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# Evaluation of Wear of Gas-Flame and Ion-Plasma Sealing Coatings with 0.3% Yttrium under Thermomechanical Loading Conditions

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**Abstract.** The article presents the results of investigation of tribological characteristics of gas-flame and ion-plasma sealing coatings of KNA-82 system with yttrium content of 0.3% used in gas turbine engine assemblies. The tests were carried out in four stages modelling different operating conditions: without heating (22°C), under medium heating (350°C), after the samples were aged at 1100°C and after repeated high-temperature loading. To evaluate the wear resistance of the coatings, linear wear, reduced wear and conditional linear wear were analysed as a function of temperature and pressure in the contact zone. It was found that both types of coatings show a tendency to stabilise the wear process under thermomechanical loading. It was found that at 1100°C the wear of ion-plasma coating is 10% lower than that of gas-flame coating under constant mechanical loading and 34% lower under step loading. A significant difference in the behaviour of the coatings was found: the gas-flame coating shows a hyperbolic decrease in the reduced wear with parallelism of the curves in the range of 350-1100°C, which indicates the stability of the wear mechanism, whereas the ion-plasma coating is characterised by instability of the wear mechanism with pressure and temperature changes.

**Keywords:** sealing coatings, yttrium, tribotechnical characteristics, wear resistance, thermomechanical loading, KNA-82, gas turbine engines, high-temperature resistance.

**Introduction**

Sealing coatings are special composite materials applied to stator elements of gas turbine engines to create effective radial seals with rotating parts. These coatings work on the principle of controlled wear - in contact with the rotor blades they work up, forming a minimum radial gap, which reduces leaks of working gas and increases the efficiency of the engine [1].

Increasing the operating temperature of sealing coatings is an important technical task dictated by modern trends in aircraft engine building. Increasing the operating temperatures of gas turbine engines allows to significantly increase their thrust and efficiency. According to research data, increasing the temperature in the combustion chamber by 50°C can increase the engine efficiency by 12.5% [2]. At the same time, to ensure reliable operation of the engine, it is necessary that all its elements, including sealing coatings, retain their functional properties at elevated temperatures.

Traditional nickel-based sealing coatings of the KNA-82 type retain their serviceability up to temperatures of 900-950°C, but modern and advanced engines require materials capable of reliable operation at temperatures of 1100-1200°C [3]. The alloying of coatings with rare-earth metals, in particular yttrium, is one of the effective ways to increase their high-temperature resistance. The presence of these elements in the coating composition promotes the formation of stable protective oxide films, which increase the resistance to gas corrosion and erosion wear [4]. Tribological properties of sealing coatings determine their ability to controlled wear in interaction with rotating turbine blades and are crucial for the efficient operation of gas turbine engines. Research in this area is focused on a comprehensive assessment of the friction coefficient, energy intensity of wear and the character of wear surface formation.

The authors in [5] found that gas-flame coatings of Co-Ni-Cr-Al-Y system with 0.1% yttrium at 20-200°C have 1.9 times higher wear than ion-plasma coatings. However, in the range 350-450°C, gas-flame coatings withstand 1.5 times higher contact pressures with 2 times lower conditional linear wear. At 400-800°C, the wear of gas-flame coatings decreases 2 times slower. At 1100°C the wear properties of both types of coatings become almost identical, although the surface layers of ion-plasma coatings can be destroyed due to structural-phase transformations.

Earlier in [6-8], the feasibility of studying coatings with yttrium content of 0.1; 0.3 and 0.5% was substantiated. The evaluation of wear of gas-flame and ion-plasma coatings with 0.3% yttrium under thermomechanical loading conditions is a logical continuation of these studies.

Test results [6] showed that coatings with 0.3% yttrium have an optimal combination of tribological characteristics. Gas-flame coatings with such yttrium content demonstrate maximum resistance to mechanical fracture - 25-40% higher than other compositions. Under static high-temperature loading (1100°C), the mass gain of gas-flame coatings is 30-35%, which is 2 times higher than that of ion-plasma coatings.

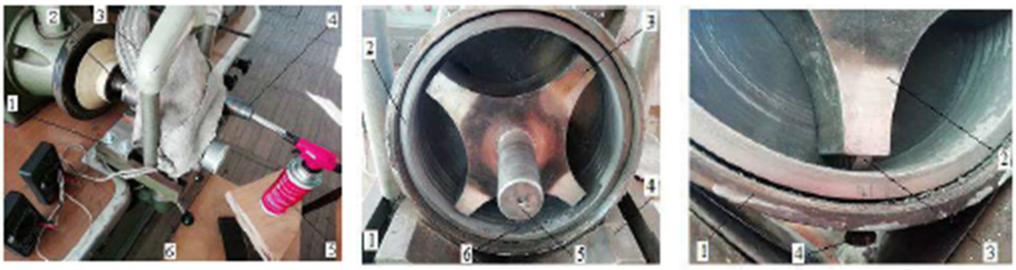
The friction coefficient of gas-flame coating with 0.3% yttrium stabilises at the level of 0.77-0.82, which indicates high structural homogeneity and strength of cohesive bonds. This makes this coating composition promising for application in high-temperature units of GTE.

The aim of the work is to obtain surface wear characteristics of coatings formed by gas-flame and ion-plasma methods with yttrium content of 0.3% in the initial composition and their tribotechnical evaluation depending on the modelled mechanical pressure and temperature.

## 1. Research methodology

For tribotechnical tests were used coatings of the composition KNA-82 nickel (base), silicon, aluminium and solid lubricants (graphite and boron nitride), which were forged on small-sized samples rings in the gas-flame method, then coating No. 1, and ion-plasma method, then coating No. 2.

The experimental equipment used in [5] was used to simulate the heat and mechanical loading of the investigated coatings. The elements of the test chamber and the investigated coatings, which were preformed on the specimen-rings 2 are shown in Figure 1. The equipment was installed on a test bench for testing generator sets of automotive engines Hiradastechniki GepgyaraU-808 series No. 326 with two modes of controlled change of drive shaft speed.



a) b) c)

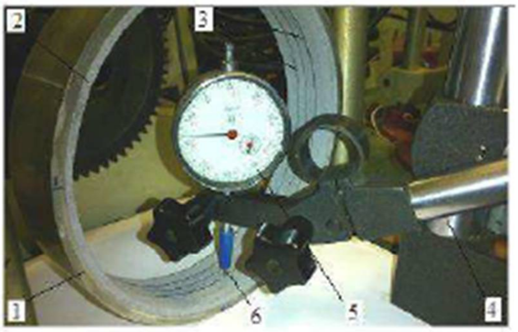
1 – chamber body; 2 – sample-ring; 3 – rotor; 4 – supporting frame stand; 5 – rotor bearing shaft; 6 – coating wear products; c – rotor wing with a plate: 1 – sample-ring; 2 – rotor wing casing with internal groove; 3 – plate with knife edges; 4 – bottom screw for fixing the sample-ring

**Fig. 1** – Generalview (a) ofthetestchamber (b) andcounterbodies (c):

The method of measuring linear wear is shown in Figure 2. In this case, the following characteristics were taken to evaluate the wear:

- linear wear h, which was recalculated into the reduced wear h1000 to the friction path of 1000 m. The necessity of such recalculation was determined by the change of rotor speed 5 (Fig. 1 b) at change of modes of mechanical loading of the coating surface and different time of duration of the tests;

- conditional linear wear hu = h1000/pcr. Average pressure in a friction zone pcp=0,5(pmin+pmax). Necessity of introduction of such parameter was determined by change of specific pressure in a friction zone. The minimum and maximum values of mechanical pressures were determined in accordance with the areas of the end faces of plates 3 (Fig.1 c), which were increased at the end of the experiment: pmax - before the test; pmin - after the test.



1 - sample-ring body; 2 - coating; 3 - wear tracks; 4 - tripod; 5 - indicator head; 6 –stylus

**Fig. 2** - Measurement of linear wear

When modelling the thermal and mechanical loading of the investigated coatings, the possible four stages of their contact interaction with gas turbine blades, unfolded in time and predictably characteristic of their operating conditions, were reproduced separately [6, 7]. At the same time, the mechanical loading was modelled as constant and stepwise with possible levels determined by the contact areas in the friction zone and the pressing force. Based on the technical capabilities of the stand, where the test chamber was mounted, as well as the mass and geometrical parameters of the pressure plates 3 (Fig. 1 c), the modes of force and velocity loading of the friction contact zones were determined.

The following conditions and modes of modelling of heat-mechanical loading of the investigated samples were inherent to the stages.

Stage No. 1: No heating of possible contact interaction zones T=22 °C, constant mechanical pressure on the surface of coatings: primary minimum - 2,45 MPa for coating No. 1 and 1,7 MPa for coating No. 2 - experience No. 1, secondary maximum - 11,4 MPa for coating No. 1 and 5,5 MPa for coating No. 2 - experience No. 2. The test time is 1 minute. Rotor rotation frequency 300 min-1.

Stage No. 2. Heating up in the chamber and contact interaction of surfaces at a steady temperature T=300-476 °C. Test No.1 - constant mechanical pressure on the surface of coating No.1 - 3.24 MPa, on coating No.2 - 2.56 MPa. Test time 53 min (of which 48 min of chamber warming up and 5 min at the specified temperature). Rotor rotation frequency 600 min-1. Test No. 2 - step loading with average mechanical pressures on coating No. 1 - 4,61 MPa, on coating No. 2 - 3,1 MPa. Test time 26 min (of which 23 min warming up the chamber and 3 min at the specified temperature). Rotor rotation frequency 600 min-1 and 1200 min-1. The test time at each of the specified frequencies was 1.5 min.

Stage No3. Separate endurance of sample-rings with coatings at temperature T-1100 °C for 3 hours with the subsequent test at heating of friction contact zones at the established temperature T=372-476 °C. Test No.1 - constant mechanical pressure on the surface of coating No.1 - 6 MPa, on coating No.2 - 4.22 MPa. Test time 35 min (of them 20 min of chamber warming up and 15 min at the specified temperature). Rotor speed 600 min-1. Test No. 2 - step loading with average mechanical pressures on coating No. 1 - 5.61 MPa, on coating No. 2 - 4.9 MPa. Test time 25 min (of which 22 min warming up the chamber and 3 min at the specified temperature). Rotor rotation frequency is 600 min-1 and 1200 min-1. The test time at each of the specified frequencies was 1.5 minutes.

Stage No4. Heating of friction contact zones of plate scallops with deepened layers of coatings up to a steady temperature T=305-412 °C and their interaction under stepwise loading with average mechanical pressures for coating No.1 - 6.69 MPa, for coating No.2 - 3.87 MPa. Deepened layers were obtained as a result of mechanical grinding of the surface at the depth of maximum plunge after the third stage of testing. The test time was 40 min (of which 38 min of chamber warm-up and 2 min at the specified temperature). Rotor speeds of 600 min-1 and 1200 min-1. The test time at each of the specified frequencies was 1 minute [9, 10, 11].

**2. Results and discussion**

Processing of data on wear of surfaces of coating materials allowed to obtain the following results, Table 1.

According to the data given in Table 1 for stages №1-№3 graphs are constructed, Fig.2. These graphical dependences display the predicted regularities of wear variation of coatings depending on pressure and temperature of the interaction medium [12].

In accordance with the data shown in Fig.2 c the following should be noted.

For both coatings with increasing pressure at Tcr=22 °C is characterised by a decrease in the reduced wear, which may indicate the tendency of the structures to elastoplastic deformation, which leads to pressurisation of the layers and an increase in their resistance to fracture.

**Table 1.** Summary data on wear characteristics of coatings

| Coatingnumber | Condition, regime (experience) | Option | Temperatureofinteraction | | | |
|---|---|---|---|---|---|---|
| | | | Stage №1 22 °C | Stage №2 350 °C | Stage №3 1100 °C | Stage №4 1100 °C |
| №1 | 1 | $h_{1000}$, μm | 73±20 | 33±7,3 | 10,4±3,4 | 40,3±16 |
| | | $h_y$, μm ·MPa$^{-1}$ | 29,8 | 10,2 | 1,73 | 6,02 |
| | 2 | $h_{1000}$, μm | 123±33 | 41±13* | 20,2±5,3* | - |
| | | $h_y$, μm ·MPa$^{-1}$ | 10,8 | 8,9* | 3,6* | - |
| №2 | 1 | $h_{1000}$, μm | 54±20 | 37±5,3 | 9,3±2,45 | 44,3±16 |
| | | $h_y$, μm ·MPa$^{-1}$ | 32,1 | 14,45 | 2,2 | 11,4 |
| | 2 | $h_{1000}$, μm | 107±26 | 35±14* | 13,3±3,6* | - |
| | | $h_y$, μm ·MPa$^{-1}$ | 19,45 | 11,3* | 2,7* | - |

*Note. * - steploading.*

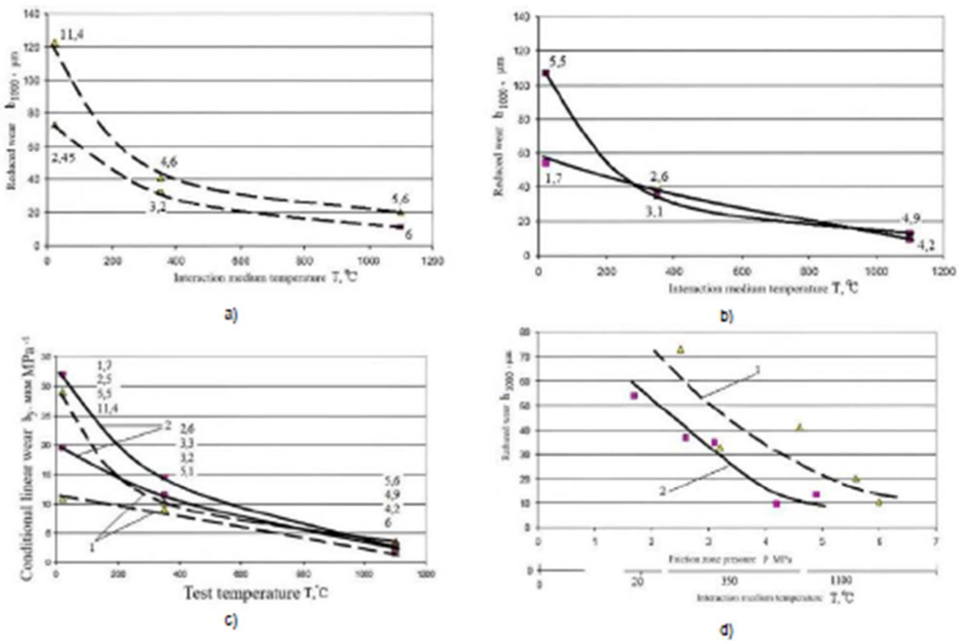
The character of change in the reduced wear shown in Fig. 2 a, b indicates the unequal nature of its reduction with heating (stages #1-#3) for both coatings.

Thus, for coating No.1 a hyperbolic reduction of the reduced wear was determined by two curves, the parallelism of their sections is preserved in the temperature range from 350 °C to 1100 °C. This may indicate the reproducibility (repeatability) of the dynamics of deformation of the structures of coating No.1 with increasing pressure and temperature.

I.e. it is possible to speak about constancy of wear mechanism manifestation without changing the parameter (s) of its estimation. For example, such a parameter can be the strength of cohesive bonds between the components of coating No. 1.

For coating No.2, both hyperbolic reduction of the reduced wear, which appears at high initial pressures p=5.5MPa in the friction zone, and angular linear reduction, which appears at lower initial pressures p=1.7MPa in the friction zone, are determined, Fig.2 b. In this case it is inappropriate to speak about parallelism of plots in the temperature range from 350 °C to 1100 °C. This may indicate the non-reproducibility (non-repeatability) of the dynamics of deformation of the structures of coating No.1 with increasing pressure and temperature. I.e. it is possible to speak about inconstancy of wear mechanism manifestation - there is a change of parameter (s) of its estimation. For example, such a parameter can be the strength of cohesive bonds between the components of coating No.1.

Heating of coatings up to Tcp=350 °C causes reduction of their conditional linear wear, Fig. 2 c. At the same time, the modelled pressure in the friction zone, which changes due to the wear of the plate scallop ends, does not cause a sharp change in the wear tendencies of the coatings at this stage. Decrease of conditional wear of coatings occurs both at insignificant increase of pressures (coating No. 1 - line 3, coating No. 2 - line 1) and at their decrease (coating No. 1 - line 4, coating No. 2 - line 2). This indicates that both coatings adapt to tangential loading in the frictional interaction zone in different ways during the warm-up phase to an average temperature of 350 °C. Coating No.2 at lower pressures is more prone to propagation of destructive stress fields per unit contact area of 1 mm$^2$, which do not match the strengths of cohesive bonds between its components in the material. The stresses arising in the surface layers of coating No.2 are greater than the strength of cohesive bonds, which causes its greater wear both at Tcr=22 °C and at Tcr=350 °C.




a - reduced linear wear of coating No.1; b - reduced linear wear of coating No.2; c - distribution of conditional linear wear;
1 - coating No.1; 2 - coating No.2; d - reduced wear at pressure in the friction zone. NumbersnearthepointsdenotepressureinMPa

**Fig 2.** - Dependence of coating wear types on the interaction temperature

Heating at constant load (stages No.1, No.2) predetermines a big difference in conditional wear of coatings. If at Tcr=22 °C coating No.1 had a conditional wear of 1.1 times less than coating No.2, then at Tcr=350 °C coating No.1 already had a wear of 1.42 times less than coating No.2. That is, the difference increased by 1.27 times, or by 27% [11].

However, during step loading and holding at Tcr=350 °C (step #2) the opposite occurs. Conditional wear of coating No.1 decreases by 1.3 times. This may indicate the formation of some safety margin in the layers of coatings by cohesive bonds between their components, within which the stresses caused by tangential deformation loading are balanced. If to estimate the indicated safety margin, then at step loading and holding at Tcr=350 °C (stage No.2) it is 1.27 for coating No.1 and 1.37 for coating No.2. Thisisevidencedbytheratiosofconditionalwear, whichareforcoating No.1 - 10.2/8, forcoating No.2 - 14.45/10.5.

The data shown in Fig.2 c for stage No3 indicates the following. Firstly, exposure of both coatings at 1100 °C predetermines the range of conditional linear wear variation from 1.73 to 3.6 μm-MPa$^{-1}$, which occurs at the pressure range from 4.2 to 6 MPa. Secondly, in comparison with stage No.2, the range of variation of conditional linear wear for both coatings is wider and ranges from 8.9 to 11.3 μm-MPa-1 and takes place at lower pressures - from 2.6 MPa to 5.1 MPa. This once again confirms the significance of the influence of long-term high-temperature exposure on the structural-phase transformations occurring in the layers of coatings, which determine the adaptability of frictional interaction zones to mechanical loading with large average pressures [13].

The data shown in Fig. 2 d for stages №1-№3 indicate the following.

Firstly, the rate of reduction of the reduced wear in both coatings in the range of pressure increase from 2 MPa to 4 MPa is practically the same, and makes 18 μm-MPa-1, which indicates the equality of the rates of destruction (change) of cohesive bonds between components in coatings No.1 and No.2. However, their quantity is different. In coating No.1 they are more due to the separation of fragments in the form of wear particles. In coating No.2 there was a smaller number of wear particles due to subsidence of structures, which predetermined an increase in the strength of cohesive bonds between components in its near-surface layers.

Secondly, there are no pressure ranges within which steady wear of the coatings takes place, except for the emerging preconditions for coating No. 2 at pressures from 4.5 MPa and presumably higher. For coating No.1 such preconditions can be observed starting from a pressure of 6 MPa. However, due to the lack of experimental data on wear at higher pressures for coatings No. 1 and No. 2, taking into account the structural-phase transformations manifested after exposure at 1100 °C, it is premature to testify about reaching the steady wear.

The evaluation of wear (Table 1) at stage No.4 indicates the following.

The reduced wear of coating No.1 in comparison with stage No.3 increased by 3.9 times, for coating No.2 - by 4.8 times. The conditional wear of pavement No.1 compared to stage No.3 increased by a factor of 3.5, for pavement No.2 - by a factor of 5.2. These data show a significant decrease in the resistance of surface layers of both coatings to failure under the action of step loads. This indicates that long-term high-temperature exposure does not provide the same flow of structural-phase transformations in the layers of both coatings in depth [14].

**Conclusions**

As a result of the conducted researches the tendencies of change of wear characteristics of coatings, caused by unequal manifestation of their physical and mechanical properties, heterogeneously distributed on their body, have been determined. Thus both coatings are inclined to stabilisation of process of wear at adaptability to thermomechanical loading that is indicated by the identical character of display of the received regularities of change of characteristics of wear.

It is determined that taking into account the average statistical variability of the investigated wear characteristics, which is 15-20% at the temperature of 1100 °C, which is the average statistical operating temperature of the power compartment of the gas turbine unit, there is a tendency to decrease the wear of coating No.2. Reduction of wear of coating No.2, in comparison with coating No.1 makes ≈10% at constant mechanical loading, and ≈34% at modelling of step loading.

Furthermore, the study demonstrates that the differing structural responses of gas-flame and ion-plasma coatings to combined thermal and mechanical loads have practical implications for their application in gas turbine engines. While both coatings exhibit a tendency toward wear stabilization, the ion-plasma coating shows superior adaptability under stepwise loading conditions, which are typical in operational cycles of gas turbines. This suggests that for components exposed to variable mechanical pressures and high temperatures, ion-plasma coatings with 0.3% yttrium can provide enhanced durability and prolonged service life, reducing maintenance requirements and improving the overall reliability of the engine assemblies.

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