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Features of Studying Coating Strength and Methods Increasing Its Indicators with Plasma Spraying Working Bodies of Gas Turbine Engines and Plants

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The current level of development of technology requires an increase in the speed of machines and mechanisms, a corresponding improvement in the durability of wear resistance of industrial mechanisms, an increase due to this service life of machine parts. An economic and technical alternative to expanding the production of spare parts for existing mechanical objects is the reuse of worn-out parts restored during the repair of units A set of issues related to the strength of coatings made with the use of plasma spraying in terms of studying the quality of the coating using both well-known techniques and using new developments of technical means of research is considered. Methods of ensuring the strength (adhesion) of coatings and methods of their control with the development of new versions of powder materials that provide the required quality of the protective layer are analysed. Particular attention is paid to the strength of the coating under thermal loads and overloads typical for the operation of gas turbine engines and installations. The stress state of the coating is described based on the developed mathematical modelling. Some directions of further development of the method of plasma spraying are presented, while impulse effects on the technological process of spraying are noted.

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Key words: turbine engines and plants, plasma spraying, strength of coatings, microstructure.

Сучасний рівень розвитку техніки вимагає збільшення кількости швидкісних машин і механізмів, відповідного підвищення довговічности зносостійкости промислових механізмів, збільшення терміну служби деталів цих машин. Економічно-технічною альтернативою розширенню виробництва запчастин для наявних механічних об'єктів є повторне використання зношених деталів, відновлених під час ремонту аґреґатів. Розглянуто вивчення якості покриття як за відомими методиками, так і з використанням нових розробок технічних засобів дослідження. Проаналізовано методи забезпечення міцности (адгезії) покриттів та методи їх контролю з розробкою нових варіянтів порошкових матеріялів, що забезпечують необхідну якість захисного шару. Особлива увага приділяється міцності покриття при теплових навантаженнях і перевантаженнях, характерних для роботи газотурбінних двигунів і установок. На основі розробленого математичного моделювання описано напружений стан покриття. Наведено деякі напрямки подальшого розвитку методи плазмового напорошення, а також відзначено імпульсні впливи на технологічний процес напорошення.

Ключові слова: турбінні двигуни й установки, плазмове напорошення, міцність покриттів, мікроструктура.

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1. INTRODUCTION

The widespread use of gas turbine engines and installations, in particular in shipbuilding and the operation of ships and ships, predetermines the need to restore and strengthen one of the most worn-out units—blades. This need arises, inter alia, from the conditions of their operation, under which they are exposed to high dynamic loads and temperatures. Plasma spraying, which is widely used in mechanical engineering for coating and which can be implemented both in a controlled atmosphere and in a normal environment using a different composition of sprayed materials, modes of different constructions of installations, *etc*. [3–5]. It can be noted that one of the main tasks that are solved when choosing a spraying algorithm is obtaining a durable sprayed layer or several layers, which make it possible to obtain coatings for various functional purposes of sufficiently good quality, while developing high productivity and can work effectively in the above practically extreme conditions.

Here is already sufficient experience in the use of plasma spraying technologies in various industries. However, there are problems that ultimately reduce the service properties of products with such coatings, including adhesion strength [6]. Some of these problems need to be solved to select the optimal method of coating equipment and the material used for use in restoration processes (during repair work, and in some cases routine maintenance with selective use of plasma spraying) and parts hardening.

Based on this, it can be concluded that further research is necessary to achieve the goal set—to improve the quality of products manufactured using plasma spraying coatings.

The purpose of this work is to further study the properties of coatings obtained by plasma spraying with the subsequent selection of conditions, materials for operating modes, new technical developments for effective solutions that provide strength (adhesion) and other characteristics that determine it when creating a coating for units and parts of gas turbine equipment.

2. EXPERIMENTAL

The criteria for assessing the surface condition of units and parts of gas turbine engines and installations subject to wear are a set of parameters: relative wear resistance, magnitude of permanent plastic deformation, degree of wear or corrosion, hardness and nanohardness—a structurally sensitive characteristic that allows obtaining information on the state of a thin surface layer.

Consideration of the problem of ensuring the strength of coatings made with a plasma flow should be carried out in several directions, the aspects of which can be rather conditionally divided into the following main groups:

– the strength of the coatings when tested for separation;

– study of thermal stability of coatings as one of the components of the strength of the sprayed layer;

– study of the stress–strain state of plasma coatings in terms of its effect on strength.

When performing a complex of studies, one should rely on two aspects: technical (new design of the installation) and technological (new compositions of materials and modes of coatings for their different thicknesses).

Such a comparative pull-off test of the coating for a number of samples was carried out by pulling the pins on a specially designed installation, which is schematically shown in Fig. 1. Let us consider the developed design of the installation, which is quite simple and effective for comparative tests.

On the metal plate *18* there are four racks *17*, on which the upper plate is fixed *16*. On the plate there are two cylindrical guides *11* along which the carriage *12* moves 'up and down' are connected by a terminal *10* with a plunger *9* of an electric motor *8*. Terminals *7* the electric motor is fixed with a torque ring *3* The diametrically located end of this ring is screwed into the transverse bar *1*, mounted on two posts *2*. The bar *6* serves as a guide for the cylindrical part of the terminal *7*. Bracket *4* is screwed into the upper bar *1*, on which the watch sample indicator *5* is installed to determine the deformation of the ring *3*.

The front panel with switching devices (shown in Fig. 1), as well as the side covers *19* are fastened to the racks *17* with screws. Electrical parts of the installation are mounted between the upper *16* and the lower plate *18*, the power supply elements *22*, *23*, mounted on the bushing *20* and fastening with the screw *21* to the plate *18*. Flange nut *15* is fixed on the top plate with screws *16*.

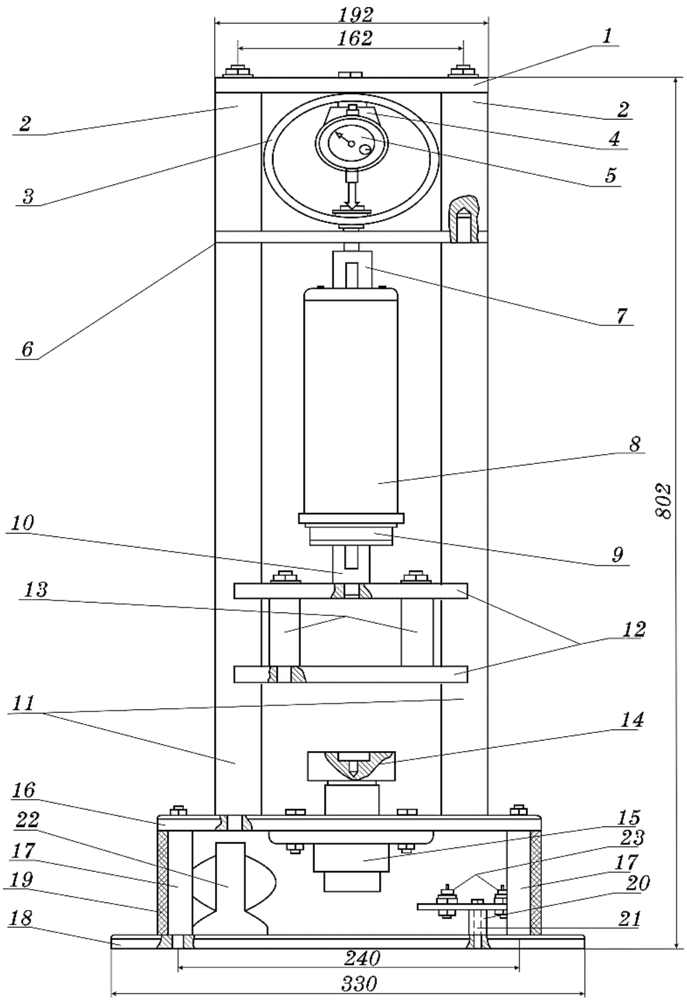


Fig. 1. Plant for determining the strength of the coating (schematic representation).

The test sample is installed between the screw *14* and the movable carriage *12*. Depending on the type of the test sample, the carriage *12* moves up or down. The electrical diagram of the installation is powered from an alternating current network (220 V) and is a complete control system for a valve electric motor with computerized regulation of the frequency of rotation of the shaft of the electric motor and gearless transmission of movement to the carriage.

The unit controls and status signalling are located on the power and control unit. The control system and the converter of the electric motor of the installation have the ability to program the frequency of rotation of the shaft of the electric motor, therefore, the movement of the carriage with a fairly wide range of frequencies (up to 60 Hz) and duty cycle and amplitude. In this case, the following types of movement are possible: smooth, impulse movement. Such possibilities of carriage movement make it possible to simulate real loads acting on the coating and thereby, for the first time in the technique of such studies, bring the conditions for measuring strength characteristics closer to the real operating conditions of installations when performing coatings.

It can be noted that the permanent magnet motor used in the installation ensures the positioning accuracy of the carriage, which is important in determining the accuracy of obtaining results at any stage of movement [7].

Before carrying out research on the installation, it is necessary to calibrate it, *i.e.*, determine the number of indicator divisions for various values of the load when stretching or squeezing the torque ring. The calibration of the torque ring with the parts attached to it was carried out on a laboratory-type hydraulic press. The readings of the pressure gauge of the hydraulic press were listed in the forces generated by the press. Since the traction capacity of the engine of the installation has certain characteristics, the dynamometric ring, which is made of 50Kh2FZA steel, was calculated accordingly.

The deviation of the indicator arrow by one division (sensitivity) corresponded to 0.6…0.7 kg. When unloading the press, the final deformations of the torque ring were practically not observed.

To determine the strength of the coating material by pulling the pin, special samples are prepared, a schematic representation of which is shown in Fig. 2.

Sample (*a*) has a sprayed layer *1* on the end surface of the sleeve *2*, into which the pin *3* is inserted. The pin is fixed in the bushing by the screw *5*, so that the ends of the bushing and the pin are in the same plane. The threaded pin C is attached to the table *6*, the movable carriage *4*, moving upwards, separates the sleeve *2* from the pin *3*. The principal difference between the sample (*b*) is that the pin does not have a cylindrical part after the tapered one. The latter is the centre

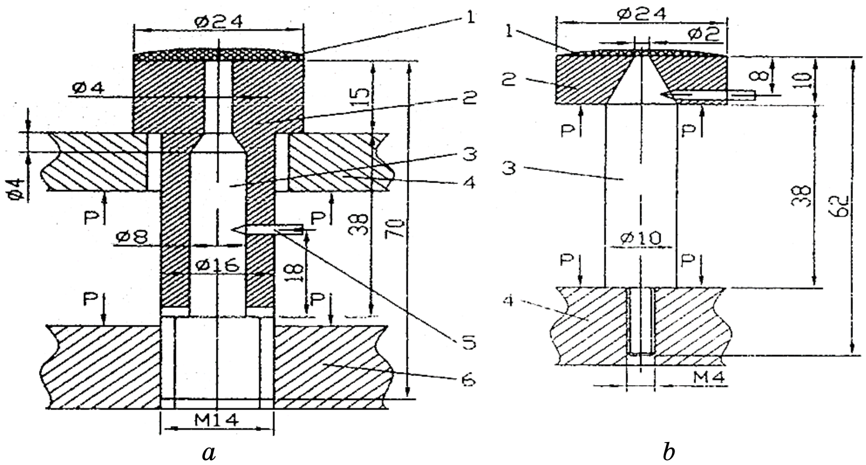


Fig. 2. Samples for material adhesion strength coating.

surface of the pin *3* relative to the sleeve *2*.

The sprayed sample is installed or fixed (depending on the type of sample) on the table of the device *14*. The second end is fixed in a movable carriage *12*. Adjustment with a screw *14* makes it possible to install samples of different lengths. The control system turns on. On the front panel of the power supply and control unit, a command to move the carriage is selected.

Restrictions on the movement of the carriage down-up are carried out by contactless limit switches or, in more advanced versions, by counting the pulses of an incremental encoder of a permanent magnet motor. The test samples are installed in the installation and the movement of the carriage according to a given algorithm is carried out by the separation of the coating from the base.

TABLE 1. Results of studies of coating strength.

No.	Coating material	Coating thickness, mm	Coating area, mm^2	Breaking load, kN		Bond strength, MPa	
				Common	Pulse	Normal driving	Impulsive driving
1	BrOF 10-7	1.4	48.3	1.5	1.2	31.0	24.8
2	BrA 10	1.1	48.3	1.8	1.4	37.3	28.9
3	BrOF 8.5-3	1.2	48.3	1.0	0.8	20.7	16.6
4	BrOF 10-1	1.2	48.3	1.6	1.3	33.1	26.9
5	PG-10K-01	0.8	48.3	2.5	2.2	51.8	45.5

In Table 1, for example, some results of studies of the peel strength of bronze coatings with various alloying and various methods of tensile effects are given, as well as for comparison of the coating. The separation mode was used with the establishment of an appropriate program for the electric motor control system with a frequency of about 25 Hz and an action step of 0.1 mm.

It should be noted that in Table 1 the breaking load is shown as the limit value of the tensile force at the moment of the separation of the sprayed layer from the substrate. The result was averaged over three dimensions and can be used as a criterion that takes into account both static and partially dynamic aspects of strength.

Note that the tensile force was measured in two ways: using a spring dynamometer and using strain gauges with electronic signal processing.

3. RESULTS AND DISCUSSION

The tendencies of a decrease in the adhesion of the sprayed layer to the base under pulsed action are also traced for other types of coatings and are often so significant that they must be taken into account when choosing materials for plasma spraying, since pulsed and pulsating loads are characteristic of the operation of the working bodies of gas turbine engines and installations.

It is important that with an increase in the adhesion strength of the sprayed layer, the relative values of the destructive force under impulse action decrease.

We believe that the value of the breaking load can be used as a criterion for the limiting state of the deposited layer, which takes into account both static and dynamic aspects of strength.

This type of study of the strength of a coating obtained by plasma spraying is shown in sufficient detail in our work [8]. The following results concerning strength problems should be noted and clarified here, while emphasizing that the strength of the coating was determined by shear tests.

The results of tests for thermal cyclic stability of sealing coatings in laboratory conditions showed that delamination occurs along the lining-coating interface, which posed the problem of optimizing the layer-by-layer composition of seals sprayed in air and in vacuum.

To select a promising layer-by-layer composition, an assessment of thermal cyclic stability was used. The thermal cyclic stability was evaluated under severe conditions (thermal shock). For this purpose, the sealing coatings were applied in air and in vacuum on plates made of a heat-resistant alloy ChS-70 with dimensions of $40 \times 40 \times 3$ mm. The ends of the plates were ground to reveal the ‘substrate–coating’ boundary and placed in a special container (5 pcs) At a distance of 20 mm. The coated plates were heated in an SMOL-1,6.2.5.1/9-114 electric muffle furnace to 900°C, and cooled in running water at a temperature of 20°C. All coatings sprayed with plasma were heat treated in vacuum at a temperature of 1070°C for two hours. Layer-by-layer composition, spraying conditions, adhesion strength and the number of thermal cycles before the destruction of coatings are shown in table 2. For this type of research, the most rational is to determine the strength during shear tests. Plasma spraying of sealing coatings was carried out on an UPU-3D unit at the following modes: current I, A—250...300; voltage U, V—80...108; flow rate argon flow rate Q (Ar), l/min—20...30. A series of experiments showed that a sealing coating based on PG-10K-01 with solid lubricant additives has maximum thermal cyclic stability and shear strength indicators when applying a sublayer with PG-10K-01 0.1 mm thick in vacuum, regardless of the composition and spraying conditions.

Corrosion and thermal cycling tests were carried out on natural samples-inserts of the best research sealing coatings according to Table 3 on the gas-dynamic stand [9]. For this, the inserts were additionally machined on an electric discharge machine in order to deepen the working surface for applying a plasma sealing coating. We prepared two inserts with cells and three without them. The deepening of the working surface was 1.8...2.0 mm. The residual depth of the cells is about 1 mm. The inserts were degreased and sandblasted before sputtering. The residual depth of the cells is about 1 mm.

After spraying, the inserts were heat treated in vacuum at 1050°C for 1.5 h. The general view of the inserts made of sprayed sealing coatings is shown in Fig. 3. Tests were carried out on inserts with coatings, the composition of which is given in the Table 2. Inserts with sealing coatings were welded to the cassette (Fig. 4). For comparison, an insert (with a hole) with a focal seal was installed. Heating was carried out with a high-temperature gas flow of combustion products, simulating

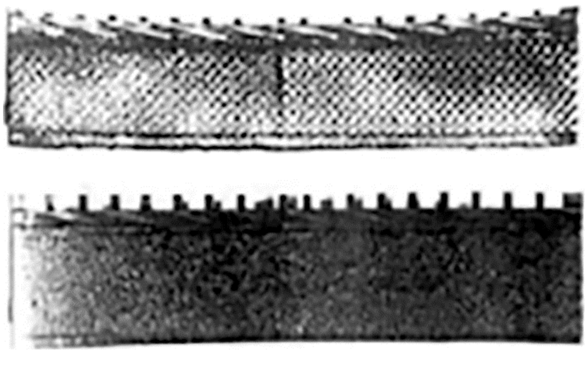


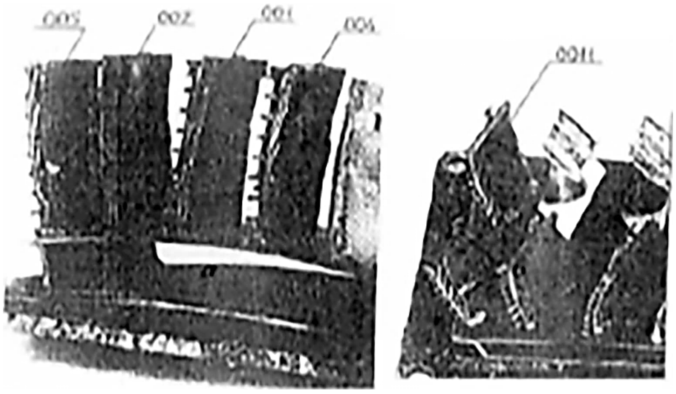
Fig. 3. Inserts 004, 005 with sealing coatings after plasma spraying.

TABLE 2. Bond strength and thermal cycling test results sealing covers.

Coating composition	Thickness, mm	Spraying conditions	Shear bond strength, MPa	The number of thermal cycles before destruction	The nature of the destruction
PG-10K-01	0.1	Air	310	142	Complete exfoliation
PG-10K 01 + 20% C(Ni)	1.9	Air	310	142	
PG-10K-01	0.1	Vacuum	350	151	Partial exfoliation
PG-10K-01 + + 20% C(Ni)	1.9	Vacuum	350	151	
PG-10K-01 + + 20% C(Ni)	2.0	Air	110	42	Complete exfoliation
PG-10K-01 + + 20% C(Ni)	2.0	Vacuum	150	83	Partial exfoliation
PG-10K-01	0.1	Air	310	37	Complete exfoliation
PG-10K-01 + + 20% BN(Ni)	1.9	Air	310	37	
PG-10K-01PG-10K-01 + 20% BN(Ni)	0.1 1.9	Vacuum	345 345	113 113	Partial exfoliation
PG-10K-01	0.1	Vacuum	350	102	Partial exfoliation
PG-10K-01 + + 20% BN(Ni)	1.9	Air	350	102	
PG-10K-01	0.1	Air	305	15	Partial exfoliation
PG-10K-01 + + 20% ZrO_2(Ni)	0.4	Air	305	15	
PG-10K-01 + + 20% BN(Ni)	1.8	Air	305	15	
PG-10K-01	0.1	Vacuum	350	145	Partial exfoliation
PG-10K-01 + + 20% ZrO_2(Ni)	0.4	Air	350	145	
PG-10K-01 + + 20% BN(Ni)	1.8	Air	350	145	

the operation of a gas turbine unit. In this case, the sprayed surfaces were located at an angle of approximately 45° to the direction of the flow. An increase in the temperature of the inserts from 80°C to 1050°C occurred in 30°C, holding at 30°C. Cooling to 80°C was carried out by blowing cold air for 2 min. After 1000 cycles, the parts were inspected.

The coating of insert No. 004 collapsed over an area of about 40%. This is due to the low bond strength resulting in swelling and loosening. An insert with a round through hole in the upper part (see Fig. 3)



a *b*

Fig. 4. General view of the cassette with inserts: *a*—side view, *b*—top view.

with UM-16P filler, used in production, contains small (100...300 μm) pores over the entire surface, which may be caused by melting or burnout or blowing out of one from components. After inspection, the cassette with inserts was heated to a temperature of 1000°C. Then, during isothermal holding, about 3 cm^3 of salt, close to the composition of sea water, was supplied to the fuel in 1 min. In this way, the work of parts was simulated as close as possible to real conditions. After 38 hours of testing, a control inspection of the inserts showed the robust resistance of all research coatings to salt corrosion, which successfully showed resistance to thermal cycling. The colour change of the coatings should be noted. Perhaps this is due to the appearance of salt compounds with fuel components on the fly at high temperatures.

After the control examination, the tests for 'burning' were resumed, then, after the end of 200 hours of operating time, the tests were continued in the thermal cycling mode in the above mode. The total number of cycles increased to 2000.

As a result of tests, it was established that two versions of the developed seals PG-10K-01 + 20% C (Ni) and PG 10K-01 + 20% BN (Ni) with corrosion-erosion and thermal resistance are superior to the serial focal (honeycomb) seals with serial filler UM-16P.

In order to assess the resistance to thermal cycles of plasma coatings, studies were carried out on a specially designed installation (Fig. 5).

Heating was carried out by electric current up to 1000°C in 30 seconds, exposure—30 seconds, cooling to ambient temperature in 60 seconds.

When the sample temperature reaches 1000°C, which is controlled by a chromel-alumel thermocouple and an SH4501 millivoltmeter, a cut-off device and a counter are triggered. Time relay 'Interval' turns

TABLE 3. Composition of coating sprayed onto inserts.

Insert number	The composition of the working layer is about 2 mm	Notes
001*	PG-10K-01 + 10% C(Ni)	Smooth surface melted by an electron beam(rows) Sputtering with delamination in several places
0011	PG-10K-01 + 20% C(Ni)	Foci with two times less than in the original compaction Coverage without significant remarks
002*	PG-10K-01 + 20% BN(Ni)	Smooth surface melted by an electron beam(rows) Spraying without comments
004	C(Ni) + 10% Si	Vacuum spraying Destruction of coatings
005	PG-10K-01 + 20% BN(Ni)	Smooth surface melted by an electron beam(rows) Sputtering with delamination in several places

on the compressor, which cools the sample with compressed air; after the compressor is turned off, the power supply starter is activated and the cycle repeats.

The content of graphite (C) boron nitride (BN) in the inserts after the tests described above was determined by the method of quantitative x-ray phase analysis on a DR0N-3 device in the diffractogram recording mode. As a result, it was found that after testing, traces of BN were found in the seals at a depth of 0.2...1.0 mm. Traces C were found at a depth of 0.8...1.0 mm. This is due to the burnout of the solid lubricant during testing, which is facilitated by porosity, which reaches 10%. Investigation of the distribution of C, Ni and Cr (sample 0011) carried out on an electrode probe microanalyzer Superproba 733 from Jol (Japan) (Fig. 6) showed that near the boundary between the sublayer and the working layer, the coating contains a certain concentration of C (Ni), which affects the strength cover.

Investigation of the microstructure of the sealing coatings was carried out on a metallographic microscope on non-etched samples. Figure 7 shows the microstructure of sealing coatings after corrosion and thermal cycling tests.

On microsections, light areas (~30%) have a comparatively low microhardness with a slight scatter of values. Gray areas (~40%) have a high, with significant scatter, microhardness. They contain borides

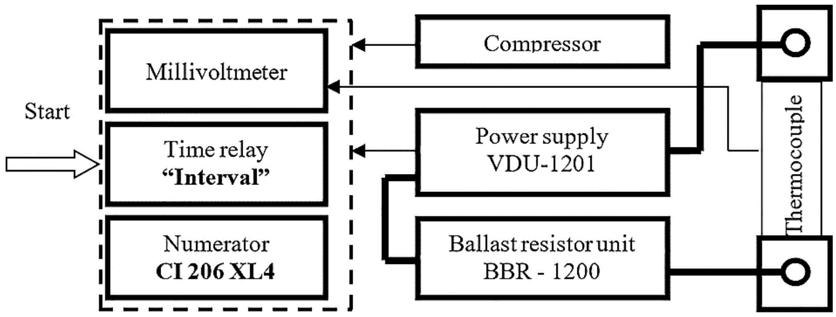


Fig. 5. Block diagram of the installation for determining the resistance coatings to heat changes per sample.

and other strengthening phases. There are about 30% of dark areas that can be identified as pores.

The study of the composition and structure of porous formations in sealing coatings is of no small importance, since they provide wear resistance during operation.

When carrying out metallographic studies, an assumption arose about the concentration of solid lubricants in the 'porous formations' of sealing coatings. The formation of pores in sealing coatings occurs both during their production and during operation as the solid lubricant (C or BN) burns out.

For a more detailed study of the structure of the seal formations, studies were carried out on a scanning electron microscope REM-100u as a result of studies by the RES method in the pores of PG-10K-01 +

Fig. 6. Distribution of carbon, chromium and nickel in coating PG-10K-01 + + 20% C (Ni).

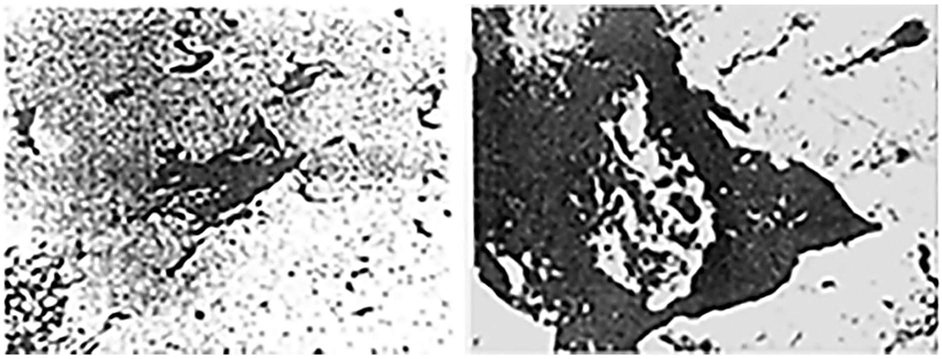


Fig. 7. Microstructure of the coating PG-10K-01 + 20% C (Ni) (simple 0011) after tests.

+ 20% C (Ni). Individual particles with a size of 30...50 microns were found. Judging by the morphology of these particles and in comparison, with the data of studies of the morphology of the powders, it can be concluded that they are C and Ni particles.

After thermal cycling, the microhardness of the coating increased significantly, especially in the coating with PG-10K-01 + 20% BN (Ni), while the industrial coating UM-16P after thermal cycling has significant porosity. In the process of microanalysis, a network of small cracks is observed at the boundary of this coating applied to inserts with cells and the substrate.

The XPS study of porous formations in large pores of sealing coatings made it possible to detect solid lubricant particles C, C (Ni), BN (Ni) in them. A microanalysis of the PG-10K-01 + 20% C (Ni) seal, deposited in a dynamic vacuum on the UPNKA installation, followed by heat treatment in vacuum at 1050°C for 1.5 hours was carried out. It contains two structural components—light and dark (15...20%). The microhardness of the light component is 6581 MPa (average value), the range of values is from 4120 to 9270 MPa.

For comparison, a coating made of PG-10K-01, sprayed and heat-treated in vacuum, was examined. In the latter, the presence of small dark areas is less than 2%. In PG-10K-01 + C (N) dark areas of large and small sizes are recorded. Microhardness of PG-10K-01 is 8630 MPa (average value). The range of values is from 7660 to 9270 MPa. A wider range of microhardness spread in the first case is explained by the presence of solid lubricant. The presence of a large number of dark areas, even in comparison with samples 0011, 005 after thermal cycling, is explained by the fact that the solid component of the lubricant practically does not burn out during spraying and heat treatment in vacuum. This is confirmed by the fact that in the coating with PG-10K-01 + C (Ni) after spraying and heat treatment in vacuum, quantitative x-ray phase analysis on a DRON-3 device revealed 4.8% graphite.

The performed complex with metallographic comparative studies of the effect of thermal effects on the strength characteristics of coatings indicates the advisability of choosing the composition of new coatings.

The resulting stresses can lead to a deterioration in the performance characteristics of the product: strength, wear resistance, heat resistance and lead to the formation of cracks, therefore, the study of the stress state during heating–cooling of samples with sprayed coatings and the establishment of quantitative dependences of the stress level on the coating thickness and material properties is theoretical and practical.

In [10], this topic is considered quite broadly, and in this material, we will focus on some individual and specific refinements and results for application in technological practice. Moreover, these studies complement the results already obtained and described above. We emphasize once again that the criterion of thermal stability of a layer sprayed by plasma is the condition of the coating after testing, in particular, the absence of cracks and delamination from the substrate.

In this case, as a rule, the influence of individual parameters, such as the ratio of coating thicknesses and substrate, their stiffness (elastic modulus), coefficient of linear thermal expansion (CTE), the presence of initial stresses, *etc.* [11]. The studies were carried out by the method of computer modelling based on the finite element method (FE) using the ANSYS software package. We studied samples of the flat plate type, which were used in tests for thermal resistance with a coating applied to the surface with an analysis of fields and stress plots with an increase in temperature by ΔT 100 deg and with the characteristics of two compared options presented in Table 4.

The resistance of the coating to destruction is greatly influenced by thermal stresses arising as a result of the difference in the coefficients of linear thermal expansion (CTE) of the substrate and the sprayed layer, temperature changes both during the manufacturing process (coating and heat treatment) and the work of the part. Analysis of the fields of longitudinal, transverse and tangential stresses showed that their nature is practically the same in both versions of the studied nodes and for all thickness ratios.

TABLE 4. Dimensions and physical and mechanical properties accepted in modelling.

Layer	Thickness a_i, mm	Elastic modulus E_i, MPa		CTE α_i, 1/deg
		Variant 1	Variant 2	
Substrate	1.0 and 2.0 mm	$2\cdot10^5$	$2\cdot10^5$	$12\cdot10^{-6}$
Coating	From 0.1 to 1.0 mm	$0.5\cdot10^5$	$3\cdot10^5$	$5\cdot10^{-6}$

In most of the study of the node, the longitudinal stresses remain constant and only near the end, at a distance equal to the thickness, begin to decrease noticeably. This corresponds to the general principles of mechanics and suggests that for most of the length of the sample in its middle part, the cross sections remain flat, curving only near the ends. This is confirmed by the fields of transverse and tangential stresses. For most of their length, they are close to zero, and appear and grow only near the ends, reaching a maximum on the lateral surface. In this case, the maximum shear stresses are concentrated at the coating-substrate interface.

Analysis of fields and diagrams shows that the maximum (in absolute value) values of longitudinal stresses are opposite in sign. When heated, the maximum longitudinal compressive stresses arise in the substrate material, and the maximum tensile stresses in the sprayed layer at the interface. In this case, the lateral stresses are concentrated on the end surfaces. Shear stresses are concentrated at the interface between the layers.

The level of all stresses both in the substrate material and in the sprayed layer depends significantly on the rigidity (elastic modulus) of the sprayed layer material. Thus, the maximum longitudinal stresses in the substrate increase from −25 MPa to −70 MPa. In the sprayed layer, the maximum of these stresses at the interface also increases from 29 to 100 MPa.

To assess the adequacy, the results of computer simulation of stresses in the coated specimens were compared with the analytical solution according to the method described in [12], which is based on the hypothesis of flat sections.

Comparison of the results of analytical calculations and computer simulation showed that the level of longitudinal stresses at any point at the same stiffness of the materials of the substrate and the sprayed layer depend only on the ratio of the layer thicknesses (a_1/a_2), remaining unchanged with a proportional change in thicknesses. The results of calculations and modelling of longitudinal stresses completely coincided (Fig. 8). The same results for other types of stress.

The most probable area of crack initiation in the sprayed layer upon heating is the interface. In this case, the best from the point of view of reducing the tensile longitudinal stresses in the sprayed coating and increasing its heat resistance is the ratio of the thicknesses a_1/a_2 more than 0.5.

Computer modelling, in full coincidence with the results of the analytical calculation of longitudinal stresses, at the same time allows, in contrast to the latter, to determine the transverse and tangential stresses in the sections of curved sections.

It is in these areas, as shown by the simulation results, that favourable conditions are created for the formation of cracks in the brittle ma-

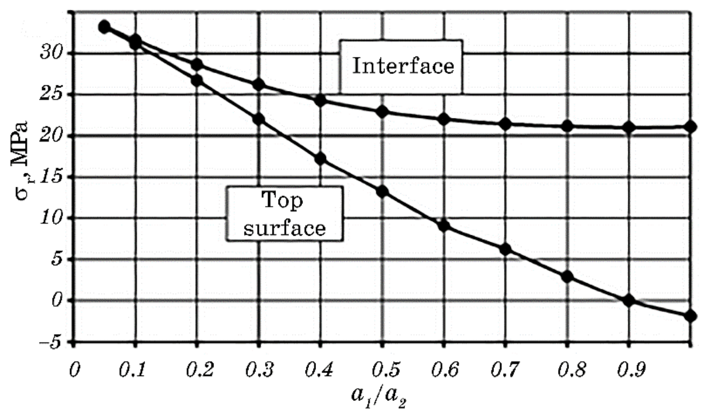


Fig. 8. Dependence of longitudinal stresses on the ratio of layer thicknesses a_1/a_2 in the coating upon heating 100°C.

terial of the sprayed layer, since tensile transverse stresses at the stage of decreasing temperature are commensurate with the longitudinal ones in the middle part of the sample at the heating stage.

In addition, large shear stresses at the interface in these areas create the danger of delamination of the sprayed layer.

However, when wear-resistant alloys are used for spraying that provide sufficient wear resistance of restored parts, there is a problem of technological strength covered with multilayer spraying, its thickness variation, as well as deformation of parts caused by the effect of a plasma jet. Therefore, new problems arise that require finding solutions.

To solve existing problems with plasma spraying, it is necessary:

– improvement of the technology of plasma spraying of coatings while expanding the range of sprayed parts;

– an increase in the range of used powder materials with in order to expand the operational properties of the plasma coating;

– increasing the reliability and service life of electric arc plasma torches, powder dispensers, chambers for spraying and abrasive processing;

– increasing the reliability and efficiency of water and gas supply systems for plasma installations;

– the creation of new methods, reasonable modes and technological processes is required, ensuring the receipt of parts with the required performance;

– optimization of the modes of the plasma spraying process;

– development, research and implementation of a technology for applying a wear-resistant plasma coating for a specific unit, part of a gas turbine engine or installation;

– development of a layout diagram of a plasma spraying unit that implements the developed technology for applying a wear-resistant coating.

One of the universal ways to improve the quality of the sprayed layer is the use of pulse technologies for the operation of equipment systems for coating. It should be noted the development of equipment for plasma spraying based on electrical solutions using processes of dynamization of processes, for example, modulation of electrical parameters, in particular, the use of additional current pulses together with the main power supply of the plasmatron [13], which makes it possible to regulate the electrical characteristics of the plasmatron, and thereby quite effectively influence the quality of the sprayed coating and increase the energy utilization factor. The adhesion to the substrate is increased and the porosity is reduced. The resulting effect is explained by the action of shock waves on molten powder particles in a modulated plasma jet. Using the results of the use of modulated systems in controlling the operation of the plasmatron, we have developed in an experimental form a system that allows organizing the control of the plasmatron operation in a pulsed arc supply mode, containing a controlled mains voltage converter to the arc supply voltage of the inverter type with a computerized control and regulation system. This development allows the formation of plasma arc current pulses of various frequencies with different values of the duty cycle. Tests of this technical solution make it possible to determine that the pulsed arc power supply can influence the coating formation processes.

In addition to the above, we have carried out a cycle of studies that allows to organize a pulsed supply of the sprayed powder in a controlled mode [14]. This allows the development of the feeder described in the work.

The prospect of these new developments is the creation of an automated installation for plasma spraying, in which a new way of functioning of the spraying process is organized due to the organization of feedback between the arc current and the powder feeding device. This will allow, in addition to the above-mentioned problems of increasing strength, to effectively solve such urgent problems today: variability of coating thickness, the presence of porosity (discontinuity) of the coating, low efficiency of the plasma process.

4. CONCLUSIONS

1. The problem of obtaining durable and high-quality coatings obtained by means of plasma spraying is multicomponent, as well as the ways to solve it. It has been determined that the main components of the strength of coatings, in particular for units and parts of gas turbine engines and installations, are tensile strength and shear strength,

thermal cyclic resistance to thermal shock with a large number of thermal cycles, and stress-strain state.

2. From a technological and economic point of view, the process of plasma spraying in a controlled atmosphere can be replaced by plasma spraying in air. In this case, it is advisable to use specially developed, studied and applied in the technological process versions of sprayed coatings PG-10K-01 + 20% C (Ni) and PG-10K-01 + 20% BN (Ni) having high strength with corrosion-erosion and thermal and sustainability.

3. Selected, specially developed and successfully used in the work means and methods for determining the characteristics of plasma spraying provide a sufficient information level for making technical and technological decisions, providing an increase in the quality characteristics of the coating.

4. The further direction of improving the process of obtaining coatings based on plasma spraying, in addition to the already known methods of influencing the characteristics, including the strength (adhesion), should be based on pulse control algorithms for systems of equipment for plasma spraying: controlled pulse changes in energy characteristics and powder injection and wire.

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