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RESISTANCE OF HEAT-RESISTANT YTTRIUM-CONTAINING SEALING COATINGS TO MECHANICAL FRACTURE WHEN FORMING CUTTING PATHS

Kubich V.[1], Fasol Ye.[1], Cherneta O.[2], Yershina A.K.[3], Sakipov N.Z.[4]

[1] National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine
[2] Dniprovsky State Technical University, Kamenske, Ukraine
[3] Kazakh National Women‘s Teacher Training University, Almaty, Kazakhstan
[4] Civil Aviation Academy, Almaty, Kazakhstan
*Corresponding author: schmirung@gmail.com

Abstract. *According to the results of tribotechnical tests of coatings made of KNA-82 alloy ligatures with the addition of yttrium of 0.1%, 0.3%, 0.5%, data were obtained that allowed us to establish the nature of changes in the dynamic coefficient of friction over the test period and numerous values of the energy intensity of material wear. The evaluation of coatings formed by the gas-flame and ion-plasma method was based on the following premise. The maximum resistance to mechanical fracture is determined by the manifestation of a constant minimum value of the dynamic coefficient of friction. This serves as an indicator of reduced friction force before reaching the fatigue limit. Another key factor is the number of separated particles produced per unit of integral work during the friction process. These evaluation parameters are lined up in a row by the number of points from 1 to 4. The maximum score corresponds to the maximum resistance, i.e., a lower value of the energy intensity of material wear and the minimum value of the stable friction coefficient. It has been determined that the same coincidence of these parameters according to the scores is almost at all stages of testing (I-III) was the coating formed by the gas-flame method with a yttrium concentration of 0.3%-0.5%. The exception was the coating formed by the ion-plasma method with a yttrium concentration of 0.1% at the fourth stage of testing.*

Keywords: sealing coating, ion-plasma method, gas-flame method, mechanical fracture resistance, cutting tracks, high-temperature loading, yttrium, mechanical stability, gas turbine engines.

1. Introduction

In the current technological environment of industrially countries, especially in the aerospace, energy and aviation industries, there is a growing need for materials that could provide reliable operation in high temperatures, aggressive environments: intense gas-erosion and gas-explosive exposures [1,2]. One of the most important areas of research and development in this context is the creation of heat-resistant sealing coatings that would be effective in conditions of high-temperature aggressive gas flow and will increase engine’s efficiency. Among the modern materials that have high thermal endurance and excellent resistance to abrasive and gas-erosion wear, yttrium-containing coatings occupy a special place. The use of yttrium in coatings can increase wear resistance, heat resistance, provide reliable adhesion to the substrate material, and improve mechanical properties [3].

An example of application is the coatings of gas turbines. One of the main parameters in the design of modern gas turbine engines (GTEs) is the efficiency. One of the main directions of improving the engine design and to reduce gas flow losses and rationalizing fuel consumption is to reduce radial clearances in the rotor-stator interface [4]. The control of the size of axial and radial clearances in the GTEs are the focus of research by many authors, but this problem has not been finally solved. It is quite difficult to ensure the size of the gap, so there is a need to use sealing coatings. In particular, coatings of the Ni-Co-Cr-Al-Y system [5].

The authors [6] note the prospects of using of rare earth metals in heat-resistant coatings. Active interaction with impurities – interstitial elements (mainly carbon and oxygen) promote the formation of stable carbides at the interfaces (phase boundaries, dislocation clusters). Yttrium in appropriate proportions stabilizes aluminum and chromium oxide films, improves the adhesion of coatings to the substrate material, increases the thermal stability of alloys, and slows down the coagulation of hardening phases [7-9]. It has been established that yttrium dissolved in a nickel matrix increases heat resistance [reference]. The introduction of yttrium in an amount exceeding its solubility limit leads to the precipitation of the phase close to Ni_3Y inside the grain and at the grain boundaries. [10]. The introduction of yttrium also contributes to the formation of $Ni(Al,Y)_2O_4$ and Y_2O_3 oxides on the alloy surface. In the coatings of the Ni-Co-Cr-Al-Y segregation of Y at the scale-coating interface leads to less cavity formation and, therefore, improves the adhesion of the oxide α-Al_2O_3 oxide scale. However, despite these studies, the experimental results of on the effect of yttrium on the high-temperature gas-erosion resistance of coatings are currently not sufficient to determine the required amount of Y to be added, as well as the efficiency of its use [11].

The main objective of the research is to determine the resistance of yttrium-containing coatings formed from KNA-82 alloy ligatures on small-sized samples using the gas-flame and plasma spray methods to mechanical destruction during the formation of the insertion tracks. In this case, the cut-in tracks perform a forcedly modeled wear profile of the material of coatings applied to the surface of the stator of a labyrinthine gas-dynamic seal, power turbine, etc. In this case, resistance is considered as a generalized quality of a multiligature material, which, according to the nature of friction and wear observed when the pointed ridges are cut in, reflects the pattern of destruction of cohesive bonds between the components of the formed powder coating [12,13].

2. Materials and research method

To conduct the research, the coatings were formed up to 5 mm thick on one side of cubic specimens of size 15×22×20 from a cylindrical forming work surface. The substrate for the sample was made of nickel alloy Inconel 600. The coatings tested were KHA-82 (nickel alloyed with silicon, aluminum, and solid lubricants (graphite and boron nitride) with the addition of 0.1%, 0.3%, and 0.5% yttrium. The coatings were applied by gas-flame and plasma sputtering methods, Fig. 1 c, d. The tribological tests were carried out at the SMC-2 unit at the modeled temperatures given in the presented stages of the study. Scheme of the rotating disk - fixed pad is presented in Figure 1a.

The prepared samples were subsequently subjected to

- high-temperature dynamic loading in the environment of a burning iso-octane-propane-butane gas mixture at a temperature of 950-1220 °C for 5 min., Fig 1, c,

- high-temperature static loading in a furnace at 1100°C for 3 hours, which was considered as a static high-temperature loading with a limited amount of oxygen as an oxidizing agent;

- high-temperature dynamic loading in the environment of a burning gas iso-octane-propane-butane mixture at a temperature of 950-1020 °C for 5 min. with modeling of a constant mechanical load, Fig1, d.

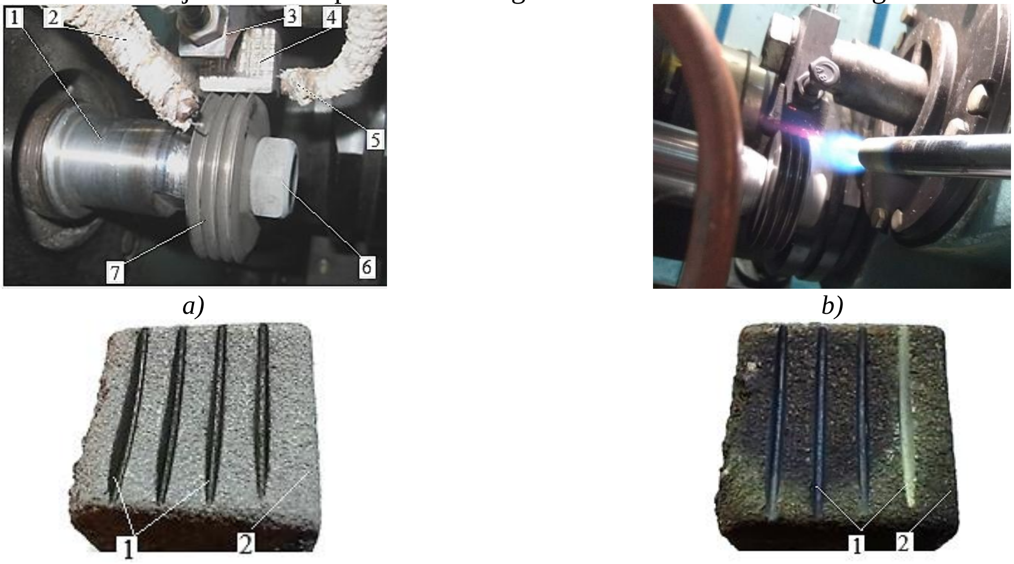
Based on the above factors of high-temperature loading, the physical modeling of mechanical fracture of the sample surfaces was carried out in four stages:

- stage 1 - tribotechnical tests at a normal ambient temperature T = 25ºC after coating. The test cycle was 5 min. at a constant load;

- stage 2 - tribotechnical tests at a normal ambient temperature of T = 25ºC after exposure of the coating to a high-temperature dynamic load of a burning gas iso-octane-propane-butane mixture at a temperature of 950-1220 °C. The test cycle was 5 min. at constant load;

- stage 3 - tribotechnical tests at an ambient temperature of T = 25ºC after exposure of the coating to a high-temperature static load in an oven at a temperature of 1100 °C. The test cycle is 5 min. at constant load;

- stage 4 - tribotechnical tests in a burning gas iso-octane-propane-butane mixture at a temperature of 950-1020 °C. The test cycle included mechanical loading without a burning gas mixture environment for 1 min, with a burning gas mixture environment for 3 min, and without a burning gas mixture environment for 1 min. The comparison of the resistance of yttrium-containing coatings to wear resistance was carried out relative to coatings that were not subjected to temperature loading and acted as reference coatings.



a) *b)*

c) *d)*

Fig. 1. Elements of methodological support for experimental studies: a) contact of the disk samples with the pad: 1 lower shaft of the SMC-2 friction machine; 2 - thermocouple casing; 3 - holder; 4 - coated sample pad; 5 - thermocouple casing; 6 - fixing nut; 7 - sample disk with ridges; b) contact of the sample disk with the pad in a burning gas mixture; c) the surface of the coating formed by the gas-flame method; d) the surface of the coating formed by the gas-flame method after temperature loading in a burning gas mixture: 1 - cut-in tracks; 2 – coating.

To evaluate the resistance of coatings to wear resistance, we used the components of the methodology for tribotechnical testing of materials for friction and wear proposed in [14,15], Fig 1, a. The tests were carried out on the SMC-2 test rig according to the friction scheme "rotating disk with ridges - fixed pad with a coating" under a static contact load with a force of P = 18.6 N and a disk rotation frequency of n = 300 min^{-1} without modeling the temperature state. The radius of the disk was 0.025 m, made of Inconel 617 alloy.

The test time was 5 min. The load during the tests of the samples after exposure to the furnace was P_1=18.6 N and P_2=3.5 N. A disk with four ridges of a trapezoidal profile with an outer diameter of d = 50 mm was installed on the lower shaft of the friction machine, Fig 1, a.

The direct parameters of tribotechnical tests were considered:

- weight loss of the coating material Δm, g
- friction torque Mt, P·m in the form of tribograms, the value of the scale of the friction recorder field was Mti=0.18 N·m.

The indirect parameters of tribotechnical tests were considered:

- dynamic friction coefficient μ;
- energy intensity of wear of the coating material I_m, g·J^{-1}.
- friction path l_i = 235.5 m

The weight loss of the samples was measured on an electronic balance Radwag AS 220.R2 with an accuracy of 0.1 mg. The number of samples for each coating was n=3. The arithmetic mean values were used for analysis. The average standard deviation was σ = 0.0055 g.

$$I_m \approx \frac{\Delta m}{N\cdot l_1\cdot \bar{\mu}_1 + P\cdot l_2\cdot \bar{\mu}_2 + P\cdot l_3\cdot \bar{\mu}_3} \approx \frac{\Delta m}{N\cdot \sum_{i=1}^{3} l_i \bar{\mu}_j}, g\cdot J^{-1}, \tag{1}$$

where Δm is the average mass wear of the coating, g; μj is the average current value of the friction coefficient during the corresponding test time; li is the average friction path over which the friction coefficient μj is manifested, m; P is the force of pressing the coated sample against the disk ridges, N.

To estimate the ranges of change in the energy intensity of wear due to the range of changes in the yttrium content and the predicted expected difference in weight wear, we propose to use the conditional maximum and minimum wear intensity, which was

$$I_{my_{max}} = \frac{\Delta m_{max}}{A_{T_{min}}}\ g \cdot J^{-1}, \quad (2)$$

$$I_{my_{min}} = \frac{\Delta m_{min}}{A_{T_{max}}},\ g \cdot J^{-1}, \quad (3)$$

where Δm_{max}, Δm_{min} are the maximum and minimum significant wear of the samples at the research stage, g; A(t_$_{min}$), A_(t_$_{max}$) are the minimum and maximum values of friction work, J.

The dynamic coefficient of friction (hereinafter referred to as the friction coefficient) was calculated according to the equation:

$$\mu = \frac{M_{t_i}}{P \cdot r}. \quad (4)$$

The analysis of the wear mechanism of the material of the studied coatings is based on the following judgment. The frictional interaction of the surfaces of the moving disk ridges with the components of the coating structures causes

- the action of a tangentially directed friction force, which in this direction loads the cohesive bonds between the microscopic particles of the coatings, and when repeatedly manifested, causes their fatigue to resist destruction, which in turn causes their gradual separation and removal from the friction zones. This is the main cause of coating failures, since during the experiments, active separation of these particles was observed, but with varying intensity;
- the effect of normal static load, which during the experiment caused the appearance of instantaneous macro and micro stresses in the surface layers of coatings that did not have time to relax and intensified the process of separation of microparticles.

Based on the above, the conditions of maximum wear resistance are constant minimum value of the dynamic friction coefficient, as an evidence of lower friction force before reaching the fatigue limit, and the number of separated particles that are accounted for the production of a unit of integrated friction force work [5]. That is, with a lower integral work of friction forces ↓A_t and a greater separation of particles ↑Δm, the fracture resistance will be lower and the parameter Im will be higher, expression (1). Conversely, with a greater integrated work of friction forces ↑A_t and a smaller separation of particles ↓Δm, the fracture resistance will be greater and the parameter Im will be smaller.

These parameters, in accordance with the research methodology, were taken into account in the form of the constructed laws $\mu = f(t)$ and the complex parameter Im.

3. Experimental data and results

Based on the results of processing the data from the obtained tribograms, graphical dependences of the change in the dynamic coefficient of friction over the test time were constructed using the arithmetic mean values, Fig 2-5,7. The energy intensities of wear of the coatings during the formation of the cut-in tracks are given in Tables 1-4 and Fig 6.

Results of the research at stage 1.

The analysis of the data obtained regarding the effect of the resistance of the initial coatings to mechanical destruction indicates the following:

- the minimum value of the weight of the separated particles was Δm_{min}=0.0747 g for the coating formed by the thermal spray method with a yttrium concentration of 0.5%, the maximum value Δm_{max}=0.2629 g was for the coating formed by the plasma spray method with a yttrium concentration of 0.5%;
- the minimum value of friction work At_{min}=1271 J was for the coating formed by the thermal spray method with a yttrium concentration of 0.5%, the maximum value At_{max}=8463 J was for the coating formed by the thermal spray method with a yttrium concentration of 0.3%.

Based on the above, the limit values of stability according to the parameters of expressions (2,3), against which the stability of the original coatings should be evaluated, were as follows:

- minimum durability corresponds to the maximum conditional energy intensity of wear $I_{mu}=20.6 \cdot 10^{-5}\ g \cdot J^{-1}$;
- maximum resistance corresponds to the minimum conditional energy intensity of wear $I_{mu}=0.8 \cdot 10^{-5}\ g \cdot J^{-1}$.

The analysis of the data obtained regarding the manifestation of the resistance of the original coatings indicates the following. In general, an ambiguous effect of yttrium content, temperature load, and the method of coating formation on the manifestation of tribotechnical characteristics is noted.

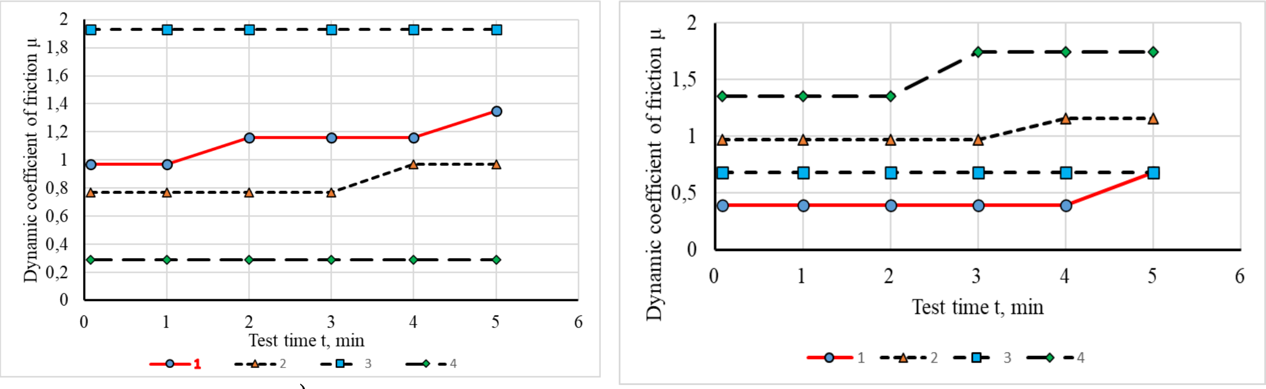
Thus, in the absence of a temperature load (Table 1)

- The plasma spray method of coating formation compared to the thermal spray method causes a decrease in wear resistance by 1.65 times and 2.6 times with an increase in yttrium concentration from 0% to 0.3%, except for a concentration of 0.5%, at which the resistance, on the contrary, increased by 1.5 times;
- the maximum resistance corresponded to the coatings formed with yttrium concentrations of 0.1% and 0.3%, but did not differ significantly from the original coating.

Table 1. Energy intensities of wear of experimental coatings $Im \cdot 10^{-5}$, $g \cdot J^{-1}$, obtained at the research stages 1 and 2

Yttrium content Y, %	Thermal spray method		Plasma spray method	
	No heating	Heating in a gas environment	No heating	Heating in a gas environment
0	3.3	8.16	5.4	7.82
0.1	3.1	8.37	5.03	9.66
0.3	2.79	6.08	7.15	10.13
0.5	5.87	8.13	3.78	11.28

For the assessment by two parameters, i.e., taking into account the friction coefficient, it is proposed to apply a point scale from 1 to 4. The maximum score corresponds to the maximum stability and the minimum value of the stable friction coefficient, the patterns of change of which are shown in Fig. 2



a)

b)

Fig. 2. Dependence of the dynamic coefficient of friction on the time of tribotechnical testing of coatings at T = 25 °C before interaction with a stream of burning gases: a) at thermal spray forming; b) at plasma spray forming; 1 - original coating; 2 - yttrium 0.1%; 3 - yttrium 0.3%; 4 - yttrium 0.5%.

An increase in the coefficient of friction by more than one indicates pathological processes of destruction of cohesive bonds with the separation of particles. That is, the friction force significantly exceeds the bonding forces between the coating components.

Thus, in the absence of temperature load, the scores had the following distribution (Table 2).

Table 2. Evaluation of coatings without temperature load

Formation method	Parameter	Number of points min→max steadiness			
		1	2	3	4
Thermal spray	I_m	0.5	0	**0.1**	0.3
	μ	0.3	0	**0.1**	0.5
Plasma spray	I_m	0.3	0	**0.1**	0.5
	μ	0.5	0.1	**0.3**	0

From the data in Table 2, it should be assumed that the coating formed by the thermal spray method has a parameter coincidence of 3 points with yttrium concentration of 0.1%. That is, this coating has the maximum resistance to mechanical fracture when forming the insertion tracks. For the coating formed by the plasma spray method, there is no obvious coincidence, but the maximum resistance is close to the same number of points for concentrations from 0.1% to 0.3%.

Results of the research at stage 2.

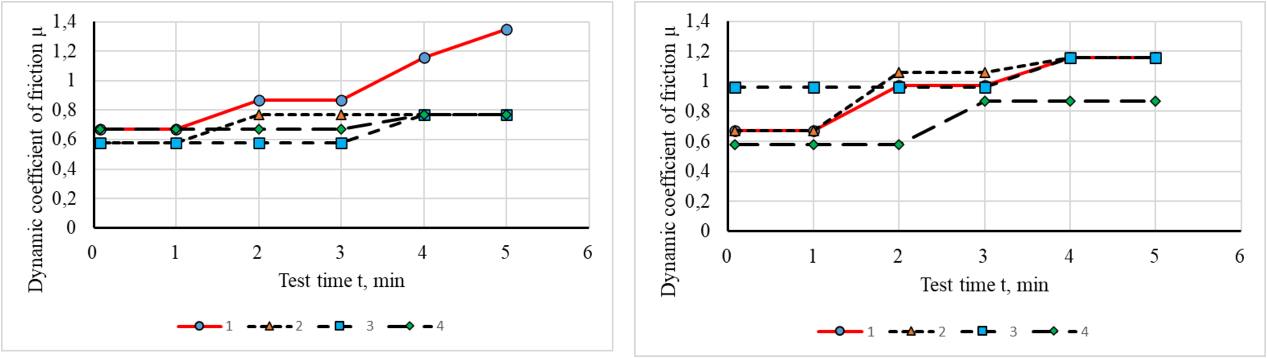
The analysis of the data obtained regarding the resistance of coatings to mechanical destruction at a temperature of T = 25°C after their heating in a gas environment at a temperature of 950-1220 °C indicates the following:

- the minimum value of the mass of separated particles was Δm_{min}=0.1802 g for the coating formed by the thermal spray method with a yttrium concentration of 0.3%, the maximum value Δm_{max}=0.4707 g was for the coating formed by the plasma spray method with a yttrium concentration of 0.3%;
- the minimum value of friction work A_{tmin}=2964.3 J was for the coating formed by the thermal spray method with a yttrium concentration of 0.3%, the maximum value A_{tmax}=4648.1 J was for the coating formed by the plasma spray method with a yttrium concentration of 0.3%.

Based on the above, the conditional limit values of stability according to the parameters of expression (2.3) were as follows:

- minimum resistance corresponds to the maximum conditional energy intensity of wear $I_{mu}=15.87\cdot10^{-5}$ g·J^{-1};
- maximum resistance corresponds to the minimum conditional energy intensity of wear $I_{mu}=3.87\cdot10^{-5}$ g·J^{-1}.

Thus, in comparison with the ultimate limits of the stability of the original coatings, it can be seen that the range of stability of the coatings after heating in a gas environment narrowed by 1.65 times, and the stability decreased in general for both methods of formation, regardless of the yttrium concentration, Table 1. At the same time, the maximum stability remained for the coating formed by the thermal spray method with a yttrium content of 0.3%, but compared to the original structure, the stability decreased by 2.18 times. However, as for the coatings formed by the plasma spray method, the maximum resistance corresponded to the coating without yttrium. The resistance of the coating with a yttrium concentration of 0.5%, which was the maximum, decreased by almost 3 times. The nature of the friction coefficient for the coatings formed by the thermal spray method is shown in Fig, 2 a. The structural-phase transformations that took place caused obvious dispersion of the mechanical properties of the coatings along the depth, as indicated by the equality of the friction coefficients for yttrium coatings during the test period from 0 min to 1 min, when μ = 0.58-0.67, and from 4 min to 5 min, when μ = 0.77, Fig 3, a. But from 1 min to 4 min, the coefficients differed. This implies that different fracture resistance according to preliminary estimates of the depth of the cut-in tracks was observed at a distance from the surface of 0.5 mm to 2 mm.



a) b)

Fig 3. Dependence of the dynamic coefficient of friction on the time of tribotechnical testing of coatings at T = 25°C after interaction with a stream of burning gases: a) at thermal spray forming; b) at plasma spray forming; 1 - initial coating; 2 - yttrium 0.1%; 3 - yttrium 0.3%; 4 - yttrium 0.5%.

For the coatings formed by the plasma method, Fig 3, b, no such distribution was observed. However, for almost all coatings, the friction coefficient μ = 1.16 was equal only in the period from 4 min to 5 min of testing, with the exception of the coating with a yttrium concentration of 0.5%, for which μ = 0.87. In this case, the same susceptibility to fracture processes was characteristic of the coating without yttrium and the coatings with its concentrations of 0.1% and 0.3%, which occurred from the 2nd min to the 3rd min of the test, Fig 3, b.

The interaction of the coatings with the high-temperature gas environment resulted in the following distribution of points in assessing their durability (Table 3). The values of the friction coefficients were selected according to the time of manifestation of obvious differences, i.e., from the 2nd min to the 3rd min of testing, Fig 3, a, b.

Table 3. Evaluation of coatings exposed to high-temperature gas loading.

Formation method	Parameter	Number of points min→max steadiness			
		1	2	3	4
Thermal spray	I_m	0.1	0	0.5	**0.3**
	μ	0	0.1	0.5	**0.3**
Plasma spray	I_m	0.5	0.3	**0.1**	0
	μ	0.1	0	**0.3**	0.5

From the data in Table 3, it should be assumed that the coating formed by the thermal spray method has a parameter coincidence of 4 points with a yttrium concentration of 0.3%, i.e., it has the maximum score. Based on this, this coating has the maximum resistance to mechanical fracture when forming the cut-in tracks. For the coating formed by the plasma method, there is no obvious coincidence, but the maximum resistance for concentrations from 0.1% to 0.3% with the same number of points borders on the number of points 3.

Research results at stage 3.

The analysis of the data obtained regarding the manifestation of the resistance of coatings to mechanical fracture at a temperature of T = 25°C after exposure to a high-temperature static load in an oven at a temperature of 1100 °C indicates the following:

- the minimum value of the weight of the separated particles was Δm_{min}=0.004 g for the coating formed by the plasma method without yttrium, the maximum value Δm_{max}=0.1331 g was for the coating formed by the plasma spray method with a yttrium concentration of 0.1%;

the minimum value of friction work A_{tmin} =1710.2 J was for the coating formed by the thermal spray method with a yttrium concentration of 0.3%, the maximum value A_{tmax} =7542.1 J was for the coating formed by the ionoplasma method with a yttrium concentration of 0.3%.

Based on the above, the limit values of stability according to the parameters of expressions (2,3) were as follows:

- minimum resistance corresponds to the maximum energy conditional wear intensity $I_{mu}=7.8\cdot10^{-5}$ g·J^{-1};
- maximum resistance corresponds to the minimum energy conditional wear intensity $I_{mu}=0.05\cdot10^{-5}$ g·J^{-1}.

Thus, in comparison with the ultimate limits of resistance relative to the original coatings, it can be seen that the range of resistance of the coatings after exposure to the furnace narrowed by 2.5 times.

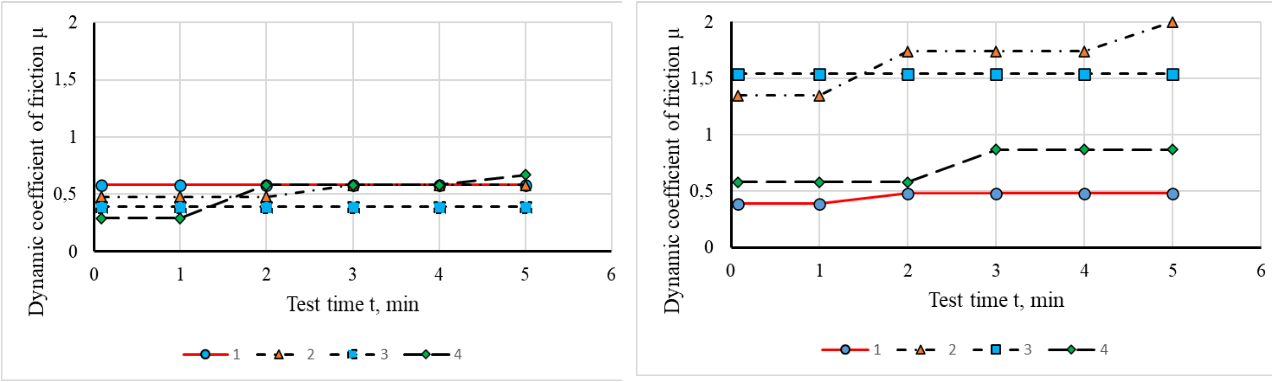
At the same time, the stability has generally increased for both formation methods, regardless of yttrium concentration. The increase in resistance for coatings formed by the thermal spray method was 6.6 times on average, and 3.8 times for the ion plasma spray method plasma method, respectively.

Table 4. Energy intensities of wear of experimental coatings Im·10-5, g·J^{-1}, obtained at the research stages 1 and 2.

Yttrium content Y, %	Thermal spray method		Plasma spray method	
	Aging in the furnace	Heating after the furnace	Aging in the furnace	Heating after the furnace
0	0.35	0.35	0.2	1.47
0.1	1.14	1.49	1.76	0.85
0.3	0.43	0.61	0.9	0.79
0.5	0.21	0.37	1.46	0.96

The coatings formed by the thermal spray method retain greater resistance. However, the highest resistance value was already achieved by the coating with a yttrium concentration of 0.5%. For coatings formed by the plasma spray method, there is no obvious pattern of increasing resistance, as is the case for gas flame coatings. A coating with a yttrium concentration of 0.3% has greater resistance. However, it should also be noted that there is a decrease in the resistance of coatings with yttrium compared to coatings without it. This is more pronounced for coatings formed by the plasma spray method.

The nature of the friction coefficient, Fig 4, indicates the following. For coatings formed by the thermal spray method, Fig 4, a, at the beginning of the experiments, a decrease in the friction coefficient is observed, which is due to the creation of surface structures capable of exerting less shear resistance with fewer separable wear particles, as indicated by the data in Table 4. However, this tribological state is not maintained in the subsequent test period, with the exception of the coating with a yttrium content of 0.3%. This indicates that the gradients of mechanical properties with depth for coatings with yttrium content of 0.1% and 0.5% are not the same.



a) *b)*

Fig. 4. Dependence of the dynamic coefficient of friction on the time of tribotechnical testing of coatings at T = 25°C after exposure to the furnace: a) at thermal spray forming; b) at plasma spray forming; 1 - original coating; 2 - yttrium 0.1%; 3 - yttrium 0.3%; 4 - yttrium 0.5%.

For the coatings formed by the ionoplasma method, Fig 4, b, an increase in the friction coefficient is observed exclusively for all yttrium-containing coatings, which is due to the creation of surface structures capable of exerting greater resistance, but with a larger number of separable particles, as indicated by the data in Table 4. The lowest values of the friction coefficient were observed for the coating with a yttrium content of 0.5%, for which the wear rate was average between the coatings with a yttrium content of 0.1% and 0.3%. Again, this indicates the peculiarity of the distribution of gradients of mechanical properties of coatings along the depth. Thus, in this case, the coating with yttrium content of 0.5% is characterized by a lower resistance to the destruction of cohesive bonds between the coating components, which actively reduces the shear resistance and causes a lower friction coefficient. However, this resistance is 1.5 to 1.8 times higher than that of a yttrium-free coating during the test.

The exposure of the coatings to static high-temperature conditions resulted in the following distribution of points in the assessment of their durability (Table 5). The values of the friction coefficients were selected according to the time of manifestation of obvious differences, i.e., from the beginning of the tests to 1 min of testing, Fig 4, a, b.

Table 5. Evaluation of coatings after exposure to static high-temperature environment.

Formation method	Parameter	Number of points min→max steadiness			
		1	2	3	4
Thermal spray	I_m	**0.1**	**0.3**	**0**	**0.5**
	μ	**0**	**0.1**	**0.3**	**0.5**
Plasma spray	I_m	**0.1**	**0.5**	**0.3**	**0**
	μ	**0.1**	**0.3**	**0.5**	**0**

From the data in Table 5, it should be assumed that the coating formed by the thermal spray method has a parameter coincidence of 4 points with a yttrium concentration of 0.5%, i.e., it has the maximum score. Based on this, this coating has the maximum resistance to mechanical fracture when forming the cut-in tracks. For the coating formed by the plasma spray method, there is no obvious coincidence, but the maximum resistance for concentrations from 0.3% to 0.5% with a point 3.

Research results at stage 4.

The analysis of the data obtained regarding the manifestation of the resistance of coatings to mechanical fracture at a temperature of T=950-1020°C after exposure to high-temperature static load in an oven at a temperature of 1100 °C indicates the following:

- the minimum value of the weight of the separated particles was Δm_{min}=0.0131 g for the coating formed by the thermal spray method with yttrium concentration of 0.5%, the maximum value Δm_{max}=0.0832 g occurred for the coating formed by the thermal spray method with a yttrium concentration of 0.1%;

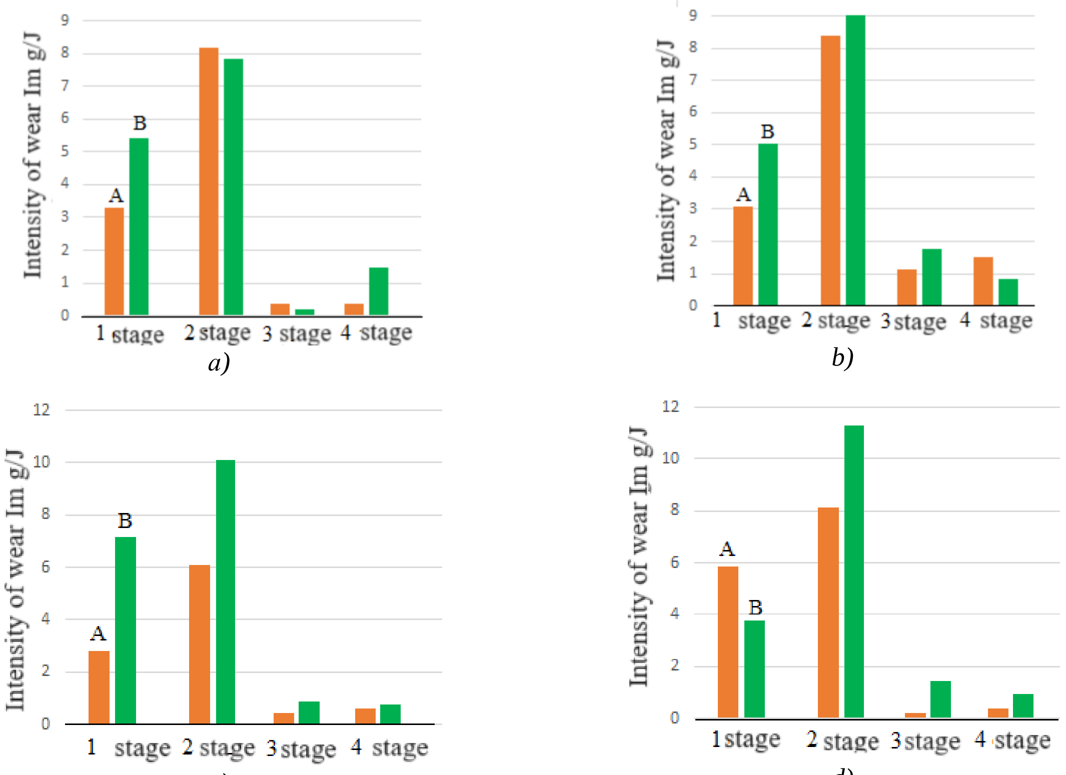
- the minimum value of friction work A_{tmin} =3140.9 J was for the coating formed by the plasma spray method with a yttrium concentration of 0.1%, the maximum value A_{tmax}=6074.7 J was for the coating formed by the thermal spray method without yttrium.

Based on the above, the limiting values of stability according to the parameters of expressions (2,3) were as follows:

- minimum resistance corresponds to the maximum energy conditional wear intensity $I_{mu}=2.64\cdot10^{-5}$ $g\cdot J^{-1;}$
- maximum resistance corresponds to the minimum energy conditional wear intensity $I_{mu}=2.15\cdot10^{-5}$ $g\cdot J^{-1}$.

Thus, in comparison with the ultimate limits of stability relative to the original coatings, it is clear that the range of stability of the coatings after exposure to high-temperature loading narrowed by almost 32.5 times. And compared to the resistance range that occurred at the previous stage, the range narrowed by 15.8 times. This indicates a significant influence of the high-temperature loading factor on the formation of fracture resistance when forming the insertion tracks.

At the same time, after repeated high-temperature loading, the resistance for coatings obtained by the thermal spray method with the addition of yttrium decreased by an average of 1.5 times, and without yttrium remained almost unchanged (Table 4). The coating with a yttrium concentration of 0.5% was more resistant. For coatings formed by the thermal spray method, the picture is the opposite, the resistance increased for coatings with yttrium by an average of 1.25 times. Coatings with a yttrium concentration of 0.5% had greater resistance (Table 4). The general picture of the trends in the energy intensity of wear of the experimental coatings is shown in Figure 5.



a)

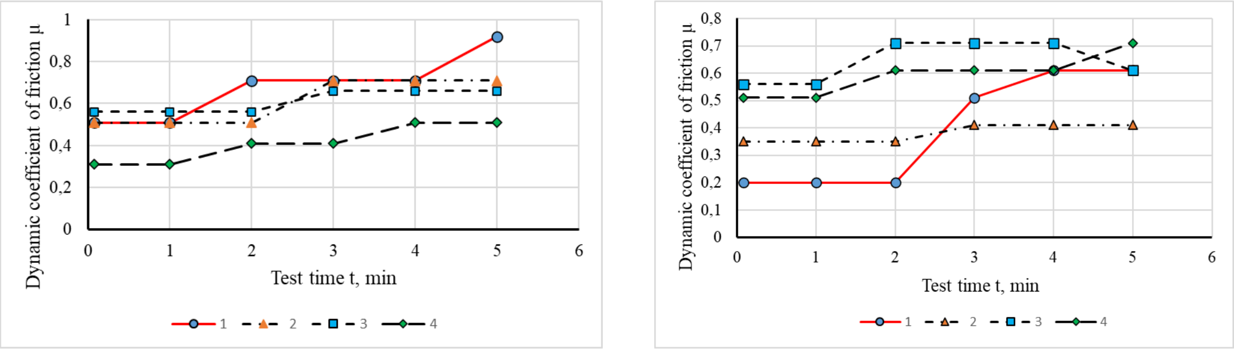
b)

c)

d)

Fig. 5. Diagrams of ratios of wear intensities $Im\cdot10^{-5}$ of coating materials by stages of research: A - coating formed by the thermal spray method; B - coating formed by the plasma method; a) without yttrium; b) yttrium 0.1%; c) yttrium 0.3%; d) yttrium 0.5%.

The character of the friction coefficient for coatings, Fig 6, indicates the following. The general picture of the mechanical behavior of coatings, which was described for the identified typological condition at stage 4, is preserved. The exception is due to the change in some numerous values of the friction coefficient and the pattern of its manifestation over the test time, which is caused, firstly, by the temperature of the interaction medium, and secondly, by an increase in load, almost 1.8 times.



a) *b)*

Fig. 6. Dependence of the dynamic coefficient of friction on the time of tribotechnical testing of coatings at $T = 950$-1020°C after exposure to the furnace: a) at thermal spray forming; b) at plasma spray forming; 1 - initial coating; 2 - yttrium 0.1%; 3 - yttrium 0.3%; 4 - yttrium 0.5%.

For all yttrium-containing gas-flame coatings, there is an increase in the friction coefficient over the test time, which indicates an increase in the resistance to movement and the manifestation of gradients in the mechanical properties of their near-surface layers. For all yttrium-containing ion-plasma coatings, a decrease in the friction coefficient by 1.3-2.6 times is observed, indicating an additional formation of surface structures capable of exerting less resistance to movement.

Table 6. Evaluation of coatings after exposure to static high-temperature environment.

Formation method	Parameter	Number of points min→max stability			
		1	2	3	4
Thermal spray	I_m	0.1	**0.3**	0.5	0
	μ	0	**0.3**	0.1	0.5
Plasma spray	I_m	0	0.5	**0.1**	0.3
	μ	0.3	0.5	**0.1**	0

From the data in Table 6, it should be assumed that the coating formed by the thermal spray method has a parameter coincidence of 2 points with yttrium concentration of 0.3%, i.e., it has an average score. Based on this, this coating has an average resistance to mechanical fracture when forming the cut-in tracks. For the coating formed by the plasma spray method, there is a coincidence of parameters in terms of the number of points, which is equal to 3 with yttrium concentration of 0.1%, i.e., it also has an average score, but higher than the gas flame coating.

4. Conclusion

The results of the four-stage experiment indicate the importance of taking into account the influence of various factors on the mechanical resistance of coatings. The first stage of the study showed that the effect of yttrium content, high-temperature, and coating formation method on their resistance to mechanical fracture is ambiguous. A decrease in resistance is observed when using the plasma spray method compared to the thermal spray method, when there is no temperature load. The second stage confirmed that the coatings obtained by the thermal spray method have the maximum resistance to mechanical fracture compared to other methods, but their properties can change after heating. The third stage indicates an increase in the stability of coatings after exposure to high-temperature loading in a furnace, regardless of yttrium concentration, but a narrowing of the stability range after such exposure is observed. At the fourth stage, it was confirmed that high-temperature loading significantly affects the mechanical stability of coatings, and the addition of yttrium can affect their stability, depending on the method of coating formation and its concentration.

In conclusion, high-temperature loading has a significant impact on the mechanical resistance of coatings, and this factor should be taken into account when using them in appropriate conditions. The addition of yttrium can be useful for improving resistance, but the effect of this element depends on the method of coating formation and its concentration. Thus, the optimal choice of coating formation parameters can only be made based on a comprehensive analysis of all these factors. To confirm the results, further studies of the microstructure and phase composition of the coatings will be carried out.

Conflict of interest statement
The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRediT author statement
Kubich V.: supervision, conceptualization, methodology; **Fasol Ye.:** investigation, data curation, software; **Cherneta O.**: validation, writing - review & editing; visualization; Yershina A.K., Sakipov N.Z.: formal analysis, writing-original draft.
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AUTHORS' INFORMATION

Kubich, Vadim Ivanovich – PhD, Associate Professor, Department of Automobiles National University «Zaporizhzhia Polytechnic», Zaporizhzhia, Ukraine, 69063, Scopus Author ID 57203875007; https://orcid.org/0000-0001-6230-9263; schmirung@gmail.com

Fasol, Yelyzaveta Oleksandrivna – Master, Senior Lecturer, Department of Physical Materials Science, National University «Zaporizhzhia Polytechnic», Zaporizhzhia, Ukraine, 69063, Scopus Author ID: 57221413434; https://orcid.org/0000-0003-4846-9046; selvluna@gmail.com

Cherneta, Oleg Georgievich - PhD, Associate Professor, Associate Professor, Department of automobiles and automotive industry, Dniprovsky State Technical University, Kamenske, Ukraine, 51918, Scopus Author ID: 57203871112; https://orcid.org/0000-0002-3871-6923; OCherneta@gmail.com

Yershina, Ainagul Kappasovna - Doctor of Phys. and Math. Sciences, Professor, Kazakh National Women's Teacher Training University, Almaty, Kazakhstan; Scopus Author ID: 55849381800; https://orcid.org/0000-0002-6811-3904; 123ainakul.yershina@gmail.com

Sakipov, Nurlan Zarkeshovich – Candidate of Phys. and Math. Sciences, Associate Professor, Civil Aviation Academy, Almaty, Kazakhstan; Scopus Author ID:6505664666; https://orcid.org/0000-0001-9853-2491; nsakipov@mail.ru