ТЕХНОЛОГІЇ ОТРИМАННЯ ТА ОБРОБКИ КОНСТРУКЦІЙНИХ МАТЕРІАЛІВ

TECHNOLOGIES OF OBTAINING AND PROCESSING OF CONSTRUCTION MATERIALS

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ENHANCING WEAR RESISTANCE OF COMPLEX-SHAPED DUAL-USE MECHANICAL COMPONENTS

Purpose*. To provide a scientific foundation for a technological approach to significantly increase the wear resistance of gas turbine engine (GTE) nozzle guide vanes (NGVs) by applying advanced protective coating deposition methods.*

Research methods*. The research methods included the selection of typical materials for investigation (ZhS6U and Inconel 718 alloys), a review of multifunctional coating systems and their classifications (Thermal Barrier Coatings (TBCs), wear resistant metallo ceramic coatings (Wear-Resistant Cermet Systems), an analysis of spraying methods (Detonation Spraying (D-Gun), High-Velocity Oxygen Fuel (HVOF), and Atmospheric Plasma Spraying (APS)), and a review of scientific studies that confirm the effectiveness of these methods.*

Results*. The analysis of existing research and literature has shown that the detonation spraying technology is uniquely and most suitably applicable for solving the stated problem, as it is capable of forming a* Cr_3C_2*-NiCr system coating with the required combination of properties: high density, excellent adhesion, and, most important, a favorable field of residual compressive stresses.*

Scientific novelty*. The systematic approach to solving the complex problem of protecting NGV blades (dual-use parts and mechanisms) by applying the detonation spraying technology, which is known for its ability to form exceptionally dense and wear-resistant coatings.*

Practical value*. Potential possibility to increase significantly the time between overhauls, reliability, and combat readiness of critically important GTE components.*

Key words*: GTE, NGV blade, superalloy, Solid Particle Erosion (SPE), high-temperature gas corrosion, oxidation, TBC, D-Gun, HVOF, APS.*

Introduction

Gas turbine engines are the basis of modern aviation, energy and maritime transport, playing a key role in both the civil and military sectors. The efficiency, power and reliability of these dual-purpose mechanisms directly depend on the durability of the components that are operating in the hot section (exhaust tract) of the engine [1]. Among such components, a special place hold parts with complex geometric shape, in particular the blades of the nozzle apparatus (NGV, Fig. 1), which are one of the most loaded structural elements. The high cost of their manufacture from heat-resistant superalloys and difficulty of replacement makes the task of extending their operational life extremely relevant from an economic and strategic point [2].

The main problem limiting the service life of NGVs is the complex multimodal degradation of their surfaces, which are simultaneously exposed to extreme thermal, mechanical and chemical loads [3]. Monolithic heat-resistant superalloys, despite their unique properties, are not able to independently withstand such an aggressive environment for a long time without the use of special protective measures [4].

Traditionally, thermal barrier coatings (TBC) [5] are used to protect hot section elements, which are applied mainly by the atmospheric plasma spraying (APS) method [6]. Although they effectively reduce the thermal load on

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the base material, their porous structure, necessary for low thermal conductivity, makes them vulnerable to intense erosion by solid particles (Solid Particle Erosion, SPE) [7]. This leads to rapid destruction of the protective layer and premature failure of the part, which indicates the need to develop more reliable and comprehensive solutions.

Despite many years of research and significant progress in the development of surface hardening materials and technologies, the complex problem of increasing the wear resistance of complex-profile parts remains only partially solved. The complex geometry of parts limits the application of many traditional and even some advanced surface treatment technologies, creating “shadow zones” [8] or uneven coating [9].

Figure 1. Typical view of a one-part solid-metal NGV of GTE (3D Model)

Analysis of Research and Publications

NGV, as a subject of research, should be considered not only as a solid-metal complex-profile part, but also as an assembly unit (AU) [1, 2]. It is due to its diversity (but not only) the purpose of the GTE is formed, which directly affects the application: flight environment, selection of operating modes, accuracy and quality obtained during manufacturing.

NGVs are located directly behind the combustion chamber and is the first fixed element of the turbine that comes into contact with the combustion products. Its main purpose is to convert the thermal energy of the hot gas flow into kinetic energy and to form and direct the flow at an optimal angle to the working blades of the first stage of the turbine. The temperature of the gas flow can exceed 1300…1600°C, which is significantly higher than the melting point of structural materials. To prevent degradation of the main structural elements, namely the path surfaces of the blades, an internal complex air cooling system is designed, which directly affects the path or passes through the entire unit (if made as a AU), but even with that, the temperature and pressure still remain quite high, and the gas flow speed reaches supersonic values (depending on the application: M > 1…1.2). In this case, the application of protective coatings is not just a measure to extend the resource, but a necessary condition for engine operation over the entire range of modes. It allows to increase the turbine inlet temperature, which is a key factor for increasing the thermal and fuel efficiency of the GTE [2].

Degradation of the surface of the NGV blades is a complex process, which is caused not by the sequential, but by the simultaneous action of several destructive mechanisms. An effective protective coating must comprehensively resist each of them, precisely:

1) Erosion by solid particles (Solid Particle Erosion, SPE). SPE is the mechanical removal of material from a surface as a result of bombardment by solid particles contained in a gas stream. The sources of these particles can be sand, dust, volcanic ash that sucked into the engine from the environment, as well as soot formed in the combustion chamber. The intensity of erosive wear depends on the kinetic energy of the particles (their mass and velocity), the angle of contact with the surface (angle of attack), and temperature [10].

The mechanisms of erosive failure may differ for ductile and brittle materials. For metal substrates, a ductile mechanism is typical, which includes the processes of plowing and cutting. For ceramic coatings, such as TBC, a brittle mechanism is more typical, which consists in the formation and joining of microcracks with subsequent chipping off of material fragments. Erosion not only thins the part, changing its aerodynamic profile, but can also completely remove the protective coating, exposing lesser resistant layers and the substrate for further degradation [10].

2) High-temperature gas corrosion and oxidation. Chemical degradation is an equally significant factor in destruction. The gas stream is a chemically aggressive medium containing oxygen, water vapor and impurities such as sulfur, sodium and vanadium compounds (especially when operating on the seas or using low-quality fuel). At high temperatures, these components actively interact with the surface of the material, causing intense oxidation and hot corrosion [3, 11].

In systems with TBCs, the critical element is the interface between the ceramic top and the metal bonding layers. During operation, a layer of Thermally Grown Oxide (TGO), mainly Al_2O_3, is formed and grows on the surfaces. The accumulation of stresses in this layer is one of the main mechanisms leading to TBC delamination [3]. For cermet coatings similar to the Cr_3C_2-NiCr system, the degradation mechanism may be the oxidation of chromium and the carbide phase at temperatures exceeding their operating conditions [12].

3) Thermomechanical fatigue and creep. The operation of a gas turbine engine is characterized by cyclicity: start-ups, ramp-ups, power reductions, shutdowns etc. Each of the cycles is accompanied by rapid temperature changes, which causes cyclic thermal stresses in the materials. These stresses arise, in particular, due to the difference in the coefficients of thermal expansion (CTE) between the metal substrate and the ceramic or cermet coating. Repeating of such cycles leads to the accumulation of fatigue damage, the initiation and propagation of cracks. This process is called thermomechanical fatigue [3, 13].

At the same time, at high temperatures, under the constant mechanical loads (from the pressure of the gas flow), the material undergoes creep – slow plastic deformation.

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The combination of thermomechanical fatigue and creep is one of the most dangerous mechanisms of gradual degradation, which can lead to the destruction of the part.

It is important to understand that these mechanisms do not act in isolation, but synergistically, creating a cascade of interconnected destruction. For example, erosive damage to the surface does not simply remove material, but creates microscopic defects and areas of increased roughness. These defects act as concentrators and, as a result, sharply accelerate the initiation of fatigue cracks. At the same time, by removing the protective oxide layer or the top layer of the coating, erosion opens access to aggressive gases to the «fresh» surfaces, repeatedly intensifying the corrosion and oxidation processes. Thus, the initial mechanical damage from SPE acts as a catalyst for further chemical and mechanical destruction. This proves that an effective coating must be not only dense (to resist erosion), but also viscous, dense and firmly bonded to the base to prevent the formation of primary damage that triggers this destructive cascade. Such a model of synergistic degradation also indicates the insufficiency of single-factor laboratory tests (for example, only for erosion or only for oxidation) to adequately predict the behavior of the material in real operating conditions.

Purpose of the Work

The main goal of this work is to scientifically substantiate the technological approach of significantly increasing the wear resistance of the NGVs of the GTE by applying advanced methods of applying protective coatings. To achieve this goal, the following tasks were set:

1. To analyze the complex wear mechanisms acting on the surface of the NGVs blades under operating conditions.
2. To review and select the optimal materials of the substrate and protective coating.
3. To perform a comparative analysis of modern coating technologies, considering the choice of detonation spraying method as the most promising one.
4. To develop a comprehensive methodology for experimental research and evaluation of the properties of the proposed coatings, based on international standards.

Materials and Research Methods

The basis for the manufacture of NGVs blades are cast or deformed nickel superalloys. These are complex multicomponent systems based on nickel with a face-centered cubic (FCC) crystal lattice, capable of maintaining strength, creep resistance and corrosion resistance at temperatures approaching 80...85 % of its own melting point. Their unique properties are achieved through complex alloying. Elements such as chromium (Cr) and aluminium (Al) form protective oxide films (Cr_2O_3 and Al_2O_3) on the surface, which provide resistance to oxidation. Molybdenum (Mo), tungsten (W), tantalum (Ta) and rhenium (Re) strengthen the solid solution (matrix). However, the key role is played by aluminum (Al), titanium (Ti) and niobium (Nb), which are dispersed particles of the intermetallic γ′-phase (for example, $Ni_3(Al, Ti)$), which is the main strengthening element that effectively blocks the movement of dislocations at high temperatures [2, 3].

As typical representatives of materials for NGV, one of the following can be noted:

а) ЖС6У (ZhS6U) is a cast heat-resistant nickel-based alloy widely used in post-soviet GTE manufacturing. It demonstrates high long-term strength: it is able to withstand a stress of 230 MPa at a temperature of 975 °C for at least 40 hours. The short-term strength limit at room temperature was 830 MPa [14].

б) Inconel 718 is one of the most common deformed superalloys on an iron-nickel basis in the world. Its feature is the strengthening by γ″-phase (Ni_3Nb), which provides high strength at temperatures up to 700 °C, as well as good weldability and processability. This alloy is often used as a model substrate material in the study of coatings [2, 3]. In the following consideration and as the main material, this material will be chosen.

To ensure reliable operation of superalloys in the conditions of the hot gas turbine tract, multifunctional coating systems are used, which can be classified according to their main purpose, namely:

1) thermal protective coatings (Thermal Barrier Coatings, TBC). The main task of TBC is to create a thermal barrier between the hot gas flow and the cooled metal part. Such a coating is able to reduce the temperature on the metal surface by 100…170 °C, which allows either to increase the gas temperature in the turbine (increasing efficiency), or to increase the service life of the part at the same temperature. Classical TBC has a multilayer structure [3, 5]:

- top ceramic layer (Top Coat). Usually made of zirconium dioxide stabilized with 7…8 % yttrium oxide (YSZ). The material provides low thermal conductivity, high melting point and thermal expansion coefficient close to the CTE of the metal base. To reduce thermal conductivity, controlled porosity is created in the structure of this layer (up to 15…20 %);
- metal bonding layer (Bond Coat). Applied between the substrate and the ceramic layer. Performs two functions: provides strong adhesion of ceramics to the metal and protects the substrate from high-temperature oxidation. Usually these are alloys of the MCrAlY type (where M is Ni, Co or their combination).

Despite the high efficiency of thermal protection, its porosity, that is key to thermal insulation properties, which becomes the main weakness of TBC under conditions of intense erosion. Erodent particles easily destroy the fragile ceramic structure, penetrating into the pores and causing destruction by the «tunnelling» mechanism. This creates a fundamental conflict of properties: a coating optimized for thermal insulation is vulnerable to mechanical wear.

2) Wear-Resistant Cermet Systems. To counteract mainly erosive and corrosive wear, cermet coatings are

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used that combine a hard ceramic phase and a plastic metal matrix bond. The most widespread are:

- Cr_3C_2-NiCr system identified as one of the best candidates for protection against wear at high temperatures (up to 850…900 °C). The hard chromium carbide (Cr_3C_2) particles provide high hardness and resistance to abrasive wear, while the nickel-chromium alloy (NiCr) matrix provides the coating with the necessary ductility, fracture toughness, and excellent resistance to oxidation and hot corrosion due to the formation of a stable Cr_2O_3 oxide film. However, during prolonged operation at very high temperatures, phase transformations may occur in the structure of this coating, in particular, the release of secondary carbides, which leads to the creation of brittleness and a decrease in crack resistance [6, 7];
- WC-Co system is considered as a reference for protection against abrasive and erosive wear at low and moderate temperatures (not exceeding 500 °C). Extremely hard tungsten carbide (WC) particles provide exceptional wear resistance, and the cobalt (Co) binder provides high viscosity. By changing the cobalt content, the balance between hardness and viscosity of the coating can be adjusted. The main disadvantage of this system is its low resistance to oxidation at high temperatures, which makes it unsuitable for use in the hot tract of a gas turbine engine, but useful for comparative studies [6, 7].

The above analysis reveals the key dilemma of «insulation versus integrity». Dense, wear-resistant metal-ceramic coatings have significantly higher thermal conductivity than porous TBCs, which leads to a higher thermal load on the substrate. Conversely, TBCs optimized for thermal insulation quickly fail due to erosion. This contradiction indicates that the monolithic single-layer coating structure is inherently a compromise. The optimal solution probably lies in the creation of multilayer or functionally graded materials (FGM) [15]. Such an architecture could combine, for example, an inner, more porous layer for thermal insulation and an outer, dense, hard and erosion-resistant layer deposited using a high-energy process. This shifts the focus of the research from the question of «Which material?» to the question of «What is material architecture?».

Consideration of types of protective coatings should be carried out in tandem with modern methods and surface technologies that allow to control the stability of the process of application to the material. The most advanced method today can be considered the detonation spraying method. Detonation Spraying (D-Gun) is a thermal spraying method invented in 1955 by a group of researchers consisting of H.B. Sargent, R.M. Poorman and H. Lamprey [2, 16]. This process is fundamentally different from other spraying methods due to the use of energy from a controlled explosion.

The working tool is a detonation gun – a long water-cooled barrel, closed on one side. A precisely dosed portion of an explosive gas mixture (usually acetylene + oxygen) and powder coating material are fed into the gun chamber. The mixture is ignited by a spark, which initiates detonation – a combustion process that propagates at supersonic speed and is accompanied by the formation of a shock wave. This detonation wave heats the powder particles to a plastic or molten state and accelerates them to extremely high speeds, reaching 1200 m/s. With high kinetic energy, the particles hit the surface of the part, undergo significant plastic deformation, and form a dense layer of coating. The process is cyclical: the frequency of «shots» is in range from 1 to 10 Hz. After each shot, the barrel is purged with inert gas (nitrogen) to remove combustion products and prepare for the next cycle. This method has the following advantages [2]:

1. High density and low porosity. Due to the enormous kinetic energy of the particles during collision, occurs effective compaction. As a result, coatings with extremely low porosity are formed, which often does not exceed 1…2 % and is critically important for preventing the penetration of corrosive agents deep into the coating and for achieving maximum wear resistance;
2. Extremely high bond strength (adhesion). High-velocity impact not only provides strong mechanical engagement of particles with irregularities of the prepared surface, but can also initiate local metallurgical processes (like «microwelding») at the surface. This results in the formation of coatings with bond strengths that significantly exceed those of other thermal spraying methods (often over 70 MPa);
3. Creation of residual compressive stresses. Bombarding the surface with high-velocity particles creates an effect similar to shot-peening. Favorable residual compressive stresses are formed in the surface layer of the coating. This is a unique and extremely important advantage, since the compressive stresses counteract the tensile stresses arising from thermal mismatch and external loads, effectively inhibiting the initiation and propagation of cracks and, thus, increasing fatigue life;
4. Minimal thermal load on the substrate. Despite the high temperature in the detonation wave, the interaction time of hot gases and particles with the substrate is very short due to the pulsed nature of the process. The total heat flux transferred to the part is significantly less than with plasma spraying. This minimizes the risk of part distortion, undesirable structural changes in the substrate material and the size of the heat affected zone (HAZ).

To justify the choice of detonation spraying technology, it is necessary to compare it with the main alternative high-energy methods: high-velocity oxygen-fuel (HVOF) and atmospheric plasma (Atmospheric Plasma Spraying, APS) spraying (Table 1):

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Table 1 – Comparative characteristics of high-energy thermal spraying methods

Parameter	Spraying methods		
	D-Gun	HVOF	APS
Heat Source	Detonation of the O_2-fuel mixture	Continuous combustion O_2-fuel	Direct current electric arc (plasma)
Velocity of the Gas (particles)	Very high (~ 1200 m/s)	High (~ 600…1000 m/s)	Middle (~ 200…500 m/s)
Temperature of the Gas (Particles)	High (~ 3000…4000 °C)	High (~ 2800…3300 °C)	Very high (up to 16000 °C)
Porosity of the coating	Very low (< 1…2%)	Low (1…3 %)	Moderate high (5…15 % and higher)
Grip Strength	Very high (> 70 MPa)	High (> 60 МПа)	Moderate (20…40 MPa)
Residual Stresses	Compressive	From weakly compressive to tensile	Mostly tensile
Main Application	Extreme wear and erosion resistance	Wear and corrosion resistance	Thermal barrier coatings (TBC)

1) High-velocity oxy-fuel spraying (HVOF). This process also uses the combustion of a fuel-oxygen mixture to heat and accelerate particles, but unlike detonation, continuous combustion occurs in a high-pressure chamber, the products of which are accelerated to supersonic speeds in a specially designed nozzle. HVOF allows for very high-quality, dense coatings with high adhesion and is considered a direct competitor to D-Gun. However, as a rule, particle velocities in the D-Gun process are even higher, which provides an advantage in density, adhesion and compressive stress levels. Analysis of the case of the failure of a Cr_3C_2–NiCr HVOF coating due to thermal embrittlement shows that even a small improvement in coating quality (density, residual stresses) that detonation spraying can provide will be crucial for extending the service life [6, 17, 18].

2) Atmospheric Plasma Spraying (APS). With this method, a plasma jet generated by an electric arc in a plasma-forming gas flow (argon, nitrogen, hydrogen) is used to heat the material. The temperature in the plasma can reach about 16000 °C, which allows melting all, even the most refractory materials. However, the particle velocity in APS is significantly lower than in D-Gun and HVOF. This leads to the formation of coatings with higher porosity and lower adhesive strength. Such properties make APS coatings less suitable for applications requiring maximum wear resistance, but ideal for applying TBC, where porosity is functionally necessary [6, 9, 19].

The choice of coating technology is determined not only by the desire to obtain «good» properties, but also by the necessity to create a specific stress-strain state in the «coating-substrate» system. The residual compressive stresses, which are an inherent property of detonation coatings, give them a unique mechanistic advantage. They directly counteract the main driving forces of coating failure – tensile stresses from thermal mismatch and fatigue loads. While the HVOF process can also produce high-quality coatings, the level of compressive stresses in them is usually lower, or they may even be tensile, making them more vulnerable to thermomechanical fatigue, as demonstrated in the analyzed failure case. This emphasizes that when evaluating and comparing coatings, measuring residual stresses is as important as determining hardness or adhesion.

Discussions

To validate the proposed technological solution and quantitatively assess the effectiveness of protective coatings, it is necessary to develop and implement a comprehensive program of experimental research and methods for assessing the properties of coatings, based on the recognized international standards ISO 2063 [20, 21] and ASTM C633 [22], as well as described in the literature [3, 4]. Let's consider in stages:

1) Stage I – formation of experimental samples: selection of the «substrate-coating» system. It includes:

- choice of substrate material. As a substrate material for experimental samples, it is advisable to choose the heat-resistant superalloy Inconel 718 or the alloy ZhS6U, which are representative of real NGVs (or in particular NGVs blades). The samples are made in the form of plates with standard sizes (for example, 25×25×5 mm);

- surface preparation. The quality of adhesion of the coating to the base critically depends on the condition of the - - surface. Therefore, before spraying, a mandatory blast-abrasive treatment with an abrasive powder (for example, Al_2O_3 based electrocorundum) is performed to clean it from dirt and oxides and create a matte and smooth relief, which improves mechanical adhesion;

- selection of coating material. Based on the analysis, a metal-ceramic powder of the Cr_3C_2-25(Ni20Cr) system was selected as the main candidate, which has proven its effectiveness in high-temperature wear-resistant applications;

- application process. The coating is applied by detonation spraying to a specified thickness (e.g. 200…400 µm). Key process parameters (oxygen/acetylene ratio, shot frequency, spraying distance) should be documented to ensure reproducibility.

Stage II – analysis of microstructural and physical-mechanical characteristics. The structure and properties of the obtained coatings are studied using the following standardized methods:

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2.1) checking microstructure, porosity and phase composition using:

- scanning electron microscopy (SEM) [24]. It is used for visual analysis of the microstructure of the coating on a cross-sections. SEM allows to estimate the thickness of the coating, its layered (or lamellar) structure, the quality of the coating-substrate interface, as well as to qualitatively assess the presence of pores and other defects;

- energy-dispersive X-ray spectroscopy (EDS/EDX) [25]. It is used as a complementary instrument to SEM to map the distribution of chemical elements across a sample cross-section. This method allows to confirm the composition of the coating, to detect the presence of oxide inclusions and to investigate possible diffusion of elements at the interface with the substrate;

X-ray diffraction (XRD) [26]. A key method for identifying crystalline phases in a coating (e.g. Cr_3C_2, Ni-based and Cr-based phases). XRD also allows for the detection of undesirable phase transformations after thermal treatment and is one of the main methods for quantitatively measuring residual stresses in a coating.

2.2) microhardness measurement. Microhardness measurement is one of the main methods for assessing the mechanical properties of a coating. Testing is performed on a cross-section of the sample using the Vickers method in accordance with ISO 6507 or ASTM E384 standards. A diamond indenter in the form of a tetrahedral pyramid is used, which is pressed into the surface under a given load (for example, 300 gf or 2.94 N). Measurements are carried out at different distances from the surface to the substrate, which allows you to build a hardness distribution profile over the thickness of the measured coating.

2.3) assessment of adhesive and cohesive strength. It is carried out in two ways:

- peel test (according to ASTM C633) – this is the main quantitative method for measuring the adhesion strength of a coating to a substrate. The essence of the method is to glue a special cylindrical pin to the surface of the coating, which is then torn off on a tearing machine, and the maximum load at which the fracture occurred is recorded. It is also important to analyze the fracture surface: if it occurred at the «coating-substrate» boundary, then the measured value is the adhesion strength; if the fracture occurred inside the coating layer – cohesive;

- by the grid incision method (according to ISO 2409). A simpler, qualitative method for rapid assessment of adhesion. A grid of mutually perpendicular lines is cut on the surface of the coating, onto which adhesive tape is glued and sharply torn off. Adhesion is assessed visually using a classification scale depending on the area of the peeled coating.

2) Stage III – assessment of operational properties. Let's divide this stage into two components:

3.1) erosion resistance test. This test is carried out on a specialized gas erosion machine according to the procedure specified in ASTM G76 [23]. This standard describes a well-established method for comparing the erosion resistance of different materials. It consists of:

- test parameters. To simulate real operating conditions, it is necessary to set key parameters: erodent material (e.g., Al_2O_3), particle size (e.g., 50 μm), flow rate, angle of attack (e.g., 30° to simulate tangential erosion and 90° to simulate direct impact), and test temperature (up to 850…950 °C);

- evaluation criterion. Erosion resistance is quantified by the loss of mass or volume of the sample relative to the total mass of abrasive that interacted with the surface.

3.2) analysis of degradation mechanisms under high temperature exposure. To assess the thermal stability of the coating, isothermal or cyclic oxidation resistance tests are proposed. The coated samples are kept in a furnace at a high temperature (e.g. 900 °C) for a long time. After the exposure, metallographic analysis (SEM/EDS, XRD) is performed to detect changes in the microstructure, phase composition (e.g. the precipitation of secondary carbides, which was observed for HVOF coatings) and to study the oxidation kinetics.

The proposed methodology poses a direct, scientifically speaking «challenge», to noted failure mechanisms. The experimental design is not arbitrary: it is specifically designed to demonstrate that the proposed solution (detonation coating of the Cr_3C_2-NiCr system) overcomes the known weaknesses of alternative technologies (HVOF Cr_3C_2-NiCr). By subjecting the detonation coating to the same thermal stress that caused the failure of the HVOF counterpart and by analyzing its phase stability and microstructure, this experiment directly tests the hypothesis that the superior microstructural quality and favorable stress state of the detonation coating prevents or slows down this specific failure mechanism. This translates the research from the general statement «detonation spraying is better» to the specific, scientific question «Does the detonation spraying process suppress the high-temperature embrittlement observed in HVOF coatings of the Cr_3C_2-NiCr system?». A positive result of such an experiment will not only confirm the choice for this application, but will also be a significant contribution to materials science regarding the comparative thermal stability of coatings obtained by various high-energy methods (Table 2).

The synthesis of the above data allows us to suggest that the detonation spraying technology is unique and most suitable for solving the problem, since it is able to form a coating of the Cr_3C_2-NiCr system with the necessary combination of properties: high density, excellent adhesion and, most importantly, a favorable field of residual compressive stresses [27]. This combination allows us to effectively resist the synergistic destructive effects of erosion, corrosion and thermomechanical fatigue. It is cardinally differs detonation spraying from APS, which forms porous structures, and HVOF, the coatings of which may have less pronounced compressive stresses or even tensile stresses, which makes them more vulnerable to thermal instability and cracking [27, 28].

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Table 2 – Standardized test methods for the characterization of coatings

The property that is found	Standard	Principle of the Method	Output indicator
Erosion Resistance	ASTM G76	Bombardment of a surface with solid particles in a gas stream at a controlled angle and speed.	Loss of mass or volume per unit mass of erodent (e.g., mg/g).
Adhesive Strength	ASTM C633	A pull-off test in which a pin glued to the surface of a coating is pulled off by tensile force.	Failure stress (MPa) and failure location.
Adhesion (qualitative assessment)	ISO 2409	A grid is cut on the coating, then adhesive tape is applied and peeled off. Adhesion is assessed by the amount of coating removed.	Classification score (at a scale from 0 to 5) based on visual inspection.
Microhardness	ISO 6507, ASTM E384	A diamond indenter (Vickers pyramid) is pressed into the surface under a certain load. The size of the imprint is measured.	Hardness value (HV) with load indication (e.g. 0.3 HV).

Despite the advantages, when implementing the technology, potential challenges must be taken into account, namely:

thermal mismatch. Even in the presence of compressive stresses, the significant difference in the coefficient of thermal expansion (CTE) between the nickel superalloy substrate (CTE $\approx 15.5\times10^{-6}$ K^{-1}) and the Cr_3C_2–NiCr coating (CTE $\approx 10.9\times10^{-6}$ K^{-1}) remains a risk factor that generates high interface stresses during thermal cycling. To mitigate this effect, one can consider using an intermediate, more ductile sublayer (e.g., NiCr) [6]. A more advanced solution is to use CCDS technology to create a functional gradient transition that will ensure smooth changes in properties from the substrate to the surface [15, 29];

process quality control. Stability of coating performance requires thorough control of the spraying process parameters. It is necessary to implement modern quality management methodologies, such as failure mode and effects analysis (FMEA) and «Six Sigma» to ensure high reproducibility and reliability of coatings [30];

complexity of geometry. Applying a coating of uniform thickness and properties to the aerodynamic profile of the NGVs blades is a complex technological task. Its solution requires the use of robotic multi-axis manipulators to move the detonation gun due to the complex spatial trajectory [6].

Based on the analysis of the exceptional properties of detonation coatings, it is possible to predict a significant increase in the operational life of the NGV. Creating a more damage-resistant surface that effectively resists the formation of primary defects (erosion ulcers, microcracks), the proposed coating destroys the degradation cascade. This leads to a nonlinear, significant increase of the durability of the component, which, in turn, increases the reliability of the engine as a whole mechanism, reduces maintenance and repair costs and increases the technical availability factor (TAF).

Conclusions

Based on the analysis, the following conclusions can be formulated:

The operational resource of the NGV of the GTE is limited by the simultaneous action of a complex of destructive factors, such as erosion by solid particles, high-temperature corrosion and thermomechanical fatigue.

A comparative analysis of modern technologies has shown that detonation spraying is the most promising method for application, does not allow the formation of a coating with practically zero porosity, extremely high adhesion and favorable residual compressive stress indicators.

As an optimal solution, a metal-ceramic coating based on Cr_3C_2-NiCr, applied by the detonation spraying method, is proposed. It provides a better balance of the strength, toughness and resistance to aggressive environments, compared to traditional or other metal-ceramic systems.

A comprehensive experimental validation program based on international ASTM and ISO standards is proposed, which allows for a comprehensive assessment of the microstructural, physical-mechanical and operational properties of the proposed coating.

The implementation of this application technology will lead to a significant increase in the durability and reliability of critically important components of dual-purpose mechanisms, which provides significant economic advantages both during manufacturing and operation.

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ПІДВИЩЕННЯ ЗНОСОСТІЙКОСТІ СКЛАДНОПРОФІЛЬНИХ ДЕТАЛЕЙ МЕХАНІЗМІВ ПОДВІЙНОГО ПРИЗНАЧЕННЯ

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Мета роботи. *Метою даної роботи є наукове обґрунтування технологічного підходу до значного підвищення зносостійкості лопаток соплового апарату(СА) ГТД шляхом застосування передових методів нанесення захисних покриттів.*

Методи дослідження. *Методи дослідження включали підбір типових матеріалів для проведення досліджень (сплави ЖС6У та Inconel 718), розгляд багатофункціональних систем покриттів та їх класифікацій (теплозахисні покриття (Thermal Barrier Coatings, TBC), зносостійкі металокерамічні системи (Wear-Resistant Cermet Systems)), методи напилення (детонаційне напилення (Detonation Spraying, D-Gun), високошвидкісним киснево-паливним (High Velocity Oxygen Fuel, HVOF, атмосферним плазмовим напиленням (Atmospheric Plasma Spraying, APS) та аналіз наукових досліджень, що підтверджують ефективність зазначених методів.*

Отримані результати. *Аналіз наявних досліджень та літератури показав, що технологія детонаційного напилення є унікальною та найбільш придатною для вирішення поставленої задачі, оскільки вона здатна сформувати покриття системи* Cr_3C_2*-NiCr з необхідною комбінацією властивостей: високою щільністю, відмінною адгезією та, що найважливіше, сприятливим полем залишкових напружень стиснення.*

Наукова новизна. *Наукова новизна роботи полягає у системному підході до вирішення складної проблеми захисту лопаток СА (деталей та механізмів подвійного призначення) шляхом застосування технології детонаційного напилення, яка відома своєю здатністю формувати надзвичайно щільні та зносостійкі покриття.*

Практична цінність. *Практичне значення дослідження полягає у потенційній можливості суттєвого збільшення міжремонтного ресурсу, надійності та боєготовності критично важливих елементів ГТД.*

Ключові слова: *ГТД, лопатка соплового апарату (СА), суперсплав, ерозія твердими частинками, високотемпературна газова корозія, окислення, TBC, D-Gun, HVOF, APS.*

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