illustrate the significance of its measuring, whereas they do not mention the possibilities of adjusting the clearance and simulating the penetration process. The research [3] states that the radial clearance growth causes the increase in rate of gas flow, which itself is additional tool for gas flow regulation.

The results of research [4] confirmed the effectiveness of the clearance control while maintaining the height, pitch, inclination and number of teeth of the labyrinth seal. It is rather difficult to provide the clearance size constructively, therefore there is a need to use sealing coatings. In particular, coatings of the Ni-Co-Cr-Al-Y system.

As designers increase the gas temperature in front of the turbine to improve the efficiency of modern aircraft engines, there is a need to develop new sealing coatings with higher operational resistance under conditions of elevated temperatures and dynamic loads. Nickel-based sealing coatings and solid lubricants are widely used in the production of gas turbine engines. However, the functional characteristics of the coatings used at domestic enterprises are maintained at temperatures that usually do not exceed 900 °C. and the use of coatings of this type cannot guarantee the maintenance of a stable gap size at operating temperatures of 1150°C due to the intensification of gas corrosion processes and the destruction of the coating material by a high-speed aggressive gas flow. There is a need to implement a number of urgent material science tasks aimed at developing sealing coatings that could be easily adjusted at the initial stage of engine operation and maintain a stable geometry of the worn coating contour during the overhaul period at temperatures of about 1100-1200 °C.

The authors of the study [5] considered ceramic coatings of the Ni-Co-Cr-Al-Y system. Although the coatings exhibit good abrasion, their resistance to environmental influences, such as particulate erosion, is limited by the porous microstructure. This negatively affects their service life. Moreover, ceramic coatings have low bending strength due to cracking under heat loads [6]. The authors of [7] consider the coating of the Sc_2O_3-Y_2O_3-ZrO_2-CaF_2-PHB system, which is tested at temperatures of 1250 °C. It is noted that the use of femtosecond laser processing technology to create surface textures on SiCf/SiC composites significantly increases the durability of Sc_2O_3-Y_2O_3-ZrO_2-CaF_2-PHB coatings subjected to abrasion under high-temperature thermal shock, improving the coating/substrate contact area and adhesion strength, thereby extending the service life of coatings and their performance in aircraft engines. However, for our study, the use of this technology is very costly, and the company uses more affordable application options.

The authors of the research [8] note the prospects of using rare-earth metals in heat-resistant coatings. Actively interacting with impurities, which are interstitial elements (mainly carbon and oxygen), they can form stable carbides and oxides at interfaces (interphase boundaries, dislocation clusters) [9]. Yttrium in appropriate proportions stabilizes oxide films of aluminium and chromium, improves the adhesion of applied coatings to the base material, increases the thermal stability of alloys, and slows down the coagulation of hardening phases [10]. Yttrium has been established to increase the heat resistance, when dissolved in the nickel matrix. The introduction of yttrium in an amount exceeding its solubility limit (for nickel, this is 0.2–0.3 wt %) causes the deposition of a compound, in and along the grain boundaries, whose chemical composition is close to that of the Ni3Y phase [11]. Also, the introduction of yttrium stimulates the formation of $Ni(Cr,Al,Y)_2O_4$ and $(Cr, Y)_2O_3$ oxides on the alloy surface. In Ni-Co-Cr-Al-Y coatings Y segregation at scale/coating interface results in less cavity formation and hence improves the oxide scale adherence α-Al_2O_3 [12]. The study [13] shows the effect of yttrium on the nature of cyclic oxidation at 1100°C. Catastrophic foliation occurs on simulation alloys without adding yttrium. Adding yttrium in the amount of 0.1 and 0.4% improves the properties. However, the content of yttrium lower than 0.1 percent gives a better result because there is less internal oxidation and, therefore, the onset of scale foliation is delayed for a longer period.

Taking into account possible contacts between the GTE rotor and stator in various operating modes, it is necessary to study their tribological properties as well as analyse the effect of yttrium on the heat-resistant properties of sealing coatings. Tribological tests of Ni-Co-Cr-Al-Y-BN were conducted using a test bench for abraded seals in research [14]. The coatings have been tested for adhesion strength, erosive wear resistance, and the results show that increasing values of abradable hardness (i.e. lower levels of coating porosity) yields higher bond strengths and improved erosive wear resistance, but the tests were conducted at room temperature without simulation of real operating conditions.

The research [15] states a differential equation and presents an analytical solution for estimating the level of seal wear. Therefore, wear is sharp in the initial state and becomes slower and slower over time until it also stops, which is a logical conclusion – the wear is less at temperature decrease, but the research is relevant to brush seals. The study [16] gives the mean values of the friction factor and the wear rate of the coating after spraying and after its oxidation, as well as the friction factor of the sprayed coating with temperature growth, except for coating slip at 200°C. The friction factor is found to decrease from 0.6 (at 25°C) to 0.29 (at 1000°C). The wear intensity of the coating decreases from 5.45 × 10–4 mm^3 H^{-1} m^{-1} to 8.42 × 10^{-6} mm^3 H^{-1} m^{-1} as the temperature rises to 800°C. The coating after spraying has a higher wear intensity, about 16.3×10^{-6} mm3 H^{-1} m^{-1} at 1000°C. However, the mentioned study does not show the effect of alloying elements on the friction factor, and there are no clearly defined methods for conducting the experiment.

Thus, the study [17] lays the foundations for a methodological study of the mechanical properties of running-in coatings, based on physical simulation of the process of penetration of the teeth of the movable part sealing contour into the body of coating formed on the fixed part. In this connection, a technique for evaluating heat-resistant running-in coatings in the temperature range of 25–35°C with a relatively low speed mode of interaction of samples under study is proposed. The friction factor, the energy intensity of wear of coating materials by weight were assessment parameters for coatings properties. At the same time, the main emphasis of tribological tests was placed on determining the trends in displaying resistance to penetration of teeth on a rotating disk into the material being tested during automatic unloading of the contact. As a result of such tests, an increased flowability of the materials being researched was established, which made it impossible to expand the load range. The coatings wore out very quickly, and the disc teeth reached the base of the pad. There was no possibility to reuse the pads in the form of plates with sprayed on material as the coating material peeled off from the pads while modelling structural-phase transformations when heated up to 1100 °C In general, the test procedure did not provide for the evaluation of contact interaction in conditions of continuous heating of the interaction medium, which was a significant drawback.

Physical simulation of the process of a lamellar sample penetration into the body of the material under test was applied by the authors in studies [18-20]. In the process, the classical friction scheme "a stationary pad with the coating being researched and a rotating disk with a destruction tool" was used. The researchers used a high-speed friction test bench that simulated the conditions under which a pair of seals operated. The main emphasis was placed on establishing the regular wear of coatings in a wide range of changes in the sliding speeds of the disk with blades (from 30 to 150 m/s) at controlled values of penetrating into the coating material – up to 400 μm. However, the factors for controlling the penetration force at a given sliding speed and the temperature state of the frictional interaction medium were not considered, the equipment only allowed measuring the current values of the normal, tangential contact force and temperature in the friction zone. The application of such a scheme, conditions and modes of interaction of samples for evaluating, for example, heat-resistant running-in coatings, is not fully acceptable since only a single mode of GTE operation is modelled.

The technique for assessing the wear resistance of coatings described in the research [21] is reduced to measuring the mass loss of stator mock sampler when modelling a continuous tangential impact interaction with plates mock sampler fixed to a rotating disk. At that, the average statistical friction track at spark colliding is 0.015 m and the pressing force during interaction is not controlled. Moreover, instantaneous contact interaction appears to be distributed over the planar field of contact, which predetermines its pathological surface destruction (scratching, smoothing) and does not create prerequisites for assessing wear by depth. The latter is important for assessing the demonstration of the strength of cohesive bonds between the structural components of the coating since normal pressures under such shear deformations are small. The disruption of fastening of plates would manifest itself otherwise. Also, the interaction environment is open, which does not imply the collection and processing of information about wear products and their relationship with the state of the near-surface-volume forming structures. Such an approach to modelling does not suppose the presence of closed interaction between the coating and the plate, distributed along the inner cylindrical perimeter, taking into account uncontrolled contact interaction. This means that a forced contact with the coating is reproduced without considering the distribution of its properties along the cylindrical contour of the stator of a power (compressor) turbine in accordance with the methods of coating.

The study [22] proposed a research technique using a test chamber, which was mounted respectively to test-pieces. Friction contact was modelled between a moving sample – a disk with teeth on its outer surface – and a fixed small-sized pad, on the surface of which the coating being researched was formed. In this case, the frictional characteristics of the contact were determined by the friction factor while the wear of the coating material was defined by the loss of mass. The studies were limited by the possibility of simulating the high-speed mode of interaction, creating a sharp power loading, and reusing of samples after forced heat treatment.

Known technical solutions for maintaining radial clearances at a minimum level through the use of active control systems [1,24] make it possible to reduce its value in all GTE operating modes. However, they may not be applied in all units, for example, of turbocharger, they have a high cost but low reliability. A promising way to solve this problem is to use a new generation of running-in sealing coatings [25]. Their main feature is insufficient hardness at the running-in stage, which makes it possible for the blade end or labyrinth seal knife edges to safely penetrate and ensure a minimum radial clearance. After the running-in stage, the hardness of the prospective coating under development increases, which ensures high resistance to erosion and gas-abrasive wear.

Thus, despite the well-studied effect of the yttrium content on the heat-resistant properties of yttrium sealing coatings, its effect on the tribological properties at different stages of GTE operation has not been sufficiently studied. There is no techniques provision for modelling the processes of contact interaction between GTE parts under conditions close to operational ones, simulating the change in power, speed, temperature loading during the manifestation of structural-phase transformations in the volumes of materials. This determines the relevance of further research aimed at improving the research techniques provision for the completeness and objectivity of assessing the service properties of GTE sealing coatings.

2. MATERIALS AND METHODS

The physical modeling of the investigated friction process is based on the idea of the existence of similar physical phenomena of mechanical interaction in a natural gas turbine engine, in particular, between the scallops of the blade ends and the coating of the power turbine housing (and possibly the compressor compartment) of the gas dynamic seal, and in a physical small-size model, in the form of a test chamber (Figure 1), in which the scallops of the plates freely planted in the rotor mechanically interact with the inner cylindrical surface of the rotor.

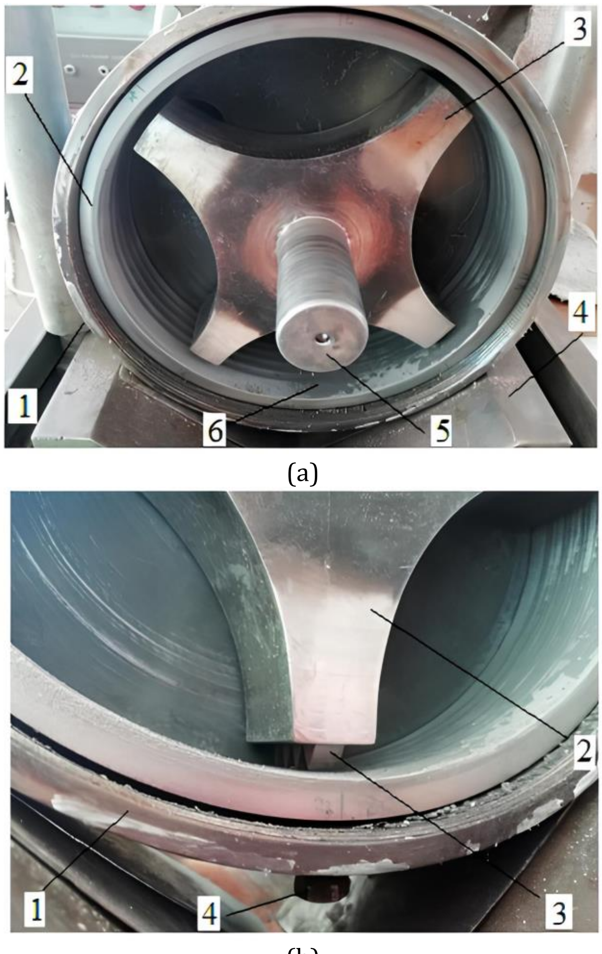


Fig. 1. General view of the test chamber (a) and counterbodies (b): a: 1 – chamber body; 2 – sample-ring; 3 – rotor; 4 – supporting frame stand; 5 – rotor bearing shaft; 6 – coating wear products; b – rotor wing with a plate: 1 – sample-ring; 2 – rotor wing casing with internal groove; 3 – plate with knife edges; 4 – bottom screw for fixing the sample-ring.

In accordance with the theory of similarity, on which physical modelling is based, a complex of physical and geometric arguments that are part of the Strouhal criterion is used to assess the degree of similarity of the simulated process of contact interaction (1):

$$K = \frac{V \cdot t}{l} \qquad (1)$$

where V is velocity parameter, m/s; t is time parameter, s; l is geometric parameter, m.

Similarity theory was used to assess the compliance with the physical model to the operational system. Taken as a geometric parameter l, is the friction track, m. Taken as a time parameter t, is the time of contact interaction along the friction track, s. Taken as the velocity parameter V, is linear velocity at frictional interaction, m/s (Table 1). As can be seen, the values of the Strouhal criterion for the simulated speed and geometric parameters of the contact interaction are equal, therefore, the physical model reproduces the friction and wear process similarly to the simulated one.

Table 1. Summarized data for calculating the similarity criterion.

Parameter	Full-scale GTE	Test chamber	
l, [m]	0,015	1507 at n=500 min^{-1}, t_T=3 min	10048 at n=500 min^{-1}, t_T=20 min
t, [s]	$3 \cdot 10^{-5}$	180 s	1200 s
V, [m·s^{-1}]	500	8,37 at n=500 min^{-1}	8,37 at n=500 min^{-1}
K	1,0	0,99	0,99

As can be seen, the values of the Strouhal criterion for the simulated speed and geometric parameters of the contact interaction are equal, therefore, the physical model reproduces the friction and wear process similarly to the simulated one.

According to the force parameter, it is not possible to evaluate the physical modelling since data on the force of interaction between the blade airfoil and the coating at the corresponding speeds of their approach are not known. To assess the wear of coatings, a linear wear model was used:

$$h_{cp} = \frac{h_0 + h_1 + h_2 + h_3}{4} \qquad (2)$$

where h_{0-3} is average wear of the coating in each of the measurement zones 0-3, which was calculated as an arithmetic mean based on the results of at least eight measurements ρ>8 for each of the four wear tracks i, j, c, q (Fig. 2):

$$h_{0-3} = \frac{\rho_i^{-1}\sum_{i=1}^{\rho_i} h_i + \rho_j^{-1}\sum_{j=1}^{\rho_j} h_j + \rho_c^{-1}\sum_{c=1}^{\rho_c} h_c + \rho_3^{-1}\sum_{q=1}^{\rho_q} h_q}{4} \qquad (3)$$

where hi, hj, hc, hq is wear depth at each of the D points in Fig.2 a, measured with a detecting head feeler.

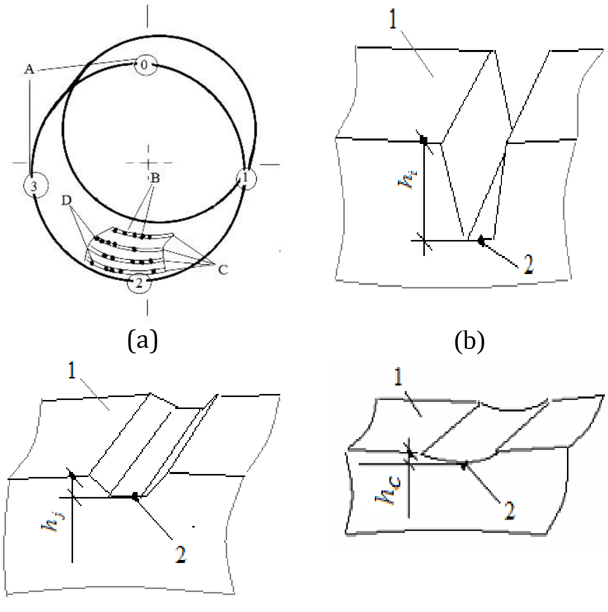


Fig. 2. Scheme of measuring the geometric parameters of wear tracks: (a) 0;1;2;3 – measurement zones; B – measurement areas (*l*=7-15 mm); C – friction tracks *i, j, c, q*; D – measurement points; (b), (c), (d) – cross-sectional shapes of wear tracks (triangular, trapezoidal, cylindrical). Section shapes are given as an example: 1 is friction surface; 2 is the point of installation of a detecting head feeler; hi, hj, hc are the depths of friction tracks (linear wear) measured in zones 0; 1; 2; 3. The probable depth on the wear track q and its sectional shape are not presented.

A general view of the device for measuring linear wear is shown in Fig. 3.

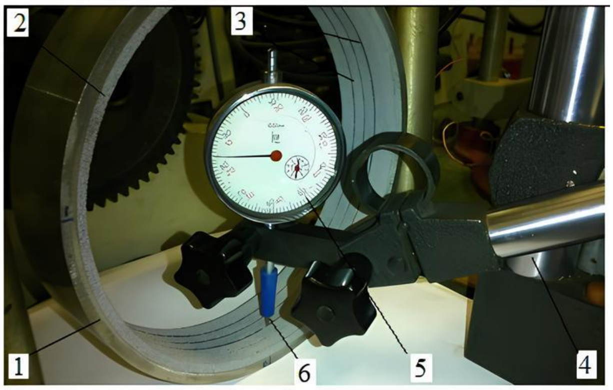
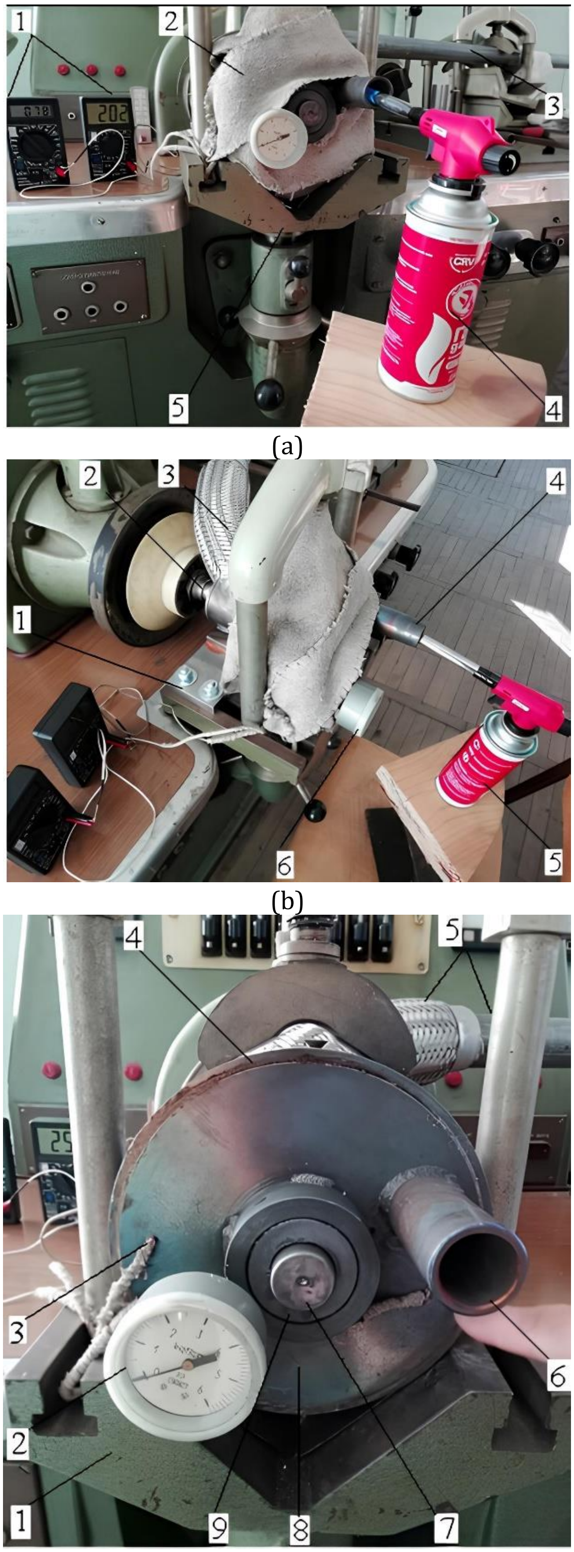


Fig. 3. General view of the device for measuring the wear of coatings. 1 – body of the sample-ring; 2 – coating; 3 – wear tracks; 4 – tripod; 5 – detecting head; 6 – feeler.



(a)

(b)

(c)

Fig. 4. General view of the test facility: (a) - front view; 1 - multimeters; 2 - insulation; 3 - outlet pipe; 4 - cylinder with isobutane-butane; 5 - stand frame; (b) - top view: 1 - side frames of the chamber body; 2 - rotor shaft; 3 - outlet goffer; 4 - an inlet branch pipe; 5 - cylinder with isobutane-butane; 6 - manometer; (c) - chamber without insulation: 1 - stand frame; 2 - manometer; 3 - thermocouple wire; 4 - chamber body; 5 - goffer with an outlet pipe; 6 - inlet branch pipe; 7 - rotor shaft; 8 - chamber lid; 9 - shaft bearing.

To perform physical modelling of heat-resistant yttrium-containing sealing coatings, the Hiradastechniki Gepgyara U-808 generating set test bench was used with two control modes for changing the drive shaft rotation: 300-2500 min-1; 2500-5000 min-1 (Fig. 4).

The possibility of a stepwise change in the frequency of rotation of the drive shaft made it possible to simulate the process of instantaneous penetration of the teeth of the plates into the coating material, for example, at fixed temperatures of the interaction medium. Instead of a generator, a test chamber with a rotor was installed on the stand frame for fixing the generator. The samples were heated with an open flame. The temperature was controlled using a thermocouple in the steady regime.

The research was carried out in several stages. At the first stage, the mechanical interaction of the plate knife edges with the coating was simulated at room temperature. At the second stage of the study, the mechanical interaction of the knife edges of the plate with the coating while being heated was modelled in accordance with the calorific value of isobutane-butane and the duration of heating the internal volume of the test chamber. At that, the samples-rings are installed in the chamber, the chamber is heated up to 350-450ºC, which is followed by the interaction of knife edges of the plates with the coating. At the last stage, the tests were performed within the temperature range of 350-450ºC, followed by the interaction of the knife edges of plates with the coating on the samples that were previously subjected to tests at the early stages. This made it possible to simulate the operation of the coating sublayer, taking into account the depths of deformation nano- and submicro- displacements in it, caused by force loading and temperature at stages No. 1, 2, and structural-phase transformations, conditioned by preserving T=1100ºC in the furnace.

When conducting physical simulation of the contact interaction of coatings with the teeth of the plates, the following parameters of the mechanical interaction mode were used:

- speedy, rotor speed is n_1=500-600 min^{-1} at a constant action of the calculated pressing force (hereinafter the pressing force) and n_2=1000-1200 min^{-1} at stepwise force loading, at which the pressing force exceeds the value F=9.6-17.4 N, which enables dynamic loading conditions to be simulated;

- force, normal pressing force of knife edges of plates to the surface of the material during friction, for example, F=10-11 N with the mass of the plates with knife edges m=0.046 kg, n=500 min^{-1} and the friction radius R=0.078-0.08 m;
- time, for example t=1-3 min.

When changing the parameters R, n and m, the pressing force was clarified as per formula:

$$F = 1{,}095 \cdot 10^{-2} \cdot R \cdot n^2 \cdot m \qquad (4)$$

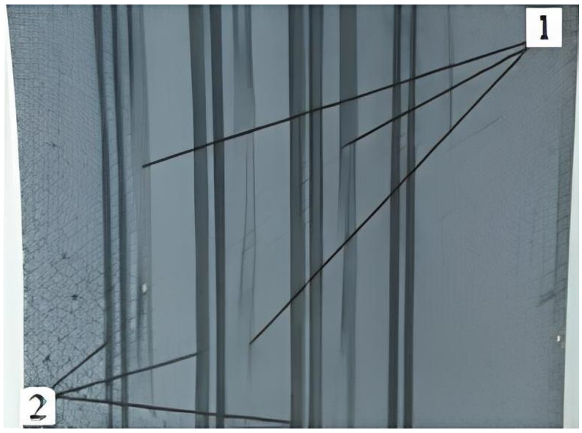
To objectively assess the wear character of the coating material, it is proposed to use the following values of linear wear:

- reduced average wear h1000 to the friction path in 1000 m, because the friction path during the test stages and simulation of the time of action of the forces of pressing the teeth of plates to the surface of coatings had different values;
- conditional wear hu numerically equal to wear on the friction path of 1000 m at normal pressure in the friction zone of 1 MPa, because as a result of wear of plate teeth the contact area increased and mechanical pressure changed.

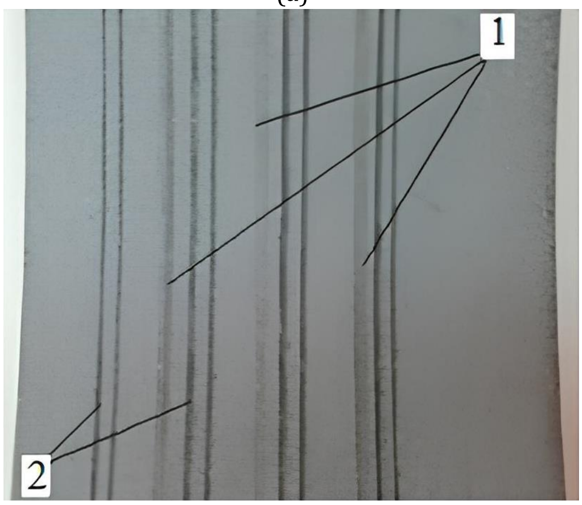
Tribotechnical tests of sealing coatings of the Co-Ni-Cr-Al-Y system with yttrium content of 0.1% were conducted in accordance with the developed research techniques provision and the stages of mechanical temperature loading simulation. Coatings were applied to the inner surfaces of the sample-rings (Fig. 5a, pos. 2) by gas-flame (coating No. 1) and ion-plasma (coating No. 2) methods. The samples were tested in the following modes:

- stage # 1: test time t_T=0.7 min at temperature T=23 ºC, n=550 min^{-1}, F=12.3 N, pressure in the friction zone p=10.25 MPa; plate teeth wear area S=1.2 mm^2; friction path L_T=347.2 m;
- stage # 2: heating at T=307-397ºC t_H=52 min, t_T=3 min, n=500 min^{-1}, F=10 N, p=3.33-4.16 MPa, S=2.4-3.0 mm^2, L_T=744.18 m;
- stage # 3: heating at T=115–(315-395)ºC, t_H=20 min, t_T=20 min, after holding for 3 hours 1100ºC, n=550 min^{-1}, F=12.3 N, p=2.28-2.41 MPa, S=5.1-5.4 mm^2, L_T=5526 m;
- stage # 4: heating at T=23–(340-355)ºC, t_T=19 min, n=550 min^{-1} after holding for 3 hours 1100ºC and polishing, F_1=12,3 N at n=550 min^{-1} t_T=1 min, F_2=49N at n=1100 min^{-1}, p=1.57-1.86 MPa; S=6.6-7.8 mm^2, L_T=5803 m.

The object of the study was the wear process of heat-resistant sealing coatings made of KNA-82 alloy with the addition of yttrium 0.1%, applied by various methods. KNA-82 alloy is currently used in aircraft engines manufactured by Motor Sich JSC. The composition of this coating includes Ni (base), Cr, Si, Al and solid mastics (graphite and BN). The coatings were applied on small-sized rings by gas-flame (coating No. 1) and ion-plasma (coating No. 2) methods.



(a)



(b)

Fig. 5. Wear tracks: a – the coating surface obtained by the gas-flame method; b – the coating surface obtained by ion-plasma method; 1 – traces after the test without heating; 2 – traces after the test when heated at stage 2.

The gas-flame method of coating deposition is based on the use of a gas flame to melt the material, which is then deposited on the ring surface.

For ion-plasma coating the MAP-1M unit is used, the formation and deposition of coatings occurs from the flow of highly ionized plasma of the vacuum arc.

The subject of the study was the wear parameters of the coating under modeling of mechanical loading and temperature of the interaction medium.

3. RESULTS AND DISCUSSION

One of the problems of creating sealing coatings for the heat part of the GTE is the tendency for clearances to change during engine operation. The reason for the change is flight loads (power and thermal) on engine parts, leading to deformation due to creep and erosion from dust particles contained in the air. The clearance growth is the result of the change in cross sections under the influence of flight loads, due to erosion, as well as thermal deformation of parts (Fig. 6).

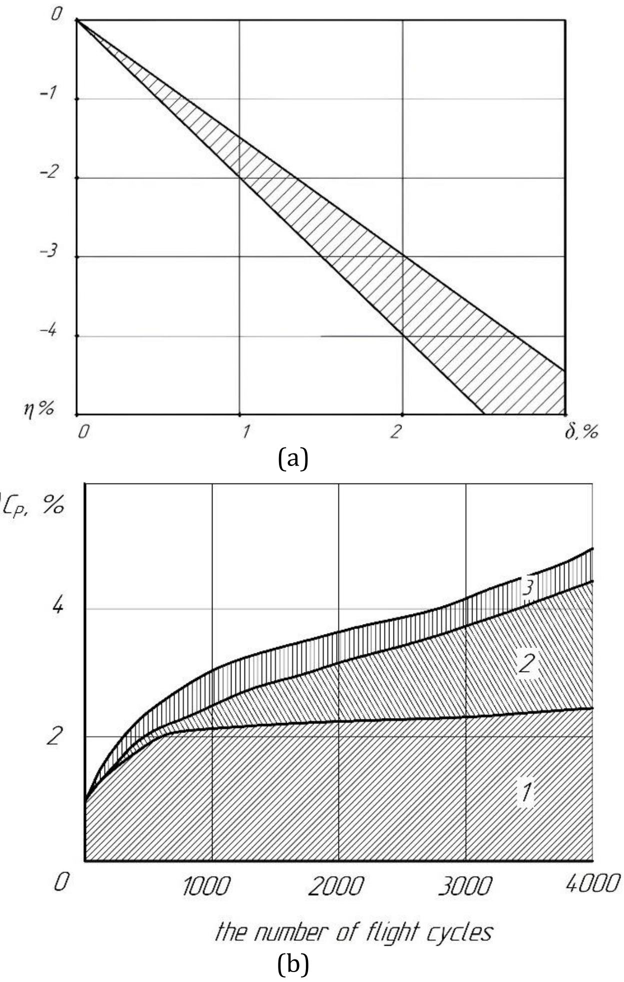


Fig. 6. Radial clearance performance: (a) - change in the value of the radial clearance during the service life of a GTE: 1- under the influence of flight loads; 2 - due to erosion; 3 - due to thermal deformation of parts; (b) - influence of the radial clearance on the change in the efficiency factor of the GTE turbine at constant air consumption.

An increase in frequency of rotor revolutions when entering the idle, cruising and take-off modes is accompanied by active interaction between the rotor and the coating, which ensures the formation of a groove, the depth of which corresponds to the maximum elongation of the rotor parts, considering its imbalance, displacement respectively the axis and distortions in frames (Fig. 7 a). For engines of the TB 3-117 family, the cold running of the rotor after assembly is about 30 s. After that, happens the start, switching to idle mode, GTE operation in this mode for 5-7 minutes and further cyclic operation in take-off/cruising modes for 2-3 hours.

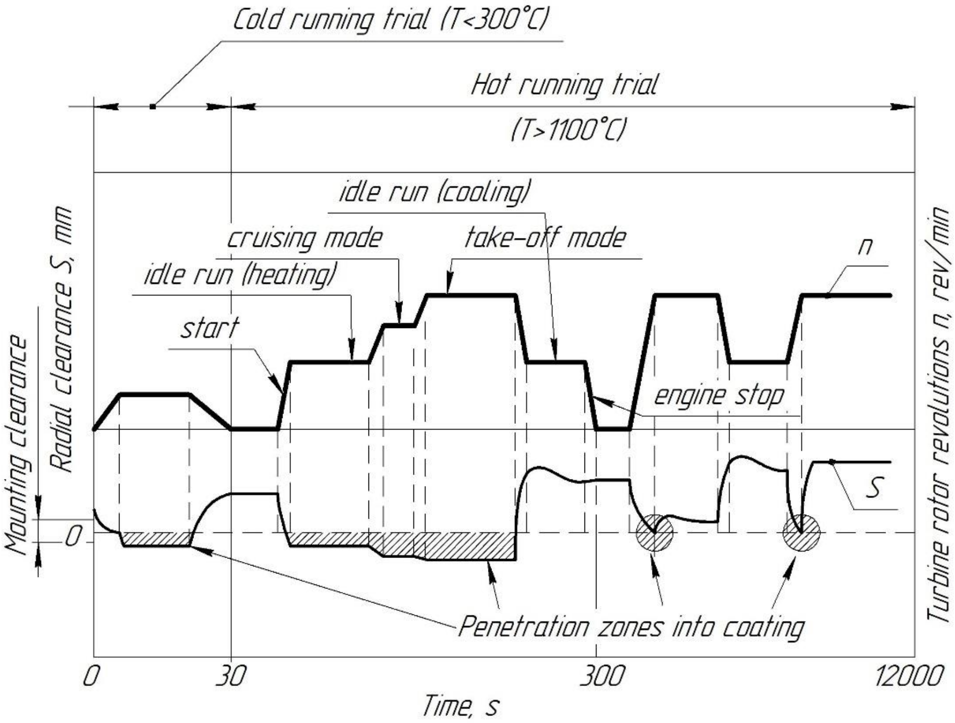
Further operation of the engine within its service life, which equals 4000-4500 flight cycles, may be accompanied by short-term contacts between the rotor and coating (T>1100°C) caused by a sharp increase in rotor revolutions (Fig. 7b).

A few studies indicate that during the life cycle the radial clearance changes, but the rotor and stator do not come into contact with each other [26].

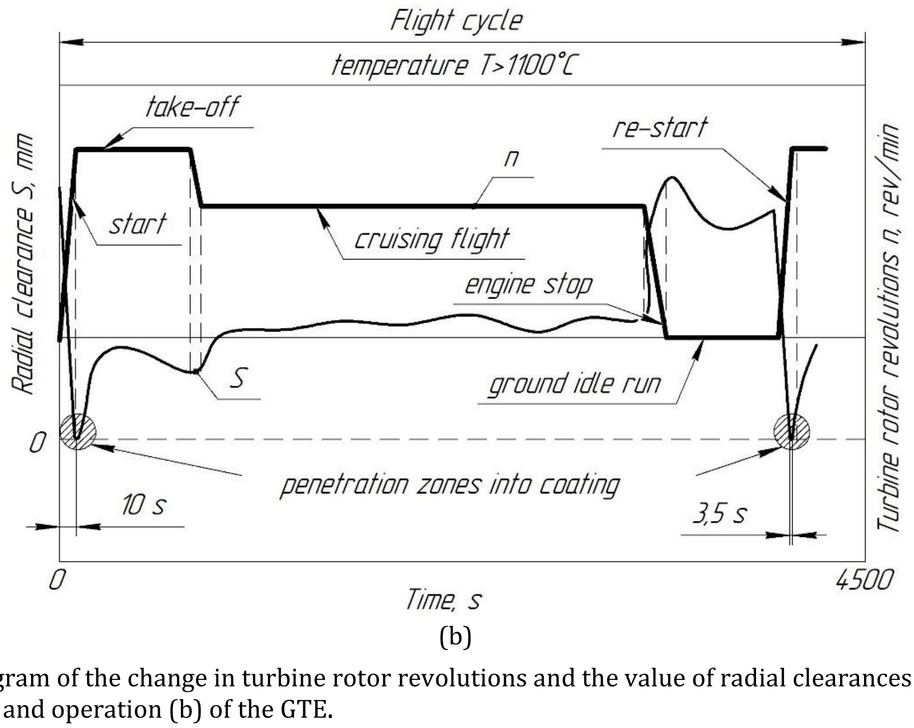
Thus, the analysis of the conditions for the interaction of GTE rotor parts and the running-in stator sealing coatings showed that their interaction occurs at the initial stage of running-in both at low and at operating temperatures. In this case, the interaction time does not exceed 300 s. During the use of a GTE, in the event of emergency operating modes or a violation of the operation practices, there may be cases of short-term interaction at operational temperature.

Considering the set operating conditions of coatings, low wear resistance in the range of normal temperatures and high resistance to erosion at elevated temperatures may be the main requirements for them.

The analysis above implies the following. Firstly, the importance of maintaining the required radial clearance by using running-in sealing coatings is quite enormous. Secondly, there are special operating modes of GTEs that determine the mechanical thermal conditions revealing their properties, with regard to predicted structural-phase transformations. As a rule, the composition of ligature is provided when forming promising coatings, for example, based on the Co-Ni-Cr-Al-Y system with the addition of a rare earth metal – yttrium. Thirdly, the justification for detecting the service properties of promising sealing coatings should certainly be related to the possibility to render their operating conditions while studying their compositions and methods of formation on GTE parts.



(a)



(b)

Fig. 7. Cycle diagram of the change in turbine rotor revolutions and the value of radial clearances at the stage of running trial (a) and operation (b) of the GTE.

Based on the analysis of the depth of the wear tracks, established were dependencies that describe the wear trends of the tested coatings in relationship to linear wear h, relative wear h1000, brought to the referential friction track Lт=1000 m and referential linear wear hy, (Fig. 8).

The analysis of set preconditions allows us to draw the following conclusions.

The average rate of wear reduction with an increase in temperature from 22°C to 350°C for coating No. 1 is on average 1.5 μm deg-1 (two intervals: from 22°C to 200°C – 2.28 μm deg-1, from 200°C to 400°C – 0.7 μm deg-1).

For coating No. 1, the pattern of change in referential linear wear with a decrease in pressure in the friction zone is comparable to the change in linear wear. For coating No. 2, the picture is different. As the pressure decreases, referential wear shows a maximum in the temperature range of 300-500 °C (Fig. 8c).

Approximation of the data on the actual wear of coatings from pressure in the friction zone (Fig. 8d) indicates the following.

Coating No. 1 does not demonstrate a typical feature of the final stage of running-in of surfaces, that is a steady wear process regardless of changes in the parameters of thermomechanical loading, at which wear is constantly minimal. Within the entire range of thermomechanical loading, the wear rate decreases. Coating No. 2 is characterized by the pressure range from 6 MPa to 10 MPa and an interaction medium temperature from 20ºC to 200ºC, within which steady wear occurs. The wear rate is maximum within these pressure and temperature ranges. This probably indicates a decrease in the strength of cohesive bonds between the components of the near-surface layers of the coating material.

This regularity may be explained by the elastoplastic form change of the contact zone. The depth of penetration increases without separation of wear particles or loosening of the surface layer material by shrinkage.

Coating No. 1 has a greater tendency to stabilize the wear process with adaptability to thermomechanical loading. For it, the minimum wear begins to appear starting from a temperature of 550-650ºC to 1100ºC. This predetermines the fact that when the GTE stator coating No. 1 comes into contact with the turbine blade, its damage will be minimal.

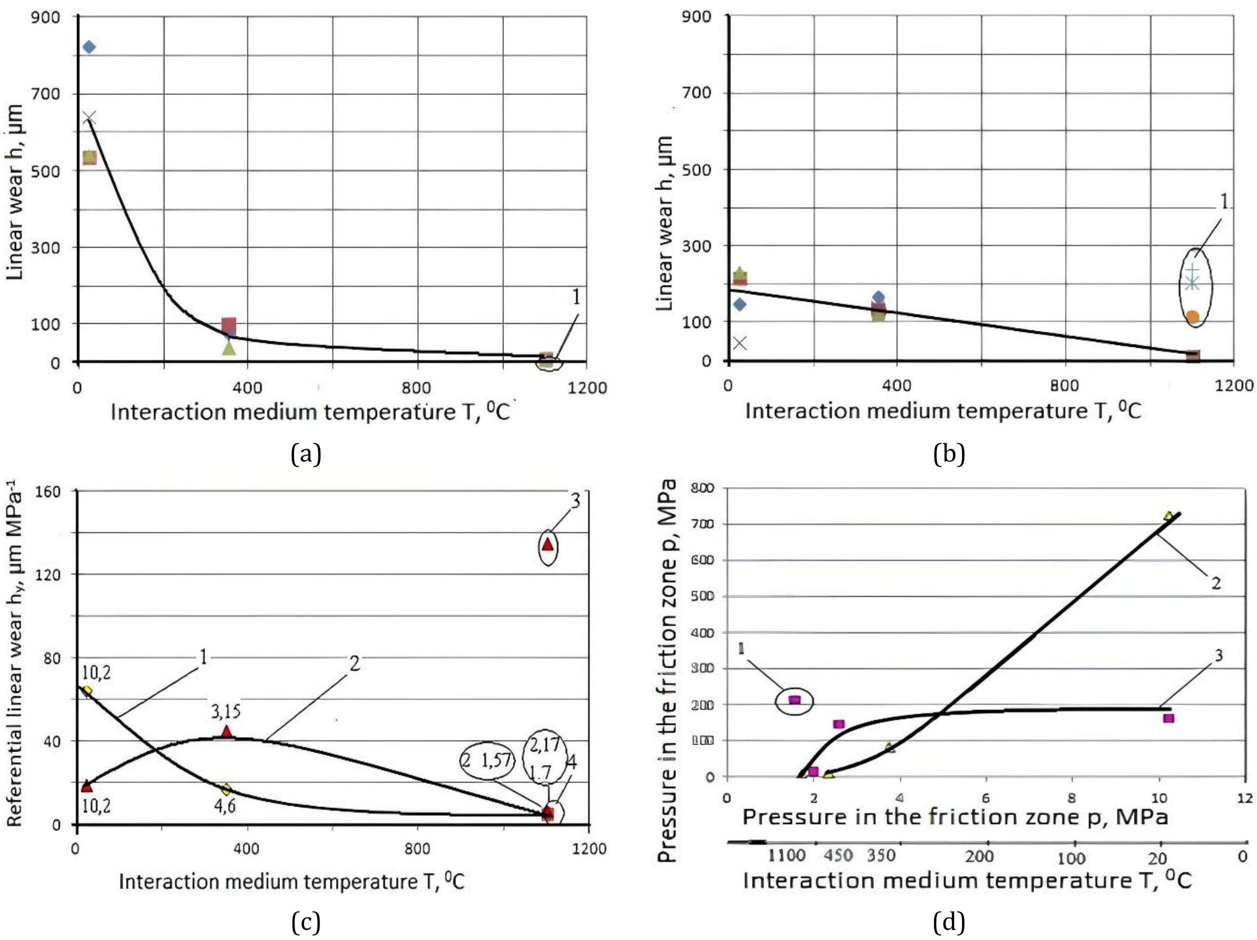


Fig. 8. Relationship of the types of coatings wear on the interaction temperature: (a) – linear coating wear No. 1; (b) – linear coating wear No. 2; 1 – distribution of wear of coating No. 2 at stage # 4; (c) –referential wear distribution with pressure change in the friction zone: 1 – coating No. 1; 2 – coating No. 2; 3 – wear of coating No. 2 at stage # 4; 4 – wear of coating No. 1 at stage # 4; (d) –actual wear at pressure in the friction zone with temperature change: 1 – pathological (catastrophic) destructions of coating No. 2; 2 – coating No. 1; 3 – coating No. 2. The numbers near the points indicate the pressure, p MPa, in the friction zone.

Coating No. 2 does not tend to stabilize the wear process while being adaptable to thermomechanical loading. It is not characterized by the stability of temperature-gradient structural changes to pressure perception in contact interaction zones. The explicit wear maximum in the temperature range of 350-400ºC accounts for this. At that, wear stabilization does not occur in the conditions and modes under consideration. This predetermines the fact that when the stator with coating No. 2 comes into contact with the turbine blade, its damage will be greater than in the case of coating No. 1.

The wear pattern is different in the GTE running-in mode. Coating No. 1 has less wear resistance than coating No. 2. This may be due to its greater porosity and tendency to brittle fracture. In this case coating No. 2 is denser in its structure before the onset of temperature exposure. Coating No. 1 is characterized by elastic deformation, which causes the separation of particles upon momentary reaching of the elastic limit in the microvolume of loading and the presence of insufficiently defined contours of wear tracks. Coating No. 2 is more liable to elastoplastic deformations, that is proved by wear track contours that are more even and more defined.

If we consider the fact of structural-phase transformations when adjusting to thermomechanical loading at a temperature of 1100ºC, within thin layers of 25-50 μm, the wear resistance of both coatings is approximately the same. This predetermines the fact that in case of the catastrophic approach of coatings No. 1 and No. 2 to the turbine blade, their surfaces will behave identically. This is possible when the GTE switches from idle to maximum operation mode.

However, in case of damage exceeding 25-50 μm, coating No. 1 remains workable. The preservation of its wear resistance, which is approximately equal to the wear resistance in the depth range of 0-(25-50) μm, supports this. Coating No. 2 with such damage is no longer operational. The plastic shaping of friction tracks, the depth of which significantly exceeds the wear tracks of coating No. 1, supports this.

From the point of preserving the mass of the deformed coating material, coating No. 2 wears out with a priority change in the shape of the friction zone, rather than separation of particles. This can be considered as a positive demonstration of coating No. 2 properties while building-up deformations of microvolumes of friction zones.

4. CONCLUSION

The thermomechanical loading of coatings of Co-Ni-Cr-Al-Y system with yttrium content of 0.1% deposited by gas-flame and ion-plasma methods at change of operation temperature has been modeled. Fundamental differences in the nature of the display of their physical and mechanical properties have been revealed.

The revealed trends are significant because, firstly, they reveal arguments in favor of changing the manifestation of mechanical properties of coatings: elasticity, plasticity, friability, shrinkage, which determines the sequence of preparation of volumetric structures of coatings for the formation of mortise tracks with optimal performance characteristics. Secondly, this information is necessary for their subsequent comparison with the results of tribomechanical tests of coatings with different yttrium content and the development of recommendations for the practical application of methods of their preparation.

It has been found that original structures of the gas-flame coating in the temperature range from 20°C to 200°C are less liable to wear resistance. At the same time, their linear wear is 1.9 times greater than for coatings applied by ion-plasma methods.

It has been established that in the temperature range from 350°C to 450°C gas-flame coatings withstand 1.5 times higher contact pressures. At that, their referential linear wear is 2 times less than for ion-plasma ones. In the temperature range of 400-800°C, wear and the rate of its change for the gas-flame coating decrease on average 2 times slower compared to ion-plasma coatings. It has been found that the wear properties upon reaching a temperature of 1100°C for both coatings are statistically indiscernible. It has also been determined that resulting from structural-phase transformations in the coating applied by the ion-plasma method, its surface layers may be destroyed.

The established dynamics of changes in the studied wear properties may be used to develop recommendations for the use of running-in coatings, considering the features of the cycloramas of operation of gas turbine engines and power plants. The use of advanced coatings KNA-82 in the design of turbine labyrinth seals allows to maintain the value of the radial gap, which can significantly increase the engine efficiency with an average annual operating time of about 800 hours.

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