Technologies for Producing Thermal Barrier Coatings for Gas Turbine Engine Blades

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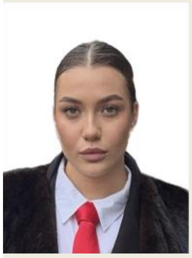
Received: 30.11.2025; Accepted: 30.12.2025
https://doi.org/10.32347/ tit 2025.9.7.01.01

Abstract. This article examines technologies for producing thermal barrier coatings for gas turbines with the aim of improving their efficiency and operational longevity. Optimal parameters are estalished for various types of coatings, including the design and component composition of individual layers. The article describes laboratory and indutrial electron-beam units used for coating depostion, which provide optimal conditions for material processing and melting. The technical features of these units, their construction, and their applicability for depositing different types of coatings are highlighted. Special attention is given to the latest L-9 unit, which differs from its predecessors by employing a cold cathode for electron-beam heaters, thereby increasing their stability and service life. The article also presents information on the control systems of the units and the operating principle of the L-9 unit, which can be used for depositing various types of protective coatings, including new micro-layered silicide coatings.

Keywords: electron-beam equipment, evaporation–condensation method, composite materials, thermal barrier coatings.



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INTRODUCTION

In the course of the development of gas turbine construction, a complex challenge has emerged—creating efficient and reliably opeaing gas turbines. The main factors contributing to this complexity are the working and nozzle blades of the turbine, whose materials and design are critical for determining the allowable gas temperature before the turbine, which directly affects the technical and economic characteristics of gas turbine engines

(GTEs). Today, technological challenges are associated with the continued advancement of convective cooling of turbine blades and the current state of metallurgy of heat-resistant alloys, both of which indicate the need to improve GTE cycle parameters. Addressing these issues requires the development of a new protection system for gas turbine blades and a transition from heat-resistant multicomponent coatings to thermal barrier coatings (TBCs). Attempts to create protective thermal coatings for gas tur-

bines were made more than 60 years ago. However, interest in these technologies has increased significantly in recent years, as modern GTEs operate at extremely high temperatures, placing new demands on materials and thermal protection technologies.
The aim of this work is to analyze technologies for producing thermal barrier coatings and to describe electron-beam equipment used for their deposition.

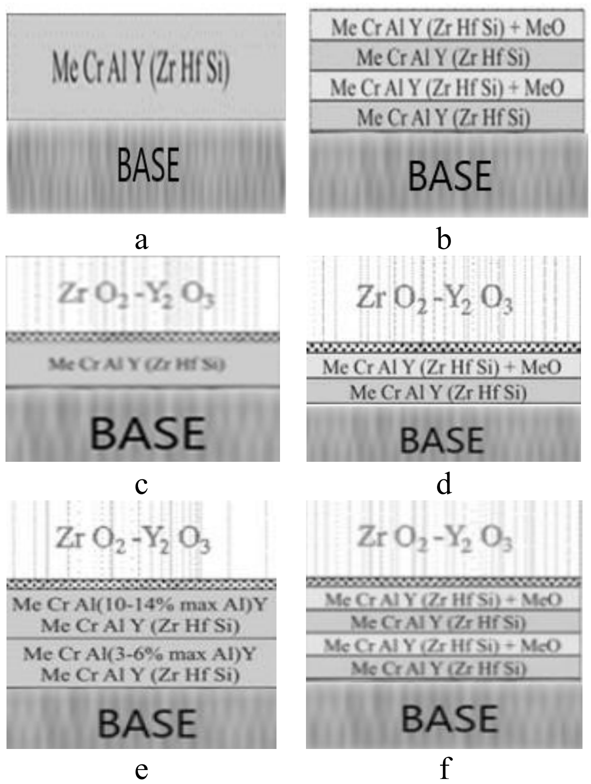
MATERIALS AND METHODS

At the R&D enterprise *Eltechmash*, protective coatings for gas turbine blades were applied by electron-beam evaporation of MeCrAlY alloys (where Me = Ni, Co, Fe), MeCrAlYHfSiZr, and ceramics based on ZrO_2 stabilized with Y_2O_3, followed by condensation of the vapor phase on the surface of working gas turbine blades of various types and applications [1-3]. The types of thermal barrier coatings are classified into the following groups:

- Single-layer metallic coatings of the MeCrAlY and MeCrAlY(HfSiZr) type (Fig. 1a);
- Single-layer composite micro-layer coatings with alternating layers of MeCrAlY (MeCrAlYHfSiZr) / MeCrAlY (MeCrAlYHfSiZr) + MeO, where MeO = Al_2O_3 or ZrO_2 + 6–8 wt.% Y_2O_3 (Fig. 1b);
- Two-layer coatings with an inner metallic MeCrAlY (MeCrAlYHfSiZr) layer and an outer ceramic layer (Fig. 1c);
- Two-layer coatings with an inner composite layer MeCrAlY (MeCrAlYHfSiZr) + MeO (dispersed-strengthened or micro-layer type) and an outer ceramic (ZrO_2–Y_2O_3) layer (Fig. 1d);
- Three-layer coatings with inner and intermediate metallic layers based on MeCrAlY (MeCrAlYHfSiZr) alloys and an outer ceramic (ZrO_2–Y_2O_3) layer (Fig. 1e);
- Three-layer coatings with an inner metallic MeCrAlY (MeCrAlYHfSiZr) layer, an intermediate composite layer MeCrAlY (MeCrAlYHfSiZr) + MeO of dispersed-strengthened or micro-layer type, and an outer ceramic (ZrO_2–Y_2O_3) layer (Fig. 1f);
- Three-layer coatings with an inner metallic MeCrAlY (MeCrAlYHfSiZr) layer, an intermediate composite layer MeCrAlY (MeCrAlYHfSiZr) + MeO of dispersed-strengthened or micro-layer type, and an outer ceramic (ZrO_2–Y_2O_3) layer containing dispersed boride particles, which, upon oxidation, seal microcracks in the outer ceramic layer that form during thermal cycling of heating and cooling (Fig. 1g).

RESULTS AND DISCUSSION

The conducted studies have shown that the application of thermal barrier coatings with a thickness of 250 μm and a thermal conductivity of 1 W/m²·K on two turbine stages makes it possible to achieve one of two outcomes [4-18]:
1. With the working temperature of the blade material unchanged, the gas temperature before the turbine can be increased by approximately 100 °C, which leads to an increase in efficiency and fuel savings of more than 13%.
2. Without changing the gas temperature before the turbine, the service life of the blades can be increased by approximately a factor of four due to the reduction of their operating temperature.



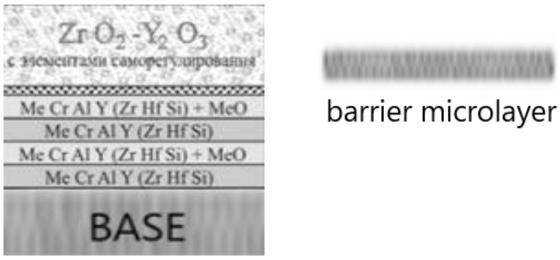


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Fig. 1. Fig. 1. Schemes of heat-resistant and thermal barrier coatings obtained by electron-beam deposition

The total thickness of single-layer heat-resistant coatings does not exceed 150 μm, two-layer thermal barrier coatings — 200 μm, and three-layer thermal barrier coatings — 300 μm. In three-layer thermal barrier coatings, the thickness of the damping inner layer with a reduced Al content (3–6 wt.%) ranges from 30 to 50 μm, the intermediate heat-resistant layer from 50 to 80 μm, and the outer ceramic layer from 80 to 120 μm.

The concentrations of chromium, aluminum, and yttrium in the heat-resistant layer are 18–24 wt.%, 10–13 wt.%, and 0.4–1.8 wt.%, respectively, while the concentrations of zirconium, hafnium, and silicon range from 0.05 to 0.2 wt.%. Additional alloying of MeCrAlY alloys with zirconium, hafnium, and silicon has made it possible, on the one hand, to improve the heat resistance of single-layer multicomponent and composite heat-resistant coatings, and on the other hand, when using these alloys as materials for the inner damping layer and the intermediate heat-resistant layer, to slow down diffusion processes at the interfaces substrate – damping layer, intermediate heat-resistant layer – outer ceramic layer, thereby increasing the overall service life of the coating.

An even greater reduction in diffusion rates within the coating is observed when the intermediate heat-resistant layer is applied in a micro-layered form. Optimal parameters are achieved when the alternating metallic and composite layers have thicknesses of 0.5 to 1 μm, and when the concentration of dispersed refractory particles (ZrO_2–Y_2O_3, Al_2O_3) in the composite micro-layer is 0.3 to 1 wt.%.

When designing thermal barrier coatings (TBCs), the formation of a barrier micro-layer at the interface between the intermediate heat-resistant layer and the outer ceramic layer becomes critically important. Typically, a 1–5 μm thick metal-ceramic layer based on complex spinels of Al_2O_3, ZrO_2, Y_2O_3, Cr_2O_3 and the MeCrAlY alloy is produced using special technological methods. Such a barrier layer inhibits the formation of an Al_2O_3 oxide film at the interface intermediate layer – outer ceramic layer of the thermal barrier coating.[18]

Two-layer metal/ceramic coatings (Fig. 1c), produced using a two-stage technology, are widely applied at the enterprise *Zorya-Mashproekt* (Mykolaiv, Ukraine) and provide a service life of up to 25,000 hours for the first-stage turbine blades of gas turbine units used for gas pumping. Currently, work is being carried out to optimize the technology for applying two-layer thermal barrier coatings with an inner micro-layered composite layer consisting of alternating layers of CoCrAlY / CoCrAlY + (ZrO_2–Y_2O_3) and an outer ceramic layer of ZrO_2–Y_2O_3. Such coatings are applied in a single technological cycle and are expected to provide a service life of up to 32,000 hours.

Increasing the durability of TBCs is reasonable through modifications in coating design, as this approach does not require changes to the technological process scheme, which would otherwise involve significant energy expenditures. Adjustments in the TBC design scheme are not limited by the capabilities of electron-beam technology.

In three-layer coatings (Fig. 1d, 1f, 1g), the inner damping layer is made of MeCrAlY or MeCrAlYSiHfZr alloys with a component ratio that ensures high plasticity (elongation at break δ = 2.5%) and sufficient heat resistance. This layer serves to reduce stresses in the TBC and to slow down and block cracks propagating from the surface into the substrate.

The intermediate layer is a composite with enhanced heat resistance and thermal stability. The outer, third layer is ceramic, formed based on zirconium dioxide stabilized with yttrium oxide. One or more refractory borides may additionally be introduced into the outer ceramic layer to heal microcracks that develop in this layer.

The latest modification of TBCs is designed to protect the first-stage turbine blades of fifth-generation military engines. These developments are being carried out for Ukrainian enterprises in the gas turbine industry, including *Ivchenko-Progress* and *Motor-Sich* (Zaporizhzhia).

For the application of heat-resistant and thermal barrier coatings, a universal laboratory electron-beam unit L-2 was developed for melting and evaporating materials in a vacuum [19], the external view of which is shown in Fig. 2.

Fig. 2. Exterior view of the universal laboratory electron beam machine L-2.

The general assembly diagram of the unit is shown in Fig. 3. Structurally, the unit consists of a technological (1) and a load-lock (2) vacuum chamber mounted on the support frames of the service platform (3), with attached mechanisms (6, 7, 8), a vacuum pumping system (11), and control system cabinets (12).

The mechanical part of the unit includes a horizontal feed mechanism (7) for the processed (coated) components, a mechanism for vertical suspension and rotation of the substrate (or feeding of the melted billet) (8), a crucible block (9) with three billet feeding (withdrawal) mechanisms (6), a viewing system (5), an evaporator block, and an ion cleaning system.

The vacuum system (11) comprises mechanical fore-vacuum pumps, booster pumps, diffusion oil-vapor pumps, as well as vacuum valves and shutters equipped with pneumatic actuators.

The electrical subsystem of the installation includes thermionic electron guns with a rated power of 60 kW (up to seven units), a high-voltage power supply providing an accelerating voltage with a power rating of 250 kW, a system for monitoring and automated control of vacuum pumping, electric drives, and electron guns, as well as an ion cleaning system and a technological gas inlet system.

Crystallization of the molten metal during melting and the formation of ingots of the required diameter are carried out in a block of copper water-cooled crucibles (9, Fig. 3). These crucibles are also used for:
a) deposition of protective coatings on components;
b) fabrication of sheet blanks of composite materials (CM) condensed from the vapor phase;
c) production of single- and multicomponent powders.

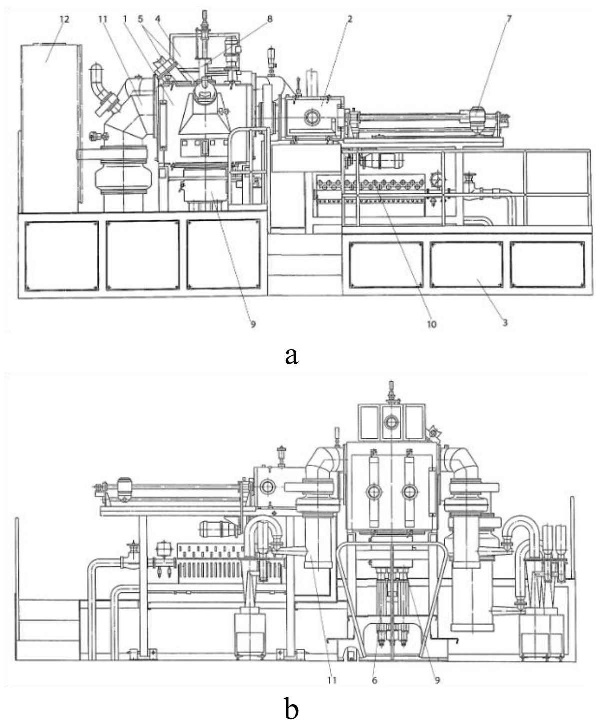

Fig. 3. General assembly diagram of the L-2 unit: (a) front view; (b) rear view.
1 – technological chamber; 2 – load-lock chamber; 3 – service platform; 4 – accelerating voltage supply box; 5 – viewing system; 6 – ingot feed/withdrawal mechanism; 7 – horizontal feed and rotation mechanism of the components;8 – vertical feed and rotation mechanism; 9 – crucible block; 10 – cooling system hydraulic

unit; 11 – elements of the vacuum system; 12 – control system cabinets.

The ingot withdrawal/feed mechanisms, used respectively during melting and evaporation, are connected to the copper water-cooled crucibles and equipped with adjustable electric drives. Unloading after electron-beam remelting and loading of evaporated ingots are performed through these crucibles directly within the technological chamber.

Three electron guns are installed for evaporation of materials from the crucibles in such a way that each electron gun, intended for evaporation of an ingot from a specific crucible, can also be used to evaporate material from an adjacent crucible. Heating of the components is carried out by three electron guns of the same power rating (two for top heating and one for bottom heating).

A shutter is installed in the technological chamber to shield the coated components during the heating of evaporated materials until a stable technological evaporation regime is established.

The horizontal feed mechanism is designed to transfer the sprayed components from the fore-chamber to the working chamber and back, as well as to rotate the tooling holding the components. To compensate for possible deflection of the rod in the fully extended position, the front support of the rod is mounted on trunnions.

The introduction of the horizontal rod into the chamber is designed such that sealing of the translational and rotational movements of the rod is performed by separate sealing assemblies. This separation prevents premature failure of the lip seal used for translational motion of the rod.

The electric drive control system provides control of the ingot feed mechanisms, the feed and rotation mechanisms of the side shaft, the viewing system, and the crucible shutter.

Incremental encoders are installed on the motors of the ingot feed mechanisms. Their output signals are supplied to frequency converters and are used to stabilize and extend the control range of the ingot feed rate.

Signals from the encoders on the ingot feed mechanisms and the side-shaft feed mechanism are also used by a system based on an industrial controller for positioning and measurement of the feed rates of these mechanisms. Zero positions of the rods are set automatically upon actuation of the home-position sensors. The positions of the mechanisms and the rotational speed of the side shaft are displayed on the operator interface.

The side-shaft feed control system enables reciprocating motion of the tooling with components during the coating deposition process within specified limits and at a заданій speed, ensuring uniform deposition of coatings over the perimeter of the components.

For industrial applications, a universal electron-beam unit L-9 was developed [20]. The general view of the unit and the coating deposition scheme are shown in Fig. 4. Technical specifications are presented in the table 1.

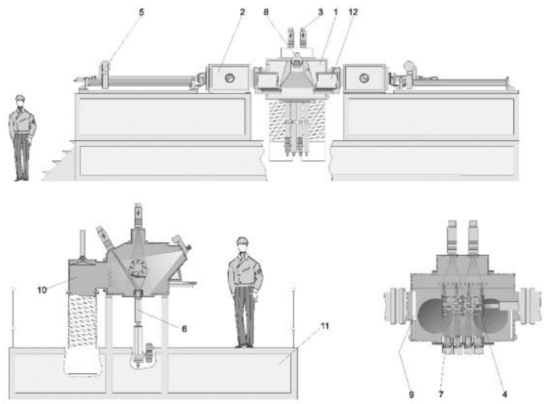

Fig. 4. General view of the L-9 unit and the coating deposition scheme: 1 – process chamber; 2 – airlock chamber; 3 – electron gun; 4 – cassette; 5 – cassette (workpiece) feeding mechanism; 6 – ingot feeding mechanism; 7 – crucible; 8 – observation system; 9 – shutter; 10 – vacuum system; 11 – service platform; 12 – control panel.

The unit consists of a block of vacuum chambers with mechanisms, devices, and systems that ensure the execution of the coating deposition process under vacuum on various workpieces. A crucible block is attached to the lower flange of the working chamber, which includes four ingot feeding mechanisms for the evaporated materials. The ingots of materials to be evaporated are loaded into the mechanisms from above through the crucibles.

A distinctive feature of the unit's design is its new power supply with acceleration voltage stabilization and electron-beam heaters with a cold cathode.

The use of a cold cathode made of a low-alloy aluminum-based material eliminates any deformation, allowing for a stable electron beam to be maintained for up to 250 hours of unit operation without replacement. On the other hand, electron-beam heaters with a cold cathode can operate stably at a vacuum of 10 Pa, whereas electron-beam heaters with a hot filament cathode require a vacuum of no less than 5×10^{-2} Pa.

Table 1

Technical Specifications of the L-9 Unit

1	Installed capacity, kW	400
2	Acceleration voltage, kV	25
3	Size of evaporating ingots, mm -diameter -length	 70 500
4	Dimensions of the cassette with sprayed shovels, mm: - diameter - length	 250 500
5	Number of crucibles, pcs.	4
6	Load capacity of the cassette feed rod, kg	50
7	Number and rated power of electronic guns, n x kW	6x60
8	Vacuum degree in the working chamber, Pa	$6x10^{-3}$ $-1x10^{-2}$
9	Cooling water flow rate, m^3/h	15
10	Area occupied by the unit, m^2	140

The use of cold-cathode electron-beam heaters allows for oxygen injection into the zirconium dioxide vapor cloud, ensuring the stoichiometric composition of the outer layer of the thermal barrier coating.

The unit is equipped with four cold-cathode electron guns for evaporating the source materials from the crucibles. These guns are arranged so that each gun, intended to evaporate an ingot from its corresponding crucible, can also be used to evaporate material from an adjacent crucible. This flexibility is necessary when the number or arrangement of crucibles is changed according to technological requirements.

Two synchronously operating shutters are used to shield the workpieces during the heating of the evaporated materials and the workpieces until the technological regime stabilizes. Two additional electron guns, installed above the process chamber, are used for heating the workpieces. Two airlock chambers are provided for reloading the workpieces to be coated.

The separation of the working and airlock chamber volumes is achieved using two vacuum gates. The airlock chambers are equipped with ion cleaning devices for the workpieces prior to coating deposition. The presence of two auxiliary chambers increases the productivity of the unit. Coatings are applied to workpieces fed sequentially from the airlock chambers without venting the working chamber, where the deposition process occurs.

The horizontal feeding mechanism is used to transfer workpieces from the airlock chambers to the deposition chamber and back, as well as to rotate the workpieces. The rods are equipped with devices for reading signals from thermocouples mounted on cassettes with blades. The unit design includes separate power supplies for each electron gun with an accelerating voltage of 30 kV.

The control system of the unit performs:

- monitoring of the technical condition of all unit systems;
- automatic preparation of the unit for the technological process;
- operator control of unit components during the process;

- real-time processing, display, and storage of technological parameters and process cycle data.

Currently, work continues on developing design documentation for a fundamentally new industrial electron-beam system for depositing all types of protective coatings, including new micro-layered silicide coatings.

It should be noted that the enterprise has implemented a closed cycle for coating deposition on turbine blades, which includes the melting of all types of ingots based on nickel, cobalt, and iron, as well as the use of ceramic ingots.

CONCLUSIONS

Thus, the application of electron-beam units for depositing protective coatings on gas turbine blades demonstrates significant potential for improving the efficiency of these engines. According to the conducted studies, the L-9 unit with cold cathodes shows stable operation for 250 hours without the need to replace the cathodes, representing a substantial improvement compared to previous models. The successful implementation of these technologies in industry demonstrates the ability of electron-beam units to provide up to 30 kV accelerating voltage for each electron gun. This enables stable deposition of coatings on turbine blade surfaces, ensuring their protection and extended service life.

Refined technical parameters, such as the reduction of vacuum requirements to 10 Pa for cold-cathode electron-beam heaters compared to 5×10^{-2} Pa for hot filament cathodes, indicate improved efficiency in the use of new technologies. This allows optimization of the coating deposition process under vacuum conditions, ensuring coating stability and quality.

The studies also show that electron-beam units enable the deposition of a wide variety of protective coatings, including new types of micro-layered silicide coatings, opening broad prospects for enhancing the reliability and service life of gas turbine engines.

These results confirm the high potential of electron-beam technologies for next-generation gas turbine engines.

REFERENCES

1. Akrymov V. A., Hrechaniuk I. M. Smashniuk Yu. O. Hrechaniuk V. H., and Liubarenko M. P. Promyslova Tekhnolohiia Nanesennia Dvosharovykh Plazmovykh Teplozakhysnykh Pokryttiv na Soplovi Lopatky Hazovykh Turbin [Industrial technology of applying two-layer plasma heat-protective coatings on the nozzle blades of gas turbines] (Sovremennaia elektrometallurhyia, № 4. – P. 28 – 31, 2020 (in Ukrainian) https://doi.org/10.37434/sem2020.04.05
2. Grechanyuk, M., Grechanyuk, V., Chornovol, V., Matsenko, O., Grechanyuk, I. (2025). Electron-Beam Evaporation–condensation Technology for Applying Heat-Protective Coatings to the Blades of Gas Turbine Engines with Boride Nanoparticles in the Outer Ceramic Layer. In: Fesenko, O., Yatsenko, L. (eds) Functional Nanomaterials, Nanocatalysts, Nanotechnologies, and Their Applications. NANO 2024. Springer Proceedings in Physics, vol 321. Springer, Cham. https://doi.org/10.1007/978-3-031-99136-3_25
3. N.I. Grechaniuk, V.G. Grechaniuk, V.O. Chornovol, I.M. Grechaniuk, and O.V. Matsenko. Designs of Electron-Beam-Assisted Heat-Shielding Coatings on Gas Turbine Blades, Including Those with Boride Nanoparticles in the Outer Ceramic Layer 255–267 (2025) https://doi.org/10.15407/nnn.23.01.0255
4. I. M. Grechanyuk, M. I. Grechanyuk, G. A. Bagliuk, V. G. Grechanyuk, O. V. Khomenko, O. V. Dudnik, and V. I. Gots, Powder Metallurgy and Metal Ceramics, No. 61: 459 (2022) https://doi.org/10.1007/s11106-023-00333-0
5. M. I. Grechanyuk, I. M. Grechanyuk, Y. N. Yevterev, V. G. Grechanyuk, T. O. Prikhna, G. A. Bagliuk, V. I. Gots, O. V. Khomenko, O.V. Dudnik, and O. V. Matsenko, Powder Metallurgy and Metal Ceramics ,No 61: 328 (2022) https://doi.org/10.1007/s11106-022-00320-x
6. T. O. Prikhna, I. M. Grechanyuk, M. V. Karpets, M. I. Grechanyuk, G. A. Bagliuk, V. G. Grechanyuk, and O. V Khomenko, Powder Metallurgy and Metal Ceramics, 2022, No. 61: 230 (2022) https://doi.org/10.1007/s11106-022-00310-z
7. T. O. Prikhna, I. M. Grechanyuk, M.V. Karpets, M. I. Grechanyuk, G. A. Bagliuk, I. M., Grechanyuk, and V. A. Chornovol, Powder Metallurgy and Metal Ceramics No.61: 70 (2022) https://doi.org/10.1007/s11106-022-00296-8

8. N. I. Grechanyuk, V. G. Grechanyuk, and A. F. Manulyk, Journal of Material Science and Technology Research: Vol. 8:19 (2021) https://doi.org/10.31875/2410-4701.2021.08.3
9. N.I. Grechanyuk, V.G. Grechanyuk, A.F. Manulyk, Journal of Material Science and Technology Research, Vol. 8:24 (2021) https://doi.org/10.31875/2410-4701.2021.08.4
10. Grechanyuk, V., Grechanyuk, M., Chornovol, V., Grechanyuk, I., Matsenko, O. (2024). The Current State and Prospects of Using the Method of High-Speed Evaporation–Condensation for the Production of Dispersed and Nanocrystalline Materials. In: Fesenko, O., Yatsenko, L. (eds) Nanomaterials and Nanocomposites, Nanostructures, and Their Applications. NANO 2023. Springer Proceedings in Physics, vol 253. Springer, Cham. https://doi.org/10.1007/978-3-031-67519-5_4
11. Grechanyuk, N.I. *et al.* (2019). New Electron-Beam Equipment and Technologies for the Production of Advanced Materials Using Vacuum Melting and Evaporation Methods Developed at SPE ["Eletekhmash"]. In: Srivatsan, T., Gupta, M. (eds) Nanocomposites VI: Nanoscience and Nanotechnology in Advanced Composites. The Minerals, Metals & Materials Series. Springer, Cham. https://doi.org/10.1007/978-3-030-35790-0_9
12. Grechanyuk, V.G., Matsenko, O.V., Kozyrev, A.V. *et al.* Structure and Mechanical Properties of Thick Vacuum TiC Condensates Obtained by Electron Beam Evaporation. *J. Superhard Mater.* **47**, 208–213 (2025). https://doi.org/10.3103/S1063457625030025 https://doi.org/10.1007/978-3-031-99136-3_25
13. Grechanyuk, V., Grechanyuk, I., Kozyrev, A., Matsenko, A., Chornovol, V., Kovalchuk, Y. (2023). Metal-Based Nanocrystalline Materials Condensed from the Vapor Phase. In: Fesenko, O., Yatsenko, L. (eds) Nanostructured Surfaces, Nanocomposites and Nanomaterials, and Their Applications. NANO 2022. Springer Proceedings in Physics, vol 296. Springer, Cham. https://doi.org/10.1007/978-3-031-42704-6_10
14. V. G. Grechanyuk, N. I. Grechanyuk, V. O. Chornovol, A. V. Kozyrev, V. I. Gots, A. V. Matsenko, V. A. Kulichenko, T. D. Grabina, and Yu. I. Kozyreva, Copper and Molybdenum-Based Nanocrystalline Materials, Metallofiz. Noveishie Tekhnol., 44, No. 7: 927—942 (2022) (in Ukrainian) https://doi.org/10.15407/mfint.44.07.0927
15. Lakiza, S.M., Grechanyuk, M.I., Ruban, O.K. et al. Thermal Barrier Coatings: Current Status, Search, and Analysis. Powder Metall Met Ceram 57, 82–113 (2018). https://doi.org/10.1007/s11106-018-9958-0
16. Grechanyuk, N.I., Grechanyuk, V.G. Precipitation-Strengthened and Microlayered Bulk Copper- and Molybdenum-Based Nanocrystalline Materials Produced by High-Speed Electron-Beam Evaporation–Condensation in Vacuum: Structure and Phase Composition. Powder Metall Met Ceram 56, 633–646 (2018). https://doi.org/10.1007/s11106-018-9938-4
17. V.A. Akrymov, I.M. Hrechaniuk, Yu. O. Smashniuk, V.H. Hrechaniuk, M.P. Liubarenko Promyslova Tekhnolohiia Nanesennia Dvosharovykh Plazmovykh Teplozakhysnykh Pokryttiv na Soplovi Lopatky Hazovykh Turbin [Industrial technology of applying two-layer plasma heatprotective coatings on the nozzle blades of gas turbines] (Sovremennaia elektrometallurhyia, (4), 28–31 (2020) (in Ukrainian) https://doi.org/10.37434/sem2020.04.05
18. Hrechaniuk, M.I., Bagliuk, G.A., Hrechaniuk, V.G. et al. Thickness Distribution and Structure of External Ceramic Coatings on Gas Turbine Blades. Powder Metall Met Ceram 63, 491–496 (2025). https://doi.org/10.1007/s11106-025-00480-6
29. N. I. Grecyanyuk, G. A. Baglyuk, P. P. Kucherenko, A. G. Melnik, I. N. Grechanyuk V. G. Grechanyuk, and Y. A. Smashnyuk, Laboratory Electron-Beam Multipurpose Installation L-2 for Producing Alloys, Composites, Coatings, and Powders, Powder Metallurgy and Metal Ceramics, No. 56(1): 113 (2017)
20. N. I Grecyanyuk, P. P. Kucherenko, A. G. Melnik, I. N. Grechanyuk, and Y. A. Smashnyuk Industrial electron-beam installation L-9 for melting and vacuum refining of metals and alloys, Powder Metallurgy and Metal Ceramics, Vol. 55(7-8): 489 (2016) doi: https://doi.org/10.1007/s11106-016-9831-y

Технології отримання теплозахисних покриттів для лопаток газотурбінних двигунів

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Анотація. У статті розглянуто технології отримання теплозахисних покриттів для газових турбін з метою підвищення ефективності та тривалості їх роботи. Встановлено оптимальні параметри для різних типів покриттів, включаючи конструкцію та компонентний склад шарів. Описано лабораторні та промислові електронно-променеві установки для нанесення покриттів, які забезпечують оптимальні умови для роботи та виплавки матеріалів. Відмічені технічні особливості установок, їх конструкція та можливості використання для нанесення різних типів покриттів. Особливу увагу зосереджено на новітній установці Л-9, яка відрізняється від попередніх холодним катодом для електронно-променевих нагрівачів, що підвищує стабільність та тривалість їхньої роботи. Подано також інформацію щодо системи управління установками та принципу роботи установки Л-9, яка може застосовуватися для осадження різних типів захисних покриттів, включаючи нові силіцидні покриття мікрошарового типу.

Ключові слова: електронно-променеве обладнання, метод випаровування – конденсації, композиційні матеріали, теплозахисні покриття.