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PROTOTYPE EQUIPMENT AND TECHNIQUES FOR OBTAINING CAVITATION-RESISTANT COATINGS TO BE APPLIED TO WORKING SURFACES OF STEAM TURBINE BLADES MADE OF VT6 TITANIUM ALLOY IN ORDER TO REPLACE IMPORTED COUNTERPARTS

Prototype equipment and techniques for obtaining the cavitation-resistant coatings to be deposited on the working surfaces of steam turbine blades made of VT6 titanium alloy have been designed and manufactured. The selection and of composition and conditions of synthesis of optimal coating for hardening the blades have been justified. The parameters of coatings deposition on the blade model have been found, the trial deposition of coatings has been made. The VT6 titanium alloy samples with the preferred coatings have been tested under simulated operational conditions. The coatings have been deposited on the blade model of up to 130 cm long and up to 30 kg heavy. The rate of TiN-based coating deposition was ~10 μm/h.

Keywords: coatings, vacuum-arc method, cavitation firmness, and turbine blades.

Within the framework of the government program for import substitution, *Turboatom*, OJSC, has established mass production of turbine blades of VT6 titanium alloy for replacing the worn-out parts of NPP turbines. According to the technical specifications for these blades, to ensure their desired service life, cavitation-resistant protective coatings should apply to the blade working surfaces inasmuch as they are exposed to high-condensed steam in the low-pressure part of the turbine. To this end, it is necessary to design and to implement new technologies for import substitution in power engineering.

For the time being, in Ukraine, at some NPP, the exhaust rows have exceeded their life cycle and should be replaced. In this regard, the *Energoatom* National Nuclear Energy Generating Company has charged *Turboatom* with mastering the serial manufacture of these blades of VT-6 alloy. Since the technical specifications for manufacturing these blades foresee application of anti-cavitation coatings, and the factory has neither appropriate equipment nor technologies, *Turboatom* ordered the National Research Center (NSC) KhPhTI to design the necessary technology and equipment.

KhPhTI has a long experience of such work, including the reinforcement of mid-stage blades. However, the *Turboatom* ordered the VT6 alloy blades with a maximum length of ∼1300 mm and a weight of ≥30 kg. At the beginning of this assignment, KhPhTI had no experience in working with equipment for processing such large products. It was necessary within a short term to make a conceptual design, to create a trial model and related techniques, to test and to work out the coatings with the most optimal properties, to make studies for justification of chosen configuration and processes, and ultimately to get a prototype. This will enable to make prototypes of products, to justify their suitability for the use under real conditions, and further to establish serial manufacture of the desired products.

The project is aimed at making conceptual design of equipment, basic processes, and a prototype for the application of cavitation-resistant coatings to large NPP turbine blades made of VT6 titanium alloy, in Ukraine.

The research, technical, and organizational measures aimed at achieving the project objectives, the following tasks have been solved:

- To design and to install laboratory equipment for the application of vacuum-arc coating on the blades having a length of up to 1300 mm and a weight of up to 30 kg;
- To select and to justify the composition of coating for reinforcing the blades with VT-6 alloy and to create a laboratory technique;
- To find optimal parameters of deposition process;
- To test coatings on the blades under simulated conditions close to the operation ones;
- To apply coating to prototypes of VT6 alloy blades;
- To prepare equipment for the production of coated blade prototypes.

DESIGN, INSTALLATION, AND DEBUGGING OF LABORATORY EQUIPMENT FOR THE APPLICATION OF VACUUM-ARC COATING TO THE BLADES

The design of equipment for applying the reinforcing coatings to the turbine blades is based on necessity to ensure the following options: treatment of large blades in the working chamber of equipment; use of advanced ion-plasma technologies for blade reinforcement by modification of titanium blade surface; reinforcement of titanium blades with maximum effectiveness and precise control of the parameters.

Large dimensions and heavy weight of processed products (turbine blades) complicate the design of laboratory equipment and require a nonstandard approach to it. Having searched and analyzed the known equipment, we chose 3-module configuration of vacuum chamber consisting of 3 serially connected vacuum chambers of *Bulat-6* basic installation.

At the initial stage, the components and assemblies which ensure required vacuum conditions for obtaining the coatings have been mounted and tested. Power supply systems have been made, connected, and debugged. The works included the mounting and debugging of six metal evaporator plants; debugging and connection of arc power supply sources; debugging and connection of ion bombarding rectifier; debugging of system for supplying and keeping the reactive gas pressure in the working chamber.

Final configuration of setup comprises vacuum-plasma unit, ion bombarding rectifier, arc power supply sources, control console, and means of plasma diagnostics. The vacuum-plasma unit consists of 3-module vacuum chamber with six plasma sources and rotary device, suction system, hydro-system, and gas supply system. The vacuum chamber is made of steel St. 3 and shaped as cylinder (Fig. 1).

The chamber axis is oriented vertically. The total length of 3-module chamber is 1500 mm, its diameter is 500 mm. At the lower and upper ends of the chamber, the covers are fixed with the hinge loops. On the side walls of the chamber, there are six openings with equal flanges to which plasma source and neck with fixed adapter to the suction system are attached. Also, on the side of the chamber, a nozzle inlet for working gas and a bracket for fixing the gas pressure regulator that automatically maintains the gas pressure at a given level. To ensure uniformity of the coating applied, the system is fitted with a rotary device having plasma sources arranged in three tiers. The rotary device ensuring the rotational-translational movement of the blade model is mounted on the top cover of the vacuum chamber. The blade model to be processed is attached to the rotary device.

The chamber body and the covers are cooled by running cold water during the measurement of plasma parameters and application of coating and are heated by hot water during the decompression, degassation, and pumping-out. All connectors are sealed with connection pads of vacuum rubber.

The chamber is connected through an interface to the high-vacuum apparatus. This device bears an air inlet valve, a ventilation valve and measuring tubes (PMT-1 PMI-10) as sensors of VIT-3 vacuum gauge.

Temperature is controlled remotely using a *Smotrych* infrared pyrometer through a window in the chamber with fluorite glass.

PROMISING COATINGS FOR REINFORCEMENT OF TITANIUM ALLOYS

A further increase in capacity of NPP turbines, which is urgently needed for the construction of new plants, requires from the designers of equipment to increase its reliability and efficiency using new advanced materials or modifying the existing ones. In this regard, titanium alloys substitute for steel in the design and manufacture of elements of powerful steam turbines. However, titanium and its alloys have low wear resistance of their surfaces, which requires modifications to improve their properties. The application of functional coatings to the working surfaces of products to improve their properties is the most effective method of targeted modification of materials surface properties.

Vacuum-arc deposition of protective coatings is the most widely used industrial technique of modifying the materials surface properties. The compounds based on transition metal nitrides, particularly, titanium nitride doped with one or more chemical elements [1] are the most widespread among the coatings obtained by this method. The advantages of nitrides are their great hardness, refractoriness, high-temperature ductility, high wear and corrosion resistance, etc. The nitride coatings are obtained from titanium plasma in the presence of nitrogen and have broadly modifiable structure, texture, and properties by varying the grain size, crystallographic orientation, lattice defects, texture, phase composition, and surface morphology.

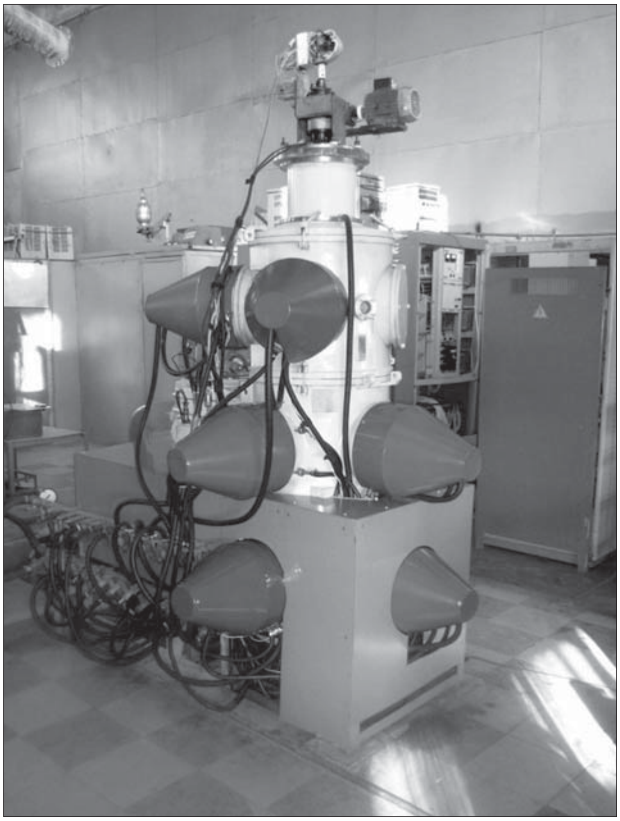


Fig. 1. General view of the facility consisting of three-modular vacuum chamber for deposition of cavitation-resistant coatings on turbine blades

Due to high physical, mechanical, thermophysical, anticorrosive and other properties, relatively cheap price and safety the titanium nitride is among the mostly used materials for alloy reinforcing coatings.

The most wear resistant materials are nonstoichiometrical monophasic coatings based on TiN; they have microhardness of about 25 GPa. The nitrogen content is about 40% [2]. TiN coatings have been used successfully to improve the erosion and corrosion resistance of the steam turbine blades made of titanium alloys and the compressor blades of aircraft turbine engines [3, 4].

Recently, the structure-phase state and functional properties relationship for the nitride coatings has been studied depending on the conditions and methods of their synthesis. It has been

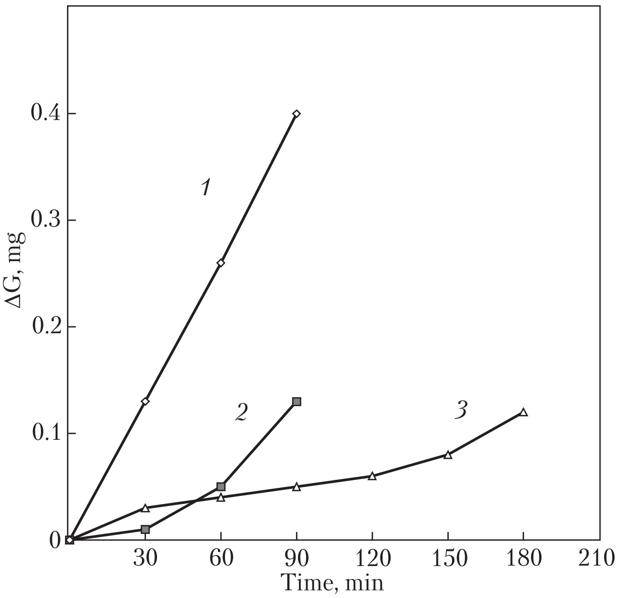


Fig. 2. Kinetic curves of cavitation wear of VT6 sample surfaces: uncoated (*1*); with TiN coatings obtained at a pressure of nitrogen $p = 0.2$ Pa (*2*) and at $p = 2.0$ Pa (*3*)

established that significant changes in the structure and properties of nitride coatings are achieved as a result of doping with such elements as Si, B, Al, Y, Ni, Cr and others. The extremely high effectiveness of nitride coatings doped with these elements insoluble under equilibrium conditions has been showed to be caused by their thermodynamically controlled segregation on the boundaries of TiN grains with the formation of grain boundary phase restraining the grain growth [5]. At the KhPTI RSC, the researchers have synthesized a series of different nitride coatings: TiN; Ti + TiN; (Ti—Al)N; (Ti—Al—Si)N; (Ti—Al—Y) N; (Ti—Zr)N; TiCN and studied their structure, texture, corrosion resistance, erosion resistance, and cavitation resistance [6—8].

Today, the most durable coatings are those based on TiAlN. In addition to possessing the high physical and mechanical properties of titanium nitride, while being heated in air, their surface is covered with a dense layer of aluminum oxide (microhardness of 12—13 GPa) [9], which prevents further oxidation of the coating and adhesive interactions with base material. The introduction of chromium and yttrium to the TiAlN-based coatings improves their resistance to oxidation.

Fig. 2 shows the kinetic curves of cavitation wear for the coatings of various composition:

TI-N; (Ti—Al) N; (Ti—Al) N + 0,4 wt. % Y; (Ti—Al) N + 1 wt. % Y.

The plasma flows were separated from macroparticles while coating with the use of straight-line magnetoelectric filter [10]. Fig. 2 shows that the kinetic curves can be conditionally divided into three setions. The first one corresponds to the removal of weakly bound particles from the coating surface; the second one descrives the destruction of the coating itseld, and the third sec-

Table 1

Summarized Data on Mechanical Properties of Doped Nitride Coatings

Composition, weight%	Thickness, μm	Hardness H, GPa	Young Modulus E, GPa	H^3/E^2, GPa	Ra, nm	Cavitation wear, mg/g	Abrasive wear, mg/g
TiN massive		26	468	0.08			
TiN	10	31	438	0.16	47	0.93	0.05
(Ti + TiN) × 6	6	29	380	0.17	63	1.66	
$Ti_{98}Al_2N$	10	36	437	0.24	50		0.1
$Ti_{90}Al_{8,5}Si_{1,5}N$	10	40	452	0.31	36	6.99	0.02
$Ti_{68}Al_{1,7}Y_{0,3}N$	10	37	448	0.25	21		0.04
$Ti_{69,5}Al_{30}Y_{0,5}N$	12	30				0.125	
$Ti_{55}Zr_{45}N$	6	35	400	0.27		0.38	

tion corresponds to the destruction of the coating together with the substrate.

Average rate of cavitation and abrasion of the (Ti-Al-Y)N coatings is 3—5 times lower than that of the (Ti-Al)N coatings and 10 times lower than that of TiN ones, due to yttrium key role in suppressing the columnar growth and formation of nano-crystalline structures with strong inter-grain boundaries. The summarized data on the mechanical properties of doped nitride coatings are given in Table 1 [6].

Vacuum arc deposition of TiSiN nitride coatings [6, 7] has been conducted in gas mixtures with various proportions of gas components, nitrogen and argon. Under the gas mixture pressure $p > 5 \cdot 10^{-3}$ Torr, the regime ensuring the highest coating hardness and the resulting dependence on the amount of argon component in the mixture have been established. For the argon share of 8—12%, the coatings of ~ 50 GPa hard have been obtained, which exceeds 1.7 times the hardness of the coatings obtained in nitrogen.

The introduction of chromium to the TiN based coatings improves their resistance to oxidation. Micro-hardness of TiCrN-based coatings ranges within 25—39 GPa. Bombarding of the

Table 2

Weight Loss of VT6 Alloy Samples with Various Coatings During the Cavitation and Erosive Wear Tests, mg

Coating	t. hours			
	0.5	1.5	2.0	3.5
	Wear, mg			
TiN — p(N_2)=0.2 Pa	0.01	0.13		
TiN — p(N_2)=2 Pa	0.03		0.06	0.12
Ti-TiN (40 layers)	0.20			
Ti-TiN (15 layers)	0.22			
TiCN	0.29			
TiCrN	0.32			
TiVN	0.10			

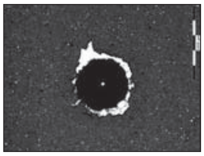
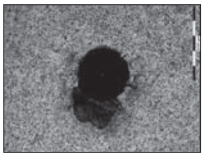
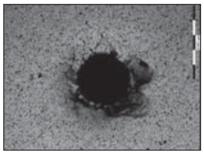
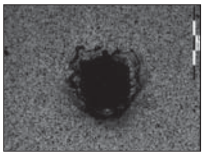
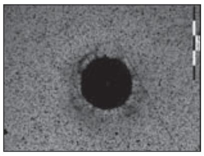
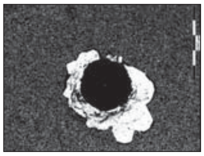
Table 3

Abrasive Wear of VT6 Alloy Samples with TiN-Based Coatings

Coating	Δt, hours	ΔG, mg
TiN — p (N_2) = 0.2 Pa	0.5	0.11
TiN — p (N_2) = 2 Pa	0.5	0.18
Uncoated VT6	0.5	56.80

Table 4

Data on Nano-Hardeness, Elasticity Modulus, and Adhesion of Coatings (TiN, Ti-TiN, TiCrN, TiVN, and TiCN) Deposited on the VT8 Titanium Alloy Samples

Type of coating	H, GPa	E, GPa	Rockwell Test	Adhesion, score
Ti — TiN (40 layers)	20	300		HF5
TiN — p (N_2) = = 2 Pa	25	450		HF4
TiN — p (N_2) = = 0.2 Pa	26	400		HF4
TiCrN	25	400		HF3
TiVN	27	400		HF1
TiCN	25	420		HF6

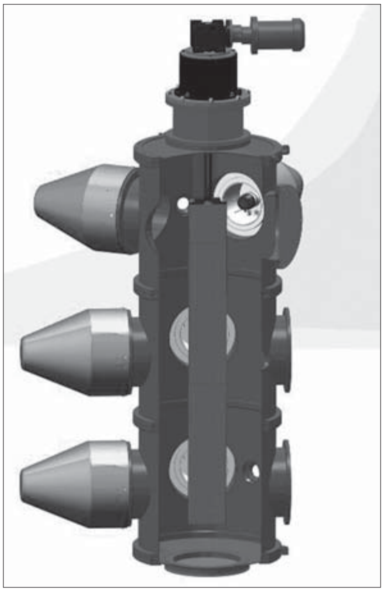


Fig. 3. Arrangement of blade models in the rotary unit inside the three-modular vacuum chamber

substrate with chromium ions improves the adhesion to the coating; in addition, chromium increases the oxidation resistance [6, 11]. The addition of chromium to the titanium cathode composition has significantly improved the physical and protective properties of TiN-based coating and shifted it up from the hard to the super-hard class. Among advantages of chromium addition to the coatings there are a significant decrease in elasticity modulus as compared with TiN-based coatings, a considerable growth in H/E and H^3/E^2 ratios characterizing the wear resistance and strength of deposited condensates, and doubled corrosion resistance. The TiCrN coatings are notable for higher durability as compared with the TiN ones. However, their properties yield to those of the TiAlN-based coatings.

The TiCN-based coatings have a high hardness and a low friction coefficient as compared with titanium nitride. The carbonitrides of transition metals are interesting due to their unique properties such as high hardness, conductivity, temperature resistance, elasticity, and resistance to corrosion. The TiCN coatings are harder than TiN, but they are more fragile and oxidized at much lower temperature [12]. The micro-hardness of coatings depends on the composition and pressure of the reacting mix during application. It grows as the acetylene content increases and can reach 40 GPa [8].

CAVITATION AND ABRASION RESISTANCE TESTS AND OPTIMIZATION OF COATING COMPOSITION

The coated samples have been tested for resistance to cavitation erosion and wear on the trial facility [13, 14]. The facility includes a magnetostrictive vibrator with ultrasonic vibration concentrator located in a bath of water and simulating intensive water shock effect on the coated samples.

Having studied the influence of the type and composition of coatings on their resistance to wear it all samples were established to improve their properties in comparison with the original samples. The previous studies reported that both one-component and multicomponent TiN-based coatings (TiN, TiN + Ti, TiAlN, TiCrN, TiCN) are the most promising in terms of practical use as cavitation resistant coatings for turbine blades. The VT6 alloy samples were coated with selected promising hardeners 10 μm thick. The samples of

Table 5

Basic Characteristics of Nitride Coatings Deposition on Turbine Blade Models

Parameters	Value
Boundary vacuum in the chamber (pressure), Pa	$1{,}33 \times 10^{-3}$
Working pressure of nitrogen, Pa	2...3 Pa
Working gas	N_2
Number of evaporators	6
Arrangement of evaporators	Three tiers
Ion current density, A/m²	1...300
Maximum size of processed products, cm	≤130
Weight of processed products, kg	≤30
Deposition rate TiN, μm/g	10
Power consumed by facility during deposition of coatings, kW	Up to 45

VT-6 titanium alloy with the selected coatings were tested for stability under the action of cavitation, on the trial facility.

Table 2 shows the data on stability of samples with cavitation- and erosion-resistant coating obtained during the test. As one can see from Table 2, the most resistant to cavitation and erosion wear are the VT6 alloy samples with TiN-based coatings. Fig. 2 shows the kinetic curves of cavitation wear of surfaces of the TiN-coated VT6 alloy samples and the uncoated ones obtained at different nitrogen pressure (0.2 Pa and 2 Pa).

Table 3 features the dependences for abrasion wear of surfaces of TiN-coated VT6 alloy samples at different nitrogen pressures ($1 - p = 10^{-1}$ Pa; $2 - p = 3.0$ Pa) on trial time.

Table 4 shows the data on nano-hardness, elasticity modulus, and adhesion of coatings (TiN, Ti-TiN, TiCrN, TiVN, and TiCN) on the samples of VT8 titanium alloy. The adhesion was measured by Rockwell-C test through hardness indentation at a load of 150 kg. The score was assigned in accordance with [15].

Based on the test results, the TiN-coatings deposited on a substrate of VT6 titanium alloy at different nitrogen pressures ($p_{N2} = 2$ Pa and $p_{N2} = 0.2$ Pa) were selected for the further study. The samples of these coatings have showed an acceptable adhesion (Table 4), a significantly higher resistance to cavitation and erosion wear (Table 2), as well as to abrasive erosion under friction (Table 3). It should be noted that the TiN coatings obtained at high nitrogen pressure have an advantage insofar as when nitrogen pressure increases up to approximately 1 Pa, the coating micro-hardness decreases, with the coatings becoming monophasic and resistant to wear and erosion [16]. The quantity and size of drop phase decrease as well.

Thus, proceeding from the requirements for the coatings, the test results, and the economic considerations, the one-component TiN-based coatings with appropriate phase-structural condition have been chosen for application to the blade model. According to the technical specifications for reinforcing the titanium turbine blades the recommended thickness of TiN based coatings ranges within 8—40 μm.

COATING DEPOSITION ON THE SAMPLES AND VT6 ALLOY BLADE MODELS

For defining the parameters and optimizing the coating process the turbine blades are modelled. The blade model is a plate made of VT6 titanium alloy. The plate is 1200 mm long, 125 mm wide, and 22 mm thick. Along the plate perimeter, there are the hollows in which the VT6 titanium alloy samples in the form of discs with a diameter of 18 mm and a thickness of 3 mm are fixed with screws.

To ensure uniformity of coating applied, the plasma sources are located in the three tiers of the vacuum chamber and the facility is fitted with rotary device bearing the blade model, with the rotary device enabling not only rotational but also translational motion along the axis of the chamber (up and down). For loading the blade model into the chamber, a special system for withdrawing the rotary unit with processed product, the blade model, from the vacuum chamber has been designed, manufactured and installed. Fig. 3 shows the layout of the blade model fixed on the rotary unit inside the vacuum chamber.

To measure the rate of application of nitride coatings, the VT6 alloy blades are weighted before loading to the chamber and after application of the coating. The rate of deposition of TiN-coating on the blade model is ~ 10 μm/h. Table 5 shows the main characteristics of the designed facility for application of nitride coatings on turbine blade models.

CONCLUSIONS

1. The key project outcomes are as follows:

- Prototype equipment and techniques for obtaining cavitation-resistant protective coatings to be deposited on working surfaces of VT6 titanium alloy turbine blades have been designed;
- The laboratory equipment with three-modular vacuum chamber for depositing the reinforcing vacuum-arc coatings on the turbine blades

having a length of up to 1300 mm and a weight of up to 30 kg has been designed, mounted, debugged, and tested.

2. The results of project activities are as follows:

- Concept facility for depositing the vacuum-arc cavitation-resistant coatings on large blades in its working chamber has been designed. It enables to use advanced ion-plasma techniques for modification of titanium blade surface in order to reinforce the blades and to ensure maximum efficiency and accuracy of parameter control;
- Facility with three-module vacuum chamber, six evaporators, and power supply sources has been assembled and calibrated;
- Technical specifications for prototype laboratory procedure for application of cavitation-resistant coatings on VT6 alloy titanium blades;
- Promising coatings have been selected and applied to VT6 titanium alloy samples; the coated samples have been tested for resistance to cavitation, erosive, and abrasive wear.

3. The project contribution to the science is as follows:

- Techniques for application of protective coatings to large VT6 alloy products have been developed;
- Nitride coatings of various composition (TiN; Ti + TiN; (Ti—Al)N; (Ti—Al—Si)N; (Ti—Al—Y)N; (Ti—Zr)N have been synthesized using the techniques; their structural properties and resistance to corrosion, erosion, and cavitation have been studied;
- All properties and economic considerations have been compared and analyzed; selection of promising coatings has been justified; their composition has been optimized;
- Prototype facility for synthesis of protective coatings on large VT6 alloy blades has been designed, produced, and tested on models of large blades; the basic operating characteristic of the prototype have been studied which enables coating the trial batches of blades to significantly reduce time and costs of creating the industrial facility.

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СТВОРЕННЯ ЕКСПЕРИМЕНТАЛЬНОГО ОБЛАДНАННЯ І ОСНОВНИХ ТЕХНОЛОГІЧНИХ ПРИЙОМІВ ОТРИМАННЯ КАВІТАЦІЙНОСТІЙКИХ ЗАХИСНИХ ПОКРИТТІВ НА РОБОЧИХ ПОВЕРХНЯХ ЛОПАТОК ПАРОВИХ ТУРБІН З ТИТАНОВОГО СПЛАВУ ВТ6 З МЕТОЮ ЗАМІЩЕННЯ ІМПОРТУ АНАЛОГІЧНОЇ ПРОДУКЦІЇ

Створено експериментальне устаткування і основні технологічні прийоми отримання кавітаційностійких захисних покриттів вакуумно-дуговим методом на робочих поверхнях лопаток парових турбін з титанового сплаву ВТ6. Зроблено вибір і обґрунтовано склад та умови синтезу оптимального покриття для зміцнення лопаток. Відпрацьовано параметри процесу осадження покриттів на макеті лопатки, отримано дослідний технологічний процес осадження зміцнюючих покриттів. Проведено випробування зразків зі сплаву ВТ6 з вибраними покриттями в імітаційних умовах, близьких до експлуатаційних. Здійснено осадження покриття на макет лопатки з габаритними розмірами до 130 см і вагою до 30 кг. Швидкість осадження покриття на основі TiN складала ~10 мкм/г.

Ключові слова: покриття, вакуумно-дуговий метод, кавітаційна стійкість, лопатки турбін.

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СОЗДАНИЕ ЭКСПЕРИМЕНТАЛЬНОГО ОБОРУДОВАНИЯ И ОСНОВНЫХ ТЕХНОЛОГИЧЕСКИХ ПРИЕМОВ ПОЛУЧЕНИЯ КАВИТАЦИОННО-СТОЙКИХ ЗАЩИТНЫХ ПОКРЫТИЙ НА РОБОЧИХ ПОВЕРХНОСТЯХ ЛОПАТОК ПАРОВЫХ ТУРБИН ИЗ ТИТАНОВОГО СПЛАВА ВТ6 С ЦЕЛЬЮ ЗАМЕЩЕНИЯ ИМПОРТА АНАЛОГИЧНОЙ ПРОДУКЦИИ

Создано экспериментальное оборудование и основные технологические приемы получения кавитационно-стойких защитных покрытий вакуумно-дуговым методом на робочих поверхностях лопаток паровых турбин из титанового сплава ВТ6. Сделан вибор и обоснован состав и условия синтеза оптимального покрытия для упрочнения лопаток. Отработаны параметры процесса осаждения покрытий на макете лопатки, получен опытный технологический процесс осаждения упрочняющих покрытий. Проведено испытание образцов из сплава ВТ6 с выбранными покрытиями в имитационных условиях, близких к эксплуатационным. Осаждены покрытия на макет лопатки с габаритными размерами до 130 см и весом до 30 кг. Скорость осаждения покрытия TiN составила ~10 мкм/ч.

Ключевые слова: покрытия, вакуумно-дуговой метод, кавитационная стойкость, лопатки турбин.

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