Mech. Adv. Technol. Vol. 7, No. 1, 2023, pp. 7–15

DOI: 10.20535/2521-1943.2023.7.1.264788

UDK 621.891

Vacuum plasma erosion resistant 2D nanocomposite coating Avinit for compressor blades of gas turbine engines of aircraft engines

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Received: 3 February 2023 / Revised: 10 March 2023 / Accepted: 27 March 2023

Abstract. *The work is devoted to the search for new vacuum-plasma coatings with high hardness to increase the durability of the compressor blades of the GTE of aircraft engines Ti-Al-N-based vacuum-plasma coatings obtained by Avinit technologies, which ensure the application of hard, high-quality coatings with dramatically reduced micro-arc damage, were selected as candidates.*
Avinit multilayer coatings have higher functional characteristics than TiN (microhardness, crack resistance, temperature resistance, erosion and corrosion resistance) and may be promising for applying erosion-resistant coatings for compressor blades. Avinit technologies are technologically closest to the vacuum-plasma technologies used in industrial production for applying TiN protective coatings.
New multi-layered 2D nanocomposite wear-resistant ion-plasma hard coatings Avinit $(TiN\text{-}AlN)_n$ *have been developed.*
The created software products made it possible to reach a qualitatively new level in terms of further modification and improvement of the designs of Avinit functional coatings, stability of technologies and improvement of their quality control when applying such coatings for use in the production of compressor blades of gas turbine engines of aircraft engines.
Special attention is paid to methods of preliminary ion-plasma treatment of surfaces before coating. Metallographic studies of the chemical and phase composition and structure of Avinit $(TiN\text{-}AlN)_n$ *coatings have been carried out. The thickness of the coatings is 7–9 μm, the microhardness is 34–35 GPa (compared to the serially used TiN coating: 27.4 GPa). The use of three-stage ion-plasma treatment in Avinit technologies using a double vacuum-arc discharge followed by the application of strengthening coatings in a single technological cycle eliminates the formation of cracks and ensures the production of tightly bonded, high-quality coatings of a given composition with the maximally reduced share of the droplet component.*
The developed coatings $(TiN\text{-}AlN)_n$ *were applied to experimental batches of working compressor blades of GTE aircraft engines for bench tests.*

Keywords: *titanium alloys; titanium boride; microstructure; mechanical properties; welded joint; electron-beam welding; heat treatment.*

1. Introduction

Gas turbine units (GTU) are widely used in both aviation and ground engineering.

Problems of ensuring reliability and durability, service life of gas turbines are the most complicated among numerous problems, arising on the way of development of modern aviation gas turbine engines.

The most important element of the gas turbine is the rotor blades, the degree of wear of working surfaces of which to a great extent depends on the service life, efficiency and other characteristics of engines as a whole.

The greatest number of damages of titanium compressor blades of aircraft engines GTU is caused by the complex influence of erosion, corrosion and corrosion-fatigue damages, connected with the impact influence of gas flow, containing foreign inclusions of dust particles, which significantly reduce the operating life [1].

To solve the problems of reliability and service life of gas turbines new heat-resistant alloys with directed columnar and monocrystalline structures, modernization of alloys with equiaxial structures are widely used.

If application of new, more heat-resistant alloys solves the problem of increased of resistance to deformations and destruction of blades under influence of high temperatures and stresses, no less reliable and durable heat-resis-

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tant protective coatings are required for reliable protection against erosion and corrosion destruction of surfaces.

2. Review of protective coatings for gas turbine compressor blades

One of the promising ways to protect titanium compressor blades operating under the influence of a high-speed, high-temperature gas flow is the application of reliable coatings with increased corrosion and erosion resistance to form protective layers on the working surface of the blades with resistance to the aggressive effects of the environment, which are several times higher than the resistance of the base material [1].

Several basic methods of applying wear-resistant protective coatings of compressor blades are used: galvanic, paint, enamel, condensation, vacuum-diffusion, etc.

Galvanic nickel-cadmium coatings are used on compressor blades to protect against corrosion, but they have very low erosion resistance and operating temperature (up to 300°C).

Multi-layer paint coatings based on epoxy enamel also protect blades from corrosion. However, blades with enamel coatings are even more prone to erosion damage.

The strengthening technologies of vacuum-plasma physical (PVD) and chemical (CVD) application of wear-resistant coatings have become the most widespread.

A large number of studies were conducted, the purpose of which was to develop a technological process of applying vacuum-plasma corrosion- and erosion-resistant coatings for compressor blades of aircraft engines.

Extensive studies [2] have been conducted on the application of vacuum-plasma corrosion- and erosion-resistant single-phase (TiN, ZrN, CrN, etc.) and multi-layer (Ti-TiN) coatings and their effect on fatigue and strength, resistance to cyclic loads, working endurance compressor blades of aircraft engines during operation.

Conducted research [3] on the development of erosion-resistant protective vacuum-plasma coatings for the purpose of comprehensive protection of titanium compressor blades in all-climate conditions at temperatures of 450–600°C.

In works [1, 4] research was carried out on the development of the technological process of applying an erosion-resistant titanium nitride coating to the compressor blades of serial gas turbine engines and the creation of an ion-plasma technological installation for the implementation of the technology on an industrial scale.

Of the currently known coatings, preference is given to vacuum-plasma coatings made of titanium nitride, which combine fairly high protective properties with relative ease of production and fairly low cost.

The developed technological process of applying an erosion-resistant coating consists of two stages: ion cleaning of the surface and actual coating application. The initial period of ion cleaning is accompanied by the intense occurrence of micro-arcs, the duration of which is determined by the cleanliness of the surfaces of the parts.

The thickness of the coating was approximately 7...8 microns on both sides of the blade. The maximum coating thickness did not exceed 10 μm. With small coating thicknesses of the order of 3...5 microns, it is not sufficiently uniform in thickness, with noticeable thickenings in the droplet phase penetration zones. When the thickness of the coating increases, this value becomes more uniform over the entire surface of the blade.

The value of microhardness of blade samples according to the developed technology is within 24...25 GPa.

Such coatings with a thickness of 2–3 microns allow the engine to work out 2–3 inter-repair resources (1500–2100 hours).

However, when operating in harsher conditions (especially in a marine climate, where the air is a suspension of seawater and dust particles), the erosion and corrosion resistance are insufficient, and there is significant wear of the blades with significant erosion damage, which is not allowed by the technical conditions.

Thus, the search for coating materials (preferably vacuum-plasma) with increased erosion and corrosion resistance, able to work at higher operating temperatures, is an urgent need to increase the durability of the compressor blades of the GTE of aircraft engines.

One of the effective countermeasures to prevent erosion under the action of solid particles is to increase surface hardness. Increasing requirements for erosion resistance requires increasing the microhardness of coatings.

As shown by the accumulated experience [5–8], as well as extensive experimental material [9, 10], optimal solutions for the drastic improvement of tribotechnical characteristics should be sought in the creation of composite coatings, which are multilayer coatings based on metal-like carbides, nitrides, transition metals (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.).

As you know, the properties of protective coatings depend significantly on the composition, structure and method of coating formation, which, in turn, are determined by the technological parameters of their production.

A large complex of studies of various methods and technologies of surface protection has been conducted. As research has shown, ion-plasma vacuum technologies based on the formation of multilayer thin nanostructured coatings have the greatest prospects. The formation of nanocomposite coatings with 2D structures (fig. 1) leads to a significant improvement of functional characteristics, such as wear resistance, erosion and corrosion resistance, microhardness, etc.

Various constructions of multi-layer wear-resistant surface coatings using alternating layers of metal and nitrides, oxides or metal carbides, as well as methods of obtaining them for the protection of compressor blades are described in the patent literature [11, 12].

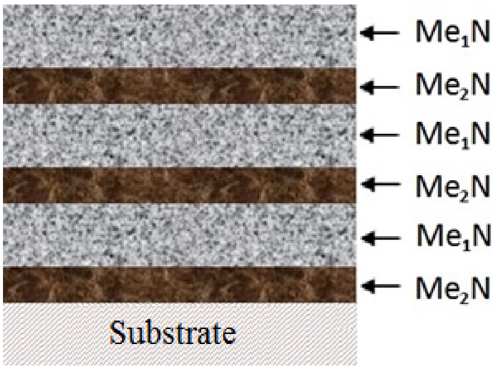


Fig. 1. Scheme of multilayer vacum ion-plasma coatings

The mechanisms of erosive wear are based on the occurrence and development of micro- and macro-cracks of fatigue failure.

When micro-designing multilayer coatings, it is advisable to create soft layers before applying hard coatings. The soft layer increases the adhesion of the coating to the substrate, ensures the presence of a large positive gradient of mechanical properties in the coating, which is a good prerequisite for normal operation under conditions of friction and shock loads.

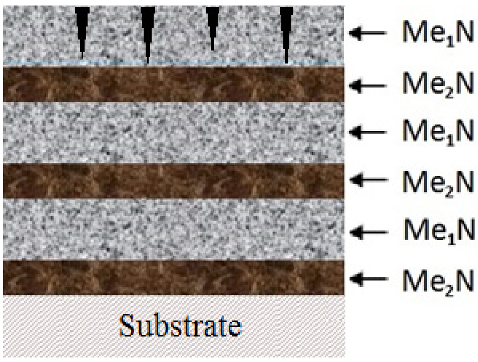


Fig. 2. Model of crack propagation in multilayer coatings

Thin low-plastic layers perceive the deformation during bombardment with dust particles and damp it on the plastic metal sublayer (fig. 2). When the damping limit is exceeded, fatigue cracks appear, which are localized in the upper low-plastic layers of the coating (fig. 2), which inhibits the development of destruction in the depth of subsequent layers, ensuring, in comparison with single-layer coatings, a significant increase in durability.

The presence of a multilayer structure with different layer properties (density, plasticity, etc.) in a certain combination prevents the propagation of cracks in multilayer coatings and increases their erosion resistance.

Chromium, molybdenum, α-Ti are usually used as soft layers.

The possibility of increasing the service life of products with erosion-resistant protective coatings of titanium nitride due to the use of multilayer compositions consisting of alternating layers of hard wear-resistant material (nitride, carbide, etc.) and thin layers of plastic metal, for example, cobalt, since it is not forms nitride or carbide compounds and leads to relaxation of internal stresses in TiN coatings to a better extent [29].

Coatings, which are a composite material consisting of high-strength nitride and carbide layers and plastic metal layers, have high hardness and heat resistance, sufficient crack resistance, good adhesion to the metal substrate, which allows to increase the wear resistance of the working surface.

Even higher than in 2D nanocomposites, microhardness values can be obtained in superhard nanocomposites (TiN – (Si_3N_4).

3D nanocomposite wear-resistant coatings (in many cases, with nanolayer or nanocomposite structures) with ultra-high hardness and temperature resistance have been developed.

A significant contribution to the development of the concept of creating superhard coatings based on 3D nanocomposites was made [9–10].

The prospect of developing protective nanocomposite coatings is confirmed by many studies [13, 14].

Mitsubishi Heavy Industries reports the successful use of Cr-N multilayer ceramic coatings obtained by PVD methods for these purposes [13].

The effectiveness of erosion-resistant nanocoatings for the protection of compressor blades is reported in [14]. Various types of coatings have been developed (wear-resistant – 2–5 μm thick, erosion-resistant 10–15 μm thick) – single-phase (TiN, ZrN, CrN, etc.), multilayer (Ti-TiN), nanocomposite multilayer (Ti/TiN & Ti/TiSiCN), (TiSiCN & ZrSiCN).

A large arsenal of modern ion-plasma methods [(Plasma Spray (thick) Plasma Enhanced Magnetron Sputter (PEMS), HVOF thick), PVD (EB-PVD) (thin), CVD (thin) is used to obtain superhard (> 40 GPa) coatings, CAPVD (nano), PEMS / PMD (nano)].

Works in this direction are developing rapidly [19].

For many years, we have been conducting extensive research on the development and industrial implementation of vacuum-plasma methods of applying functional coatings using low-temperature non-equilibrium plasma [5–8]. Developed ***Avinit*** vacuum-plasma technologies, successfully implemented in production, and provide a significant increase in operational characteristics in aggregate and engine engineering [5], transport engineering [8], energy engineering [7].

We conducted research on the development of vacuum-plasma processes for applying 2D nanocomposite coatings ***Avinit*** C on a nitride basis and ***Avinit*** D on a carbide basis [8].

According to studies, ***Avinit*** vacuum-plasma multilayer coatings have higher functional characteristics than TiN (microhardness, crack resistance, temperature resistance, erosion and corrosion resistance) and may be promising for applying erosion-resistant coatings for compressor blades. The technologies developed by ***Avinit*** are technologically closest to the vacuum-plasma technologies used in industrial production for applying TiN protective coatings.

Therefore, the development of vacuum-plasma erosion-resistant nanostructured ***Avinit*** coatings with increased microhardness, suitable for increasing the durability of the compressor blades of the GTE of aircraft engines, is extremely appropriate.

The purpose of this work is

1. Development of vacuum-plasma erosion-resistant nanostructured 2D-composite coatings of ***Avinit*** with increased microhardness, suitable for increasing the durability of compressor blades of gas turbine engines of aircraft engines, and technologies for their production. Research of the chemical and phase composition and structure of coatings.
2. Applying the developed coatings to experimental batches of working gas turbine compressor blades for bench tests.

3. Experimental results

All further experimental and technological developments were carried out on the Avinit automated vacuum-plasma cluster created by us, which allows the implementation of complex methods of applying multilayer functional coatings (plasma-chemical CVD, vacuum-plasma PVD (vacuum-arc, magnetron), processes of ion saturation, implantation and ion treatment surface), combined in one technological cycle [5, 8].

A significant increase in the spectrum of sources, which is ensured by the complexity of the methods used, allows you to obtain coatings from almost any elements and alloys, refractory oxides, carbides, nitrides, metal-ceramic compositions based on refractory metals and oxides. This significantly expands the possibilities of creating fundamentally new materials and coatings for nodes and parts of various purposes that work in extreme conditions in terms of temperature, the influence of aggressive environments, and mechanical loads.

When obtaining ***Avinit*** coatings, it is possible to move to the nano range for the implementation of processes of controlled formation of multi-component nano- and micro-structured coatings with specified characteristics.

This is achieved due to the radical restructuring of the operation management of all technological equipment systems based on the technology of end-to-end synchronization of ion-stimulated deposition systems and nano-sized coatings equipment due to the introduction of new microprocessor systems for power supply, synchronization and management of synthesis and diagnostic processes, and a complex of development of control methods technological parameters in the process

It becomes possible to form multilayer structures containing a large number of layers of different chemical composition (metal, nitride, carbide, oxide, etc.) with a thickness from units to hundreds of nanometers. The structure of the layers is provided by programmable coordinated modes of operation of plasma sources (both PVD and CVD), working gases and high potential applied to the substrate.

3.1. Development of *Avinit* strengthening erosion-resistant coatings for gas turbine blades

We have conducted a number of experimental studies on the development of vacuum-plasma processes for applying 2D nanocomposite multilayer coatings ***Avinit*** C on a nitride basis (Ti-Al-N) and ***Avinit*** D on a carbide basis (Ti-C) [8].

The main efforts were focused on the development of processes for obtaining Avinit C coatings (on the basis of Ti-Al-N) and studying their properties.

Due to the high heat resistance of Ti-Al-N coatings, the upper-temperatureupper temperature limit of their operation is much higher than that of TiN coatings and reaches temperatures of 800–900^{o}C . These coatings have significantly better tribological characteristics, which is extremely important for their use as a material for promising erosion-resistant coatings [38, 39].

The characteristics of coatings (Ti-Al-N) depend significantly on the aluminum content. As the aluminum content increases, the microhardness of the coating increases to 40 GPa at an aluminum concentration of 40–50 at %.

Multilayer coatings had a layered structure of layers of different composition with the thickness of each layer ~ 10–15 nm.

The results of metallophysical measurements of the ***Avinit*** C coating on a JSM T-300 scanning electron microscope are shown in fig. 3.

Coatings have good adhesion to the substrate material. There were no cases of delamination of the coatings when the scratch mesh was applied.

Conducted research [5] on the application of functional coatings based on titanium, aluminum and their compounds with nitrogen by vacuum-plasma deposition methods showed that multi-component multilayer coatings demonstrate higher wear resistance and tribological characteristics compared to single-layer coatings based on one compound.

On the basis of these studies, the temperature-time parameters of obtaining ***Avinit*** C reinforcing coatings to increase the wear resistance of the working surfaces of the compressor blades of the gas turbine engine of aircraft engines, which ensure the production of coatings of the given composition with a thickness of 8–9 microns, were determined.

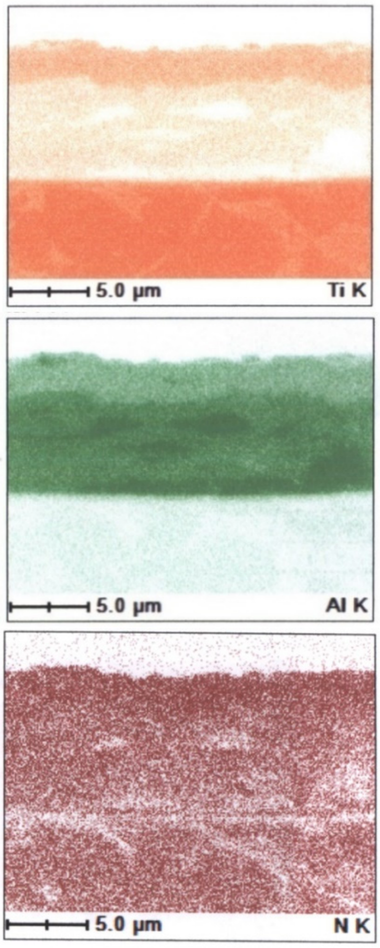


Fig. 3. The appearance of the ***Avinit*** C coating (transverse cut) in the coverage area mapping mode.

Software products were developed for obtaining such coatings on the ***Avinit*** cluster and testing technologies of applying functional multi-component multi-layer coatings on real serial parts.

On the basis of the conducted experiments, ***Avinit*** cluster management programs for obtaining TiN-AlN nanolayer coatings were created.

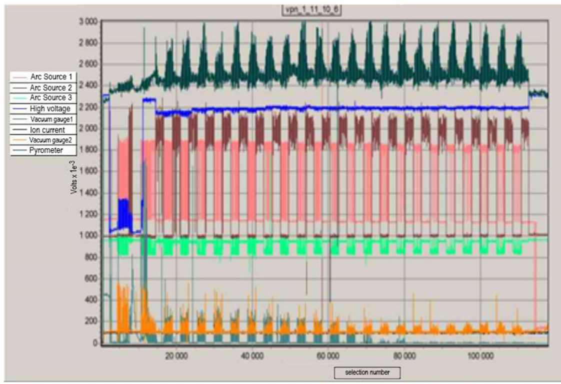
Fragments of the protocols of the automated control system of these processes are presented in fig. 4.

Many authors [9, 10] note that nano- and micro-layer multicomponent coatings in "metal-carbon" systems are promising for use as anti-friction wear-resistant coatings.

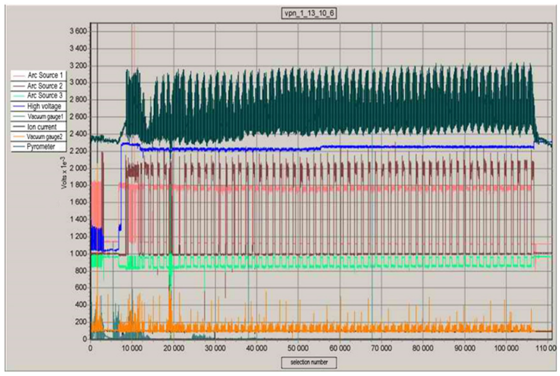
We have developed processes (PVD and hybrid PVD + CVD) of controlled formation of ***Avinit*** D multi-component nano- and microstructured coatings using vacuum-plasma (PVD) and plasma-chemical (CVD) processes of applying multi-component multilayer and nano-layer “metal-carbon” coatings (MeC, MeC : H, Me-CN, MeC-C) (Me = Ti, Mo) [15].

The microhardness of the coatings is 30–35 **GPa**.

Metallophysical measurements of ***Avinit*** D/P 100 coatings (fig. 5, 6) give the following results - the thickness of the coating is ~ 6–9 microns, the carbon content is ~ 10–15 %, fairly evenly distributed in the structure of the coating.

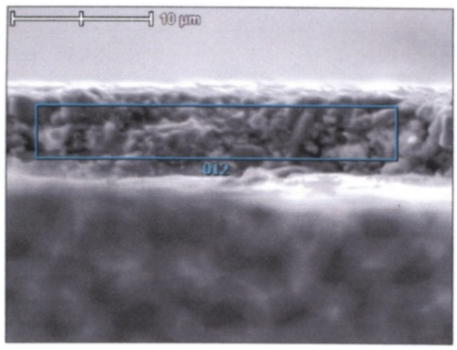


a



b

Fig. 4. Fragments of the protocols of the automated control system of the technological process of TiN-AlN nanocoating application: *a*) TiN-AlN nanocoating (50/50) with a repetition period of 20 nm and the same thickness of nanolayers; *b*) TiN-AlN nanocoating (30/70) with a repetition period of 12 nm and a nanolayer thickness of 4 and 8 nm



a

Point	C	Ti	Total, %
012	10.30	89.70	100

b

Fig. 5. Appearance of the **Avinit** D/P 100 coating (on the basis of Ti C) (transverse cut) with the specified analysis zones – *a*; approximate chemical composition of the analyzed zones – *b*

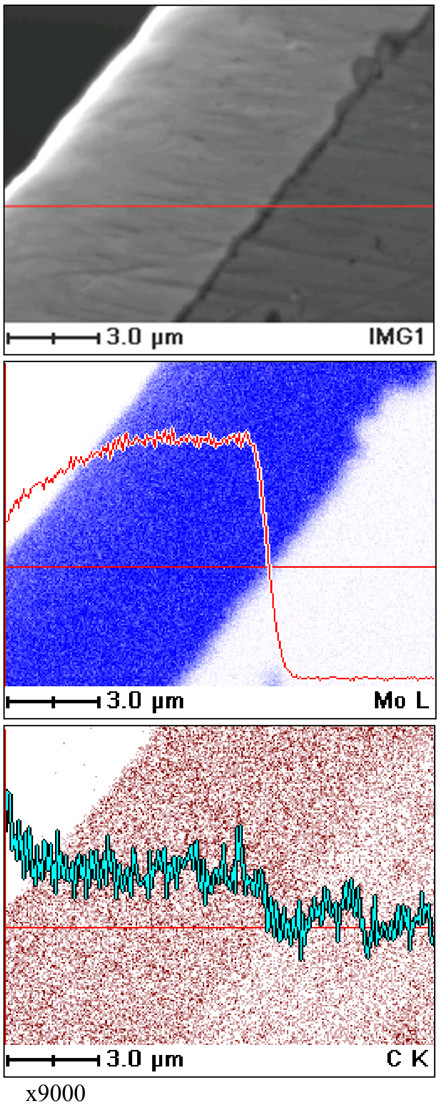


Fig. 6. Appearance of the ***Avinit*** D/P 200 coating (based on the Mo-C system) in line analysis mode

3.2. Surface preparation

When applying high-quality coatings using vacuum-arc methods, researchers face a number of problems related to surface preparation for coating. The most typical of them are the elimination of micro-arc breakdowns and the separation of plasma from the "droplet" component.

The condition of the working surfaces to be covered has a significant impact on the operational properties of coatings.

A characteristic feature of condensates (coatings) obtained by the vacuum-arc method is the presence of the so-called droplet component in the plasma flow generated by the vacuum arc. A large number of macroparticles appear on the surface of the coatings (mainly, metal droplets, which, depending on the time of their appearance on the growing surface, are covered by subsequent layers), inherent in condensation from unseparated plasma flows. Without the use of separating devices, the quality of the initial surface with a roughness of class 12c when applying coatings during normal deposition without a separator is greatly reduced (class 7c).

The efficient separating devices for the formation of a plasma flow with a sharply reduced fraction of the "droplet" component, improved by us, applied in the Avinit cluster, and developed within the framework of the production technological process, ensure the formation of plasma flows cleaned of microparticles of the cathode material, which allows obtaining a coating on products with a high surface quality, polished to V 11–12 cleanliness class.

As the long-term experience of operating the Avinit cluster in industrial conditions shows [13, 15, 16], the introduced design improvements (three-level protection against micro-arc breakdowns and a special design of the plasma separator) allow us to successfully overcome the problems of eliminating micro-arc breakdowns and separating the plasma from the "droplet" component.

A very important problem is ensuring high adhesion when applying coatings to materials with a high affinity for oxygen, for example, titanium and its alloys.

As world experience shows, ion-plasma technologies have great potential in this regard due to pre-treatment of the surface with a stream of high-energy ions, which, thanks to additional modification of surface properties, usually has a positive effect on the properties of the formed coatings.

We have developed ***Avinit*** technologies [6, 15] for surface cleaning that precede vacuum-plasma coating and, in addition to standard processes of preliminary surface preparation: chemical etching, ultrasonic washing, etc., include a three-stage treatment of the surface of the product in a glow discharge plasma of inert gas argon, surface treatment in a high-density plasma of a two-stage vacuum-arc discharge of inert gas argon and, finally, ion treatment with metal ions according to the optimal process modes

Carrying out such a three-stage treatment, as shown by industrial experience when applying functional coatings to blades and steam distribution elements of steam and atomic turbines [6, 15], ensures high-quality surface cleaning before applying coatings and obtaining strongly bonded coatings.

The process of multistage ion-plasma cleaning of the surface is described in detail in [16].

It consists of the following stages

1) – plasma treatment of a glowing discharge of inert argon gas;

2) – processing in a high-density plasma of a two-stage vacuum-arc discharge of inert argon gas;

3) – ion processing (cleaning with metal ions).

At the 1st stage, when processing in a glow discharge plasma of inert argon gas, due to the low values of the plasma density and ion current density on the treated surface, the cleaning speed (spraying of surface layers) in the glow discharge plasma is much lower than the cleaning speed in the electric arc discharge plasma. A higher potential (600 V), required for the burning of a glow discharge in such conditions, can cause the appearance of micro-arcs on surface contamination and deterioration of the cleanliness class. It is not possible to completely suppress the process of occurrence of micro-arcs, even despite the presence of a well-formed system of protection against micro-arcs. Therefore, glow discharge treatment was used for preliminary degassing and "activation" of fairly clean surfaces with a very smooth potential increase.

At the 2nd stage, a gas plasma generator of the Avinit cluster was used as a powerful plasma source of high-density plasma of a two-stage vacuum-arc discharge [5].

The comparative probe measurements of technological plasma parameters of the Avinit cluster showed [30] that the ratio of the flow of ions and neutral atoms for the plasma of a double arc discharge gives an approximately 300–1000 times more intense flow of ions compared to the case of a glow discharge. Such a much denser plasma is used in the ***Avinit*** cluster for highly efficient ion cleaning of the surface and ion assistance, which ensures strong adhesion of the coating to the substrate and the application of high-quality functional coatings.

During ion-plasma cleaning using high-density gas plasma created by a gas plasma generator, there is no problem of deposition of metal particles on the surface, and therefore the potentials on the part can be changed smoothly, starting from a zero value. At the same time, the complete absence of electrical breakdowns on the contaminated surface areas is achieved in comparison with the case when the surface is completely cleaned with metal ions, and thus the initial cleanliness of the treated surface is preserved.

At the 3rd stage, treatment with ions of the sputtered metal from the electric arc discharge plasma began to be carried out immediately after the termination of treatment in the gas plasma.

This made it possible to completely avoid the intensive creation of micro-arcs, the cause of which may be increased gas release due to additional heating of the surface of the product and equipment during processing, insufficient degree of pre-cleaning of the equipment and products before vacuuming the chamber, etc.

After that, the process of applying a protective multilayer coating began directly.

Conducting processes of ion-plasma cleaning and formation of layers with specified thicknesses of individual layers during vacuum-arc deposition of a protective coating is carried out by programmed cyclograms that provide program-synchronized control of inert and reaction gas pressure regulators and electrical process parameters.

It is important that the processes of multi-stage ion-plasma cleaning and subsequent vacuum-arc deposition of a protective erosion-resistant multilayer coating are carried out in one vacuum volume in a single technological cycle.

Coating is the finishing operation – no further surface treatment of parts is required after manufacturing.

3.3. Applying the developed coatings to test batches of gas turbine working compressor blades for bench tests

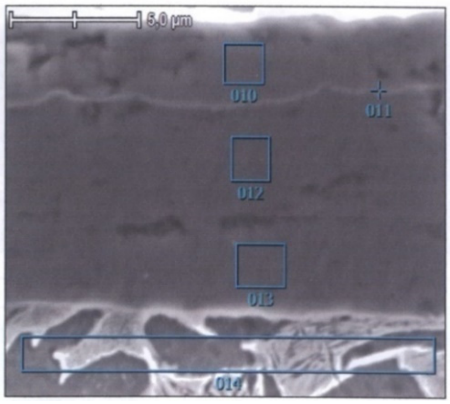
The composition of vacuum-arc nanolayer (10–100 nm) – 2D nanocomposite coatings $(TiN\text{-}AlN)_n$ was adopted as the basic version of the coating composition.

Taking into account the extensive experience of successful industrial implementation of such coatings $(TiN\text{-}AlN)_n$, as well as the maximum proximity of technological regulations to those used serially in production, this allows, with positive results of industrial tests, such coatings with small technological refinements can be implemented in the production of compressor blades of gas turbine engines of aircraft engines

In order to study the possibility of increasing the inter-repair specification of parts, erosion and corrosion resistance and operating temperatures of the coatings, nanolayer (10–100 nm) – 2D nanocomposite coatings $(TiN\text{-}AlN)_n$ were applied to the titanium blades of 1–8 stages of turbocompressors of gas turbine engines in the Avinit cluster fig. 8)

Coating thickness ~ 9 μm. Coatings have a nanolayer structure and consist of layers 5–10 nm thick based on aluminum, titanium and their compounds with nitrogen. Avinit coatings are deposited on the surface of the blades without reducing the class of surface cleanliness.

Metallophysical studies of multilayer ***Avinit*** coatings were carried out on a JSM T-300 scanning electron microscope (fig. 7).



a

No point	N	Al	Ti
010	9.10	27.93	62.96
011	6.89	16.73	76.38
012	10.7	45.87	43.44
013	10.71	47.22	42.07
014	–	3.64	88.94

b

Fig. 7. Appearance of the ***Avinit*** coating (cross-section) with the specified analysis zones – *a*; approximate chemical composition of the analyzed zones – *b*

Fig. 8. ***Avinit*** 2D nanocomposite $(TiN\text{-}AlN)_n$ coating on titanium blades of turbocompressors of gas turbine engines

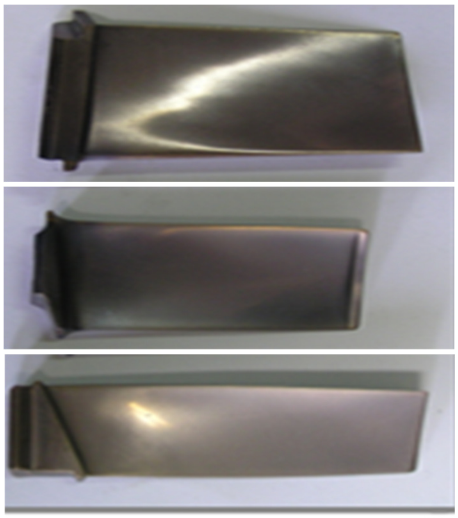


Fig. 9. Strengthening of blades of turbocompressors of gas turbine engines with wear-resistant coatings ***Avinit*** D (based on Ti-C)

The applied 2D nanocomposite $(TiN\text{-}AlN)_n$ coatings (fig. 8) have a high microhardness 34 GPa, compared to the TiN coating: of 27.4 GPa. Coatings have good adhesion to the substrate material. There were no cases of delamination of the coatings when the scratch mesh was applied.

Test batches of gas turbine working compressor blades with developed coatings $(TiN\text{-}AlN)_n$ are prepared for bench tests.

Also, to study the possibility of further application, Ti-C coatings with a thickness of 5–5.5 μm was applied to the blades (fig. 9).

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

The successful experience of applying solid TiC coatings to the working blades of the compressor convincingly shows that, if necessary, with small technological refinements, it is possible to implement a wide range of new vacuum-plasma erosion-resistant 2D nanocomposite coatings $(TiN\text{-}AlN)_n$, $(TiN\text{-}ZrN)_n$, $(TiN\text{-}NbN)_n$, $(TiN\text{-}CrN)_n$, $(TiC\text{-}MoC)_n$ from the arsenal of ***Avinit*** technologies.

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Вакуум-плазмові ерозійно-стійкі 2D- нанокомпозитні покриття Avinit для компресорних лопаток ГТД авіаційних двигунів

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Анотація. *Робота присвячена пошуку нових вакуум-плазмових покриттів з високою твердістю для підвищення довговічності компресорних лопаток ГТД авіаційних двигунів*
В якості кандидатних обрані вакуум-плазмові покриття на основі Ti-Al-N, отримувані за технологіями Avinit, які забезпечують нанесення твердих якісних покриттів з різко зменшеним пошкодження мікродугами.
Багатошарові покриття Avinit мають *більш високі, ніж TiN, функціональні характеристики (мікротвердість, тріщиностійкість, температуростійкість, ерозійну та корозійну стійкість) і можуть бути перспективними для нанесення ерозійно-стійких покриттів для компресорних лопаток. Технології Avinit технологічно найбільш близькі до використовуємих у промисловому виробництві вакуум-плазмових технологій нанесення захисних покриттів TiN.*
Розроблені нові багатошарові 2D-нанокомпозитні зносостійкі іонно-плазмові тверді покриття Avinit $(TiN\text{-}AlN)_n$.
Створені програмні продукти дозволили вийти на якісно новий рівень щодо подальшого модифікування та вдосконалення конструкцій функціональних покриттів Avinit, стабільності технологій та підвищення контролю їх якості при нанесенні таких покриттів для використання у виробництві компресорних лопаток ГТД авіаційних двигунів.
Особливу увагу приділено методам попередньої іонно-плазмової обробки поверхонь перед покриттям. Проведені металографічні дослідження хімічного і фазового складу і структури покриттів Avinit $(TiN\text{-}AlN)_n$ *.Товщина покриттів 7-9 мкм, мікротвердість 34–35 GPa (в порівнянні з серійно використовуємого покриття TiN: 27,4 GPa). Застосування в технологіях Avinit тристадійної іонно-плазмової обробки з використанням подвійного вакуум-дугового розряду з подальшим нанесенням зміцнюючих покриттів в єдиному технологічному циклі, виключає тріщиноутворення і забезпечує отримання міцнозчеплених високоякісних покриттів заданого складу з максимально зменшеною долею крапельної складової.*
Нанесені розроблені покриття $(TiN\text{-}AlN)_n$ *на дослідні партії робочих компресорних лопаток ГТД авіаційних двигунів для проведення стендових випробувань.*
Ключові слова: *компресорні лопатки ГТД, багатошарові покриття Avinit, трибологічні характеристики, зносостійкість.*