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Plasma-chemical synthesis of carbide-based vacuum-plasma functional coatings and study of tribological characteristics of friction pairs

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Abstract. *The work is devoted to the search for new materials with high functional characteristics using the Avinit vacuum-plasma technologies developed by us, based on the complex use of coating methods (plasma-chemical CVD, vacuum-plasma PVD (vacuum-arc, magnetron), processes of ion saturation and ion surface treatment), stimulated by non-equilibrium low-temperature plasma.*
Processes of controlled plasma-chemical synthesis of the formation of multicomponent coatings in "metal-carbon" systems – Avinit coating (TiC, MoC) using vacuum-arc sources of ionized atomic fluxes of titanium and molybdenum in an argon-benzene plasma environment were developed and their characteristics were studied depending on their conditions formation.
Metallographic studies confirm the possibility of low-temperature application of high-quality wear-resistant high-hard "metal-carbon" coatings with a hardness of 18,000–30,000 MPa, while ensuring good adhesion to the substrate materials (steel DIN 1.2379) without reducing strength and without deteriorating the cleanliness class of the original surface.
The conducted tribological tests using the "cube-roller" scheme reveal high tribological characteristics of steel DIN 1.2379 tribopairs with developed coatings and testify to the promisingness of the developed multi-component multilayer coatings Avinit (Ti-C, MoS) for increasing wear resistance and reducing the coefficient of sliding friction in friction nodes.
The developed plasma-chemical vacuum-plasma coatings are applied to mock-up samples of the working compressor blades of the GTE of aircraft engines. Proven modes allow to get high-quality, uniform coatings with high adhesion.
This gives reason to consider the developed process as an alternative for expanding the range of new Avinit vacuum-plasma erosion-resistant coatings and developing structures of anti-friction wear-resistant coatings to increase the performance of friction pairs in "coating-steel" and "coating-coating" systems.

Keywords: *Avinit multi-component multi-layer coatings, plasma chemical synthesis, tribological characteristics, friction, durability.*

1. Introduction

Ever-increasing requirements for increasing the durability of various newly created parts and mechanisms sharply require the search for new materials, surface treatment methods that increase the functional properties of materials. The problem of creating new high-performance materials is especially acute for the most modern branches of mechanical engineering – aircraft construction, aggregate construction, shipbuilding, rocket and space engineering.

The most effective way to meet the often-contradictory requirements for surface properties (high hardness and wear resistance, high anti-friction characteristics) and volumetric properties (high strength and impact toughness) is to create compositions with layer-by-layer placement of materials that perform different functions.

Our main efforts in the field of development and practical implementation of multi-component coatings of various functional purposes to improve the operational characteristics of materials, components and parts of machines are focused on the formation of nano- and micro-layer multi-component coatings as the most promising for achieving the required functional characteristics.

A feature of the coating processes being developed is their complexity: various methods of coating (plasma-chemical CVD, vacuum-plasma PVD (vacuum-arc, magnetron), processes of ion saturation and ion surface treatment) are combined in one technological cycle. The use of

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gas-phase and plasma-chemical methods in combination with other methods of applying coatings and surface modification (methods of ion doping, implantation, vacuum-plasma, diffusion, vacuum-thermal methods, etc.) under conditions of non-equilibrium low-temperature plasma significantly expands the possibilities of creating fundamentally new materials.

The completed set of materials science research and tribological tests [1]–[3] showed high prospects for the use of Avinit multi-component nanolayer coatings based on titanium, molybdenum, aluminum and their compounds with nitrogen in friction nodes.

Improved Avinit coatings based on Ti-Al-N and their production technology have already found industrial application in the production of friction pairs of pumps and regulators of fuel supply units and regulation of aircraft engines to increase wear resistance and reduce the sliding friction coefficient of tribopairs [1]–[3].

Nevertheless, the complexity and complex nature of the requirements for structural materials operating in frictional contact conditions require the constant search for new materials with improved tribotechnical characteristics and the development of technologies for their production.

When choosing materials for friction nodes, their compatibility should be taken into account, first of all, adhesion and subsequent burr, which is related to chemical affinity, closeness of the structure and values of crystal lattice parameters, etc.

So far, no general theory has been created that allows for analytical estimation of friction and wear coefficients for entire classes of materials, for example, for crystalline materials. There are only semi-empirical dependencies of various kinds of individual cases.

In this situation, it is advisable to consider the conditions under which frictional resistance can be minimized, and to select appropriate materials based on them. Particularly promising is the direction based on the self-organization of selected friction pairs – "the material of the part with applied wear-resistant and anti-friction coatings – the counterbody", when the system itself forms the optimal microgeometry of the surfaces, protective films, rebuilds the structure of the surface layers of the metal, depending on the conditions functioning.

High hardness is considered to be the main requirement for the material when the contact surface is subjected to wear.

In production, TiN vacuum-plasma coatings are used to protect the compressor blades of GTEs of aircraft engines.

The paper [13] describes the Avinit vacuum-plasma erosion-resistant hard coatings for the compressor blades of the GTE of aircraft engines, which can, as shown by the test results, increase the stability of the serial compressor blades of the GTE.

At the same time, the expediency of developing new alternative vacuum-plasma erosion-resistant hard nanostructured coatings on a carbide basis with increased microhardness, suitable for increasing the durability of the compressor blades of GTE of aircraft engines, is noted.

As shown by the accumulated experience [1]–[3], as well as extensive experimental material [4]–[7], optimal solutions for the drastic improvement of tribotechnical characteristics, especially for friction pairs, should be sought in the creation of composite coatings, which are multilayer coatings based on metal-like carbides , nitrides, transition metals of the Big Nine (Mo, Nb, Ti, Zr, etc.), as well as oxide and oxygen-free compounds of boron, aluminum, silicon (BN, B_4C, AlN, Al_2O_3, SiC, Si_3N_4, etc.).

From this point of view, functional carbide-based coatings and complex vacuum-plasma technologies for their production are a promising choice for improving the wear behavior of structural materials, since such ceramics have both high hardness and chemical inertness.

Technologies for applying such coatings based on metal-like carbides, nitrides of IV-VI groups of transition metals have become widely used in industrial practice as strengthening, wear-resistant coatings, coatings for reducing friction coefficients and other purposes [7]–[9].

Titanium carbide stands out among this group of compounds, first of all, by a unique combination of functional properties – high hardness, modulus of elasticity, melting temperature, which allows it to be considered as a candidate material for erosion-resistant coatings to increase the reliability and service life of responsible friction pairs.

To date, a large volume of experimental material has been accumulated regarding the structural, mechanical, and other characteristics of titanium carbide coatings, as well as the high tribological characteristics of Cr-C, Mo-C, W-C type materials and the prospects for their use as antifriction wear-resistant coatings for friction pairs [10]–[12].

When applying coatings to critical parts that are used in mechanisms with high reliability requirements, in particular in aviation units, it is important to ensure the stability of the characteristics of the corresponding coatings. This was taken into account when considering possible schemes for sputtering metal carbide coatings using vacuum arc sputtering sources. The formation of such coatings is possible from ionized atomic flows of metal and carbon, or from ionized atomic flows of titanium in a carbon-containing gas environment. According to the first of the schemes, it is quite difficult to ensure the constancy of the ratio of the corresponding atomic fluxes on the substrate, and therefore the composition of the coating during its growth due to the instability (breakdowns) of the vacuum arc combustion, especially when sputtering sources with graphite cathodes work. Therefore, preference was given to the method of forming metal carbide coatings from ionized titanium atomic flows in a mixture of argon and carbon-containing gas.

The main goal of this work is the search for new vacuum-plasma high-hard erosion-resistant multi-component Avinit coatings on a carbide basis (in the "metal-carbon" systems – Ti-C and Mo-C) using vacuum-arc sources of ionized atomic flows of titanium and molybdenum in argon-benzene environment stimulated by non-equilibrium low-temperature plasma, suitable as alternative protective coatings of compressor blades of gas turbine engines of aircraft engines in contact with surfaces with high hardness.

As candidate coatings for further research, we have chosen multi-component coatings of "metal-carbon" systems – Ti-C and Mo-C.

2. Methods of experiments

All experimental and technological developments were carried out on the Avinit automated vacuum-plasma cluster created by us, which allows implementing complex methods of applying multilayer functional coatings (plasma-chemical CVD, vacuum-plasma PVD (vacuum-arc, magnetron), processes of ion saturation, implantation and ion surface treatment), combined in one technological cycle [1]–[3], [13].

Methods of sample preparation and methods of experimental research are described in detail in works [1]–[3], [13]. When studying the coatings on the blades, the same methods of experimental research were implemented as in [13] for a more complete comparison with the Avinit vacuum-plasma erosion-resistant coatings for the compressor blades of gas turbine engines of aircraft engines, described in [13].

Cathodes made of Ti and Mo were used as cathode materials of vacuum-arc sputtering sources, and high-purity argon and benzene vapor C_6H_6 were used as reaction gases.

The introduction of working gases into the chamber, control and maintenance of gas flow at a given level was carried out using a Bronkhorst EL-FLOW PRESTIGE FG-201CV flow meter.

Before applying the coatings, the vacuum chamber was evacuated to a pressure of residual gases $\leq (2–3)\cdot 10^{-3}$ Pa. Then the substrates were cleaned in a glow discharge plasma at a pressure of Ar $\sim 1\cdot 10^{-1}$ Pa and a potential on the substrate of 1300 V for up to 10 min. and a transition was made to cleaning with metal ions in a vacuum-arc discharge plasma with a current of 100 A with the curtain in front of the samples closed, in order to reduce the probability of micro-arc discharges when the plasma arc source is turned on. After operating the plasma source in this mode for 1–3 min. "passivation" of the vacuum environment took place due to the binding of chemically active components by a film on the surfaces of the vacuum chamber and its additional degassing, as a result of which the pressure of residual gases decreased to values $\leq (0.7–1)\cdot 10^{-3}$. The transition to coating was carried out by lowering the negative potential of the substrate in the range from 25 V to 300 V, injecting the reaction gas to a given pressure in the range from 2.5×10^{-2} Pa to 2.5 Pa, which was then automatically maintained, and opening the curtain before samples.

To determine the control of the multicomponent composition of material vapors, as well as the composition of residual gases in the vacuum volume, a quadrupole mass spectrometer of the MX-7304A was used. The design of the analyzer allows it to be used to control the ionic component in sputtering methods with plasmonization of the vapor-gas phase. The mass spectrometer can be connected to an external computer and work in a single system of automated control and management of technological processes.

The temperature of the substrates was monitored by a Raytek IR pyrometer, which was previously adjusted based on the temperature measurement of a reference sample with a chromel-alumel thermocouple attached to its backside. The study of the characteristics of the obtained coatings was carried out using the methods of metallographic, X-ray structural and micro-X-ray spectral analysis.

The study of the characteristics of the experimental samples (structure and properties of the working surfaces (microgrinding, hardness of the coating, determination of the surface geometry) was carried out using methods of electron, raster and optical microscopy, chemical, X-ray structural and micro-X-ray spectral analysis, measurement of microhardness, roughness of friction surfaces.

Metallophysical measurements of the obtained coatings were carried out on a JSM T-300 scanning electron microscope.

Control of the thickness of the layers was carried out using a pre-calibrated thickness gauge FTC-2800, which allows measuring the growth rate of the coating from 0.01 A/sec.

Metallographic studies and determination of material parameters (thickness of coatings, uniformity, defects and structure of the material itself) were carried out on a Tesa Visio 300 gL microscope. The microhardness of the coatings was measured using a "BUEHLER" microhardness tester at a load of 50 G and microhardness tester AMN-43 of the LECO company, in automatic mode at a load of 50 G.

The surface hardness of the samples was determined using a QNESS Q60M hardness tester from the company "KEMIKA" (Austria) at a load of 5 kg.

Adhesion of the coatings was measured by the scratch grid application method adopted in production. In addition, adhesion was measured by a scratch meter Revetest Scratch Tester (RST).

The roughness of the coatings was determined using a JENOPTIK nanoscan 855 profilometer (Germany). Surface topography before and after tribological tests was studied using an Altami MET-1C optical microscope with a digital camera.

3. Experimental results

3.1. Application of coatings

Samples for tribological tests according to the "cube-roller" scheme on the friction machine 2070 SMT were used as substrates for coatings. The hardness and roughness of the surface of such samples was, respectively, 56...61HRC and Ra = 0.063 µm. The coatings on the samples were applied on the same equipment that is used at the enterprise in order to obtain, during tribological studies, the characteristics of the coatings, which would be identical to the characteristics of the coatings when they are applied to real products.

Using the possibilities of complex implementation of vacuum-plasma (PVD) and plasma-chemical. (CVD) methods in the Avinit cluster, we have developed fundamentally new processes (PVD and hybrid PVD+CVD) of controlled formation of multicomponent coatings in the "metal-carbon" Ti-C and Mo-C systems.

3.1.1. Development of Avinit Ti-C coating processes

The technological parameters of the processes (PVD and hybrid PVD+CVD) of applying multilayer Ti-C coatings to samples made of steel DIN 1.2379 (nitrided and cemented steel) with a hardness of 56...61HRC have been worked out.

Samples with the obtained coatings (micro-grinding, hardness of the coating) were studied.

The thickness of multilayer coatings is 10...15 microns. The measured hardness values of the coatings on the witness samples were 18,000–30,000 MPa.

Examination of samples after applying coatings of various compositions show that the applied regimes ensured the formation of high-quality coatings.

The proven modes allow to obtain a coating with high adhesion while maintaining the hardness of the base – steel DIN 1.2379 within the specified limits – the hardness and microhardness of the base material in the selected modes of coating practically do not decrease compared to the initial state. There were no cases of delamination of the coatings when applying the scratch mesh. Metallographic studies of samples with coatings confirmed the integrity and uniformity of the thickness of the coatings on the entire surface of the samples.

Profilographic measurements confirmed that after coating the test samples with a roughness corresponding to cleanliness class 12–13, the surface roughness of the samples practically does not change or the surface cleanliness class deteriorates slightly (by one or two units).

Table 1 shows data on the value of microhardness HV at a load of 0.05 N for Ti-C coatings obtained at different values of benzene pressure.

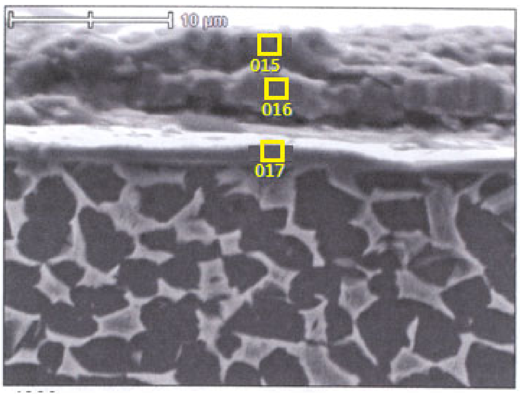
As can be seen from the Table 1, with the specified parameters, it is possible to obtain a Ti-C coating with a thickness of 5–10 microns with good adhesion quality.

A monotonous increase in the hardness of coatings based on Ti-C to the maximum value occurs with an increase in the pressure of the reactive carbon-containing gas in the coating, up to a certain value. The maximum hardness has coatings that have a composition close to the stoichio-

Table 1. Dependence of microhardness of Ti-C coatings obtained at different values of benzene pressure

№	Technological parameters			Coating characteristics		
	Current Ip(Ti), A	Voltage Uc, V	Partial pressure of benzene P, Pa	Thickness, µm	Microhardness, MPa	Adhesion*
1	90	130	0,25	5,0	18000	Good
2	100	120	0,65	8,5	20000	Good
3	120	120	2,5	9,6	30000	Good

* Adhesion of coatings was determined by the method of applying a scratch grid adopted in production



a

№ point	Ti, at %	C, at %
15	61,8	38,2
16	62,4	37,6
17	62,0	38,0

b

Fig. 1. The appearance of the Ti-C coating *a* – lumbar cut with marked analysis zones, *b* – the approximate chemical composition of the analyzed zones

metric in the Ti-C compound. With a further increase in the reaction gas pressure, the concentration of carbon in the coating increases, and the hardness decreases, which indicates that the coating hardness value of 30,000 MPa is close to the maximum that can be obtained on this equipment under the given conditions of their production.

On a JSM T-300 scanning electron microscope in the mode of micro-X-ray spectral analysis, a study of the phase composition of TiC coatings was carried out on samples obtained by deposition of titanium in benzene vapors at a pressure from 2.5×10^{-2} Pa to 2.5 Pa and a bias potential of 25 V.

The TiC phase was recorded, according to X-ray structural analysis, in coatings obtained at a pressure above 1.3×10^{-1} Pa.

On the samples obtained at higher benzene pressures (0.65 Pa and 2.5 Pa), the carbon content in the coatings was approximately 38 at, respectively % and 46 at %.

Fig. 1 shows the results of metallophysical studies of Ti-C coatings on a JSM T-300 scanning electron microscope.

Thus, the experimental results confirm the possibility of low-temperature application of wear-resistant high-hard coatings based on titanium carbide in modes that ensure good adhesion to substrate materials (steel DIN 1.2379) without reducing the strength characteristics of steel (< 200°C) and without deterioration of the clean surface.

3.1.2. Development of Avinit Mo-C coating processes

As with the application of Avinit Ti-C multilayer coatings, based on the capabilities of the Avinit automated vacuum-plasma cluster and the concept of nanolayer coatings, technological parameters of the processes of applying multilayer and nanolayer Mo-C coatings were worked out.

The technological parameters of the processes (PVD and hybrid PVD+CVD) in argon-benzene plasma for applying multilayer Mo-C coatings to samples (nitrided and cemented steel) were worked out.

Table 2 shows data on the microhardness value of HV at a load of 0.05 N for Mo-C coatings obtained at different values of benzene pressure.

As testified by the samples, the developed regimes ensured the formation of high-quality coatings with a thickness of 5–10 microns with a microhardness of the coatings of 2000–2500 MPa with good adhesion quality.

Metallographic studies of samples with coatings confirmed the integrity and uniformity of the thickness of the coatings on the entire surface of the samples.

Fig. 2 shows the results of metallophysical studies of Mo-C coatings on a JSM T-300 scanning electron microscope.

Profilographic measurements show that the application of coatings practically does not change the roughness of the original surface.

Thus, the experimental results confirm the possibility of low-temperature application of wear-resistant high-hardness "metal-carbon" Mo-C coatings in PVD and hybrid PVD+CVD nanocoating processes, while ensuring good adhesion to the substrate materials. (steel DIN 1.2379) without reducing the strength characteristics of steel (< 200°C) and without deteriorating the class of cleanliness of the original surface.

Table 2. Dependence of microhardness of Mo-C coatings obtained at different values of benzene pressure

№	Technological parameters			Coating characteristics		
	Current Ip (Ti), A	Voltage Uc, V	Partial pressure of benzene P, Pa	Thickness, μm	Microhardness, MPa	Adhesion*
1	100	150	0,3	5,0	20000	Good
2	120	160	0, 5	8,0	22000	Good
3	130	160	3,5	10,0	25000	Good

* Adhesion of coatings was determined by the method of applying a scratch grid adopted in production

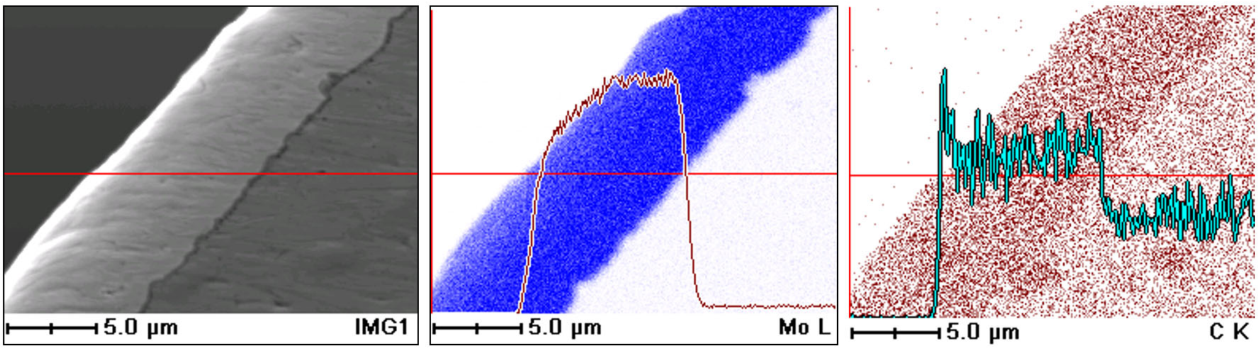


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Fig. 2. Appearance of the Mo-C coating on the sample in line analysis mode

3.2. Study of friction and wear characteristics of samples with coatings

To carry out tribological tests, samples with developed coatings were made on the same equipment that is used at the enterprise when coating real products [1]–[3].

The material of the main samples for coating is steel DIN 1.2379, 56...61 HRC.

Counterbody materials for applying anti-friction, wear-resistant coatings: steel 20Х3МВФ-Ш (ЕІ415-Ш), nitrided, ≥ 800 HV; steel 20Х3МВФ-Ш (ЕІ415-Ш), 28...37 HRC.

3.2.1. Tribological characteristics of samples with Ti-C coatings

Samples with developed coatings were made for tribological tests. Multi-layer and nano-layer Ti-C coatings were obtained on the counterbodies (rollers) and on the main samples (cubes) for tribological tests according to the developed modes.

Tests were conducted to determine the tribotechnical characteristics of samples with counterbodies having the investigated coatings, according to the "cube-roller" scheme.

The dependences of the friction coefficients on the load for friction pairs that worked without wear and burr are shown in fig. 3.

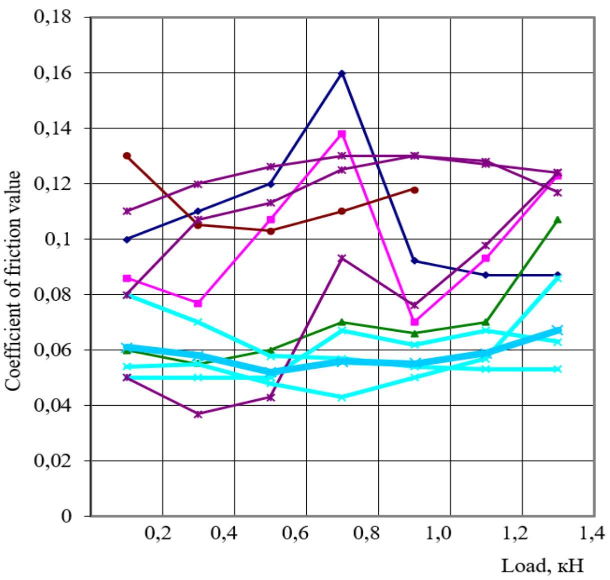

Fig. 3. Dependence of friction coefficients on load: — cube (TiC) / rollr (cementation); — cube (TiC) / roller (Ti-Al-N); — cube (TiC:H) / roller (Ti-Al-N); — cube (TiC) / roller (MoN); — cube (steel DIN 1.237) / roller (MoN); — cube (MoN) / roller (MoN); — cube (TiC) / roller (MoN), average values

A study of samples with coatings (micro-grinding, coating hardness, determination of surface geometry, surface morphology, roughness, yield) was conducted after coating.

3.2.2. Tribological characteristics of samples with Mo-C coatings

Multicomponent Mo-C coatings were applied to the main samples - cubes - made of steel DIN 1.2379 with a hardness of 56…61HRC and to the counterbodies (rollers) for tribological tests according to the proven modes.

Tests were conducted to determine the tribotechnical characteristics of samples with counterbodies having the investigated coatings, according to the "cube-roller" scheme.

The results are shown in fig. 4.

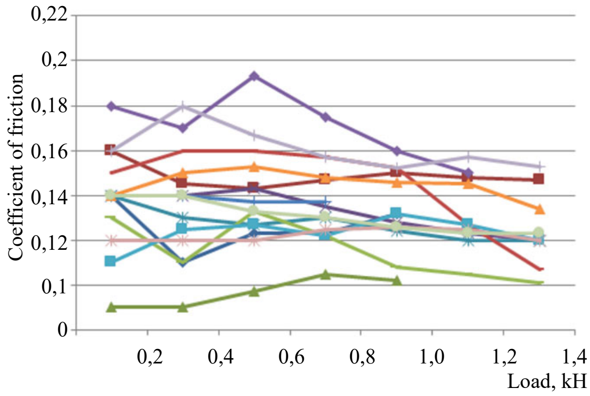

Fig. 4. Tribological testing of samples with Mo-C coatings: – steel DIN 1.237 MoC:H; – MoN MoC:H; – TiAIN MoC:H; steel DIN 1.237 MoC; – MoN MoC; – TiAIN MoC; – steel DIN 1.237 MoC; –MoN MoC; – MoN repeat 50 °C MoC; – TiAIN MoC; – steel DIN 1.237 MoC

The experimental results of metallographic and tribological studies obtained in this work are given in table. 1, 2 and fig. 1–4, comparable to the characteristics of the protective coatings used in the production of compressor blades of gas turbine engines of aircraft engines [13].

This allows us to draw a conclusion about the prospects of the developed hard multicomponent plasma-chemical vacuum-plasma coatings Avinit Ti-C and Avinit Mo-C for improving the tribological characteristics of materials.

Thus, in this work, for the first time, the processes of controlled plasma chemical synthesis of the formation of multicomponent coatings in "metal-carbon" systems – Avinit coating (TiC, MoC) with the use of vacuum-arc sources of ionized atomic flows of titanium and molybdenum in an argon-benzene environment stimulated by non-equilibrium low-temperature plasma, and their characteristics were studied depending on the conditions of their formation.

The carried out developments can be a basis for the selection of coating materials and the development of new structures of anti-friction wear-resistant coatings to increase the performance of friction pairs in the "coating-steel" and "coating-coating" systems, as well as working out the processes of their application.

4. Applying coatings to models of compressor blades

In work [13], the processes (PVD and hybrid PVD + CVD) of forming multi-component solid Avinit coatings in “metal-carbon” systems using vacuum-arc (PVD) processes according to the two-cathode scheme (cathodes Me (Ti, Mo) and carbon C.

Proven modes allow to get high-quality, uniform coatings with high adhesion.

The successful experience of applying solid Ti-C coatings to the working blades of the compressor convincingly proves that, if necessary, with small technological improvements, it is possible to implement a wide range of new vacuum-plasma erosion-resistant 2D nanocomposite coatings (TiN-AlN)n into production, (TiN-ZrN)n, (TiN-NbN)n, (TiN-CrN)n, (TiC-MoC)n from the arsenal of Avinit technologies.

The results obtained in this work allow to draw a conclusion about the prospects of the developed multi-component plasma-chemical vacuum-plasma coatings Avinit Ti-C and Avinit Mo-C, obtained in an argon-benzene plasma environment, for increasing wear resistance and reducing the friction coefficient of steam sliding.

These results can be the basis for the selection of coating materials and the development of designs of anti-friction wear-resistant coatings to increase the performance of friction pairs in the “coating-steel” and “coating-coating” systems, as well as the development of their application processes

This gives reason to consider the developed processes as alternatives for expanding the range of new Avinit vacuum-plasma erosion-resistant coatings and developing new designs of anti-friction wear-resistant coatings to increase the performance of friction pairs in the “coating-steel” and “coating-coating” systems.

According to the developed processes, plasma-chemical vacuum-plasma coatings Avinit Ti-C and Avinit Mo-C were applied to model samples of compressor blades.

Fig. 5. Avinit Ti-C plasma chemical vacuum-plasma coatings on a mock-up sample of a compressor blade

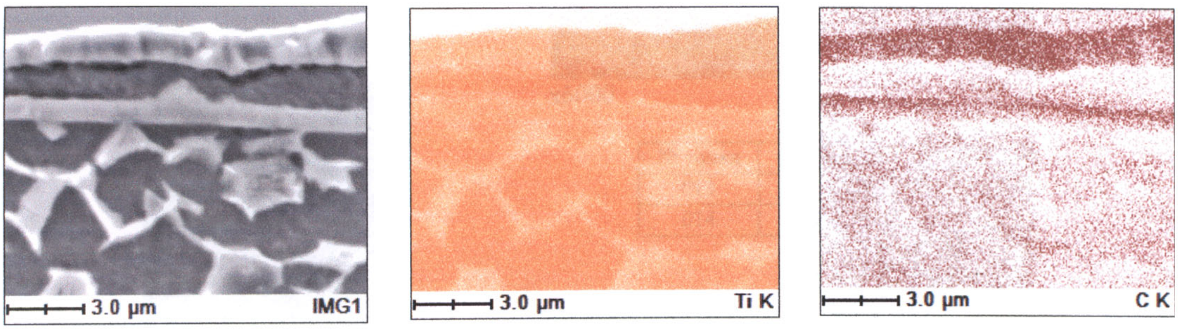

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Fig. 6. The appearance of the Avinit Ti-C plasma chemical vacuum-plasma coating (lumbar cut) in the mode of mapping the area of the compressor blade

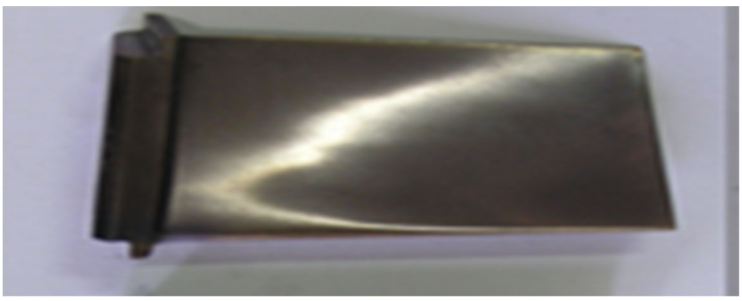
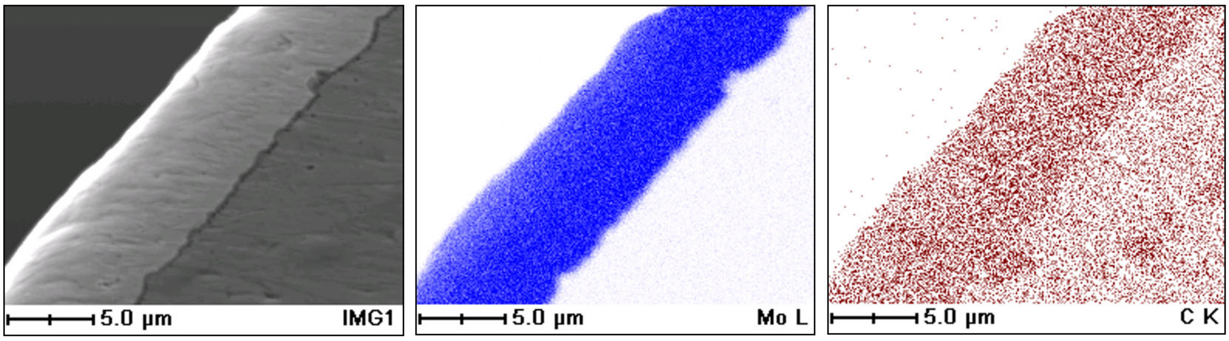


Fig. 7. Plasmochemical vacuum-plasma coatings Avinit Mo-C on a model blade sample. The thickness of the Ti-C coating is 8–8.5 microns. Microhardness 20000 MPa



×5500

Fig. 8. The appearance of the Avinit Mo-C plasma-chemical vacuum-plasma coating (lumbar cut) in the mode of mapping the area of the compressor blade

Proven modes allow to get high-quality, uniform coatings with good adhesion.

All comparisons of the characteristics of mock-up compressor blades with developed coatings are made in relation to the characteristics of protective coatings on serial working compressor blades of gas turbines and the characteristics of alternative coatings on mock-up compressor blades developed in work [13].

The high quality of applied Ti-C and Mo-C hard coatings on C on mock-up samples of the blades allows to significantly expand the range of new vacuum-plasma erosion-resistant technologies from the Avinit arsenal [13] when put into production to improve the characteristics of the working compressor blades of GTE aircraft engines.

5. Conclusions

1. For the first time, processes of controlled plasma-chemical synthesis of the formation of multicomponent coatings in "metal-carbon" systems - Avinit (TiC, MoC) coating using vacuum-arc sources of ionized atomic flows of titanium and molybdenum in an argon-benzene environment stimulated by non-equilibrium low-temperature plasma were developed.

2. Avinit Ti-C and Avinit Mo-C multilayer coatings have been created using the developed processes.

3 Optimization of the processes of applying high-quality strongly bonded reinforcing and anti-friction coatings on experimental samples has been carried out. The characteristics of the coatings (microhardness, hardness, roughness) have been measured.

Metallographic studies confirm the possibility of low-temperature application of high-quality wear-resistant high-hard "metal-carbon" coatings in the developed PVD and hybrid PVD+CVD processes of applying metal carbide coatings with a hardness of 18,000–30,000 MPa, while ensuring good adhesion to substrate materials (steel DIN 1.2379) without reducing strength and without deterioration of the cleanness class of the original surface.

4. Avinit multi-layer coatings (Ti-C, Mo-C) have been obtained on the counterbodies (rollers) and on the main samples (cubes) for tribological tests.

Tribological tests have been conducted using the "cube-roller" scheme reveal high tribological characteristics of steel DIN 1.2379 tribocouples with developed coatings.

This testifies to the promisingness of the developed multi-component multilayer coatings Avinit Ti-C and Avinit Mo-C for increasing the wear resistance and reducing the coefficient of sliding friction of tribocouples.

5. The obtained results can be a basis for the selection of coating materials and the development of structures of anti-friction wear-resistant coatings to increase the efficiency of friction pairs in the "coating-steel" and "coating-coating" systems, as well as working out the processes of their application

6. Plasmochemical vacuum-plasma coatings Avinit (Ti-C, MoC) have been applied to model samples of compressor blades. Proven modes allow to get high-quality, uniform coatings with high adhesion. The experimental results of metallographic and tribological studies of coating characteristics obtained in this work are comparable to the characteristics of the protective coatings used in the production of compressor blades of gas turbine engines of aircraft engines.

7. The developed Avinit plasma-chemical vacuum-plasma coatings (Ti-C, MoC) can be considered as alternatives for expanding the range of new Avinit vacuum-plasma erosion-resistant coatings and developing new designs of anti-friction wear-resistant coatings to increase the performance of friction pairs in "coating-steel" systems and "cover-cover".

The high quality of Ti-C and Mo-C solid coatings applied to mock-up samples of the blades allows to significantly expand the range of new vacuum-plasma erosion-resistant technologies from the arsenal of Avinit technologies when put into production to improve the characteristics of the working compressor blades of GTE aircraft engines.

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Плазмохімічний синтез вакуум-плазмових функціональних покриттів на карбідній основі і вивчення трибологічних характеристик пар тертя

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Анотація. *Робота присвячена пошуку нових матеріалів з високими функціональними характеристиками з використанням розроблених нами вакуум-плазмових технологій Avinit, заснованих на комплексному використанні методів нанесення покриттів (плазмохімічні CVD, вакуум-плазмові PVD (вакуум-дугові, магнетронні), процеси іонного насичення та іонної обробки поверхні), стимульованих нерівноважною низькотемпературною плазмою.*

Розроблені процеси контрольованого плазмохімічного синтезу формування багатокомпонентних покриттів у системах "метал-вуглець" – покриття Avinit (TiC, MoC) із застосуванням вакуум-дугових джерел іонізованих атомарних потоків титану та молібдену в середовищі аргон-бензолової плазми і вивчені їхні характеристики в залежності від умов їх формування.

Металографічні дослідження підтверджують можливість низькотемпературного нанесення якісних зносостійких високотвердих покриттів "метал-вуглець" з твердістю 18000–30000 МПа, при цьому забезпечується хороша адгезія до матеріалів підкладинки (steel DIN 1.2379) без зниження міцності та без погіршення класу чистоти вихідної поверхні.

Проведені трибологічні випробування за схемою "кубик-ролик" виявляють високі трибологічні характеристики трибопар steel DIN 1.2379 з розробленими покриттями і свідчать про перспективність розроблених багатокомпонентних багатошарових покриттів Avinit (Ti-C, MoC) для підвищення зносостійкості і зниження коефіцієнта тертя ковзання у вузлах тертя.

Розроблені плазмохімічні вакуум-плазмові покриття нанесені на макетні зразки робочих компресорних лопаток ГТД авіаційних двигунів. Відпрацьовані режими дозволяють отримувати якісні рівномірні покриття з високою адгезією.

Це дає підстави розглядати розроблений процес як альтернативний для розширення гами нових вакуум-плазмових ерозійностійких покриттів Avinit та розробці конструкцій антифрикційних зносостійких покриттів для підвищення працездатності пар тертя в системах "покриття-сталь" та "покриття-покриття".

Ключові слова: *багатокомпонентні багатошарові покриття Avinit, плазмохімічний синтез, трибологічні характеристики, тертя. зносостійкість.*