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MODEL FOR EVALUATING THE PLASMA COATING METHOD

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Abstract:
The article considers the main prospects for the use of the method of coating plasma spraying. The essence of plasma spraying is disclosed, and the main advantages and disadvantages of this coating formation method are indicated. The method is characterized by high productivity and the possibility of forming high-quality coatings on machine parts for various functional purposes. It was found that the low stability of the spraying process, the structural complexity of the plasmatron and the need for mathematical modeling are constraining factors in designing new technological processes of plasma spraying. The possibility of further increasing the efficiency of plasma spraying by developing methods and means of automation and computerization of the spraying process is substantiated. Obtaining the required physical and mechanical properties of coatings applied to worn working surfaces of machine parts by plasma spraying is achieved by using modern electronic computing machines in the development of technological application processes. Based on the research a mathematical model for evaluating the method of plasma coating deposition was obtained. It allows the choice of applied materials and technological processes, as well as modeling options of design and technology solutions that meet the optimization condition. The data obtained from the results of studies allow evaluation of the impact of technological modes of coating formation on the optimization parameter.

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1. INTRODUCTION

Plasma spraying is one of the most promising and modern technological methods of applying various functional coatings [1-8]. The method is characterized by high productivity and the possibility of forming high-quality coatings on machine parts for various functional purposes. The wide application of the plasma spraying method in various industries is due to high technical and economic indicators. Plasma spraying is reasonable to use when reconditioning worn-out machine parts, when it is necessary to recover the original dimensions, and in the manufacture of new parts in order to give the working surfaces special properties: wear resistance, corrosion resistance, and heat resistance.

Plasma spraying is based on heating the sprayed material to a liquid or plastic state, transferring it by a high-temperature plasma jet to the substrate (base), followed by forming a coating layer [9-12]. In plasma spraying, powders, wires and rods can be

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used as sprayed materials. Powder spraying is the most widespread [13-17]. The plasma jet temperature can reach 5000-55000°C, and the velocity of the jet can reach – 1000-3000 m/s. In the plasma jet, the powder particles melt and acquire a velocity of 50-500 m/s. The flight velocity of the powder particles depends on their size, material density, arc welding current strength, nature and consumption of the plasma-forming gas, plasmatron design [18-22].

The main advantages of plasma spraying are: high productivity (up to 10 kg/h) [1-5,19-24], high quality of formed coatings [6-10,24-26], shallow penetration depth of the base metal (up to 5%), the possibility of forming relatively thin layers (0.5-5.0 mm) [1-20,23-27].

Plasma spraying technology makes it possible to create coatings with different performance characteristics. Applying special protective coatings can significantly increase the service life of machine parts. For example, wear-resistant composite coatings reduce the friction pair's wear by 2-2.5 times [15-24,27-29]. Plasma spraying can be used to deposit coatings on flat surfaces, bodies of rotation, and curved surfaces. A layered structure with high physical and mechanical properties heterogeneity characterizes the coating. The type of bonds between the coating and the part (substrate) and between coating particles is usually mixed - mechanical adhesion, physical and chemical interaction force [30-31].

The low stability of the sputtering process, the structural complexity of the plasmatron, and the need for mathematical modeling are restrictive factors in designing new technological processes of plasma spraying. Further increase in the efficiency of plasma spraying is associated with the development of methods and means of automation and computerization of the spraying process. Obtaining the required physical and mechanical properties of coatings deposited on the worn working surfaces of parts by plasma spraying is achieved by using modern computers in the development of deposition processes.

The aim of the study is to obtain a mathematical model for assessing the method of deposition of plasma wear-resistant coatings, which allows for choosing rational technological modes.

2. MATERIALS AND METHODS

The first stage of the research consisted of choosing statistically significant technological parameters that characterize the cost and productivity of the deposition process. During the second stage of the research, the choice of criterion characterizing economic efficiency is carried out.

Calculation of the cost of the coating was carried out according to the Eq. (1):

$$\mathrm{C}_{ci} = E_n \cdot K_i + C_i = \frac{1}{T_n} \cdot K_i + C_i, \qquad (1)$$

where:

i - option index;

K_i - book value of technological equipment (capital investments), rub.;

E_n - normative payback factor of capital investments;

T_n - normative payback period of capital investments, years;

C_i - the cost of the coating material, rub.

The expression will determine specific costs for coating one part:

$$S_{ci} = \frac{C_{ci}}{N_i} = \frac{\frac{K_i}{T_n} + C_i}{N_i}, \qquad (2)$$

where:

N_i - annual reconditioning program, pcs.;

$$N_i = \frac{n_{oi} \cdot \gamma_{oi} \cdot \gamma_{ki} \cdot \eta_{oi} \cdot 60}{T_{cti}}, \qquad (2a)$$

n_{oi} - nominal annual operating fund of the equipment, h;

T_{cti} - process cycle time or deposition time, h;

$\gamma_{oi} = 1 - (\delta_1 + \delta_2)$ – the factor that takes into account the loss of the nominal time fund for organizational reasons;

δ_1 - time loss factor for inspections and repairs;

δ_2 - loss factor for downtime;

γ_{ki} - time loss ratio due to underloading of equipment;

$$\eta_{oi} = \frac{1}{1+\delta_3+\delta_4} \text{ – safety factor;} \qquad (2b)$$

δ_3 - Specific downtime due to changeover and adjustment of equipment (set based on experience with a particular type of equipment);

δ_4 - specific downtime due to equipment failures.

Thus, we get the expression:

$$S_{ci} = \frac{T_{cti}}{60 \cdot \eta_{oi}} \left(\frac{K_i}{T_n \cdot n_{oi} \cdot \gamma_{oi} \cdot \gamma_{ki}} + \frac{C_i}{T_n \cdot n_{oi} \cdot \gamma_{oi} \cdot \gamma_{ki}} \right). \qquad (3)$$

The first summand (3) is the capital investment, referred to 1 hour of the actual operating fund of the equipment, i.e. specific capital investment. The second summand is the technological cost of 1 hour of equipment operation, i.e. the specific production costs for the deposition operation – let's denote it by C_{oi}.

Since there is a dependence (4), we get expression (5), which is the technological cost of coatings:

$$T_{cti} = F_{oi} t_i / f_{oi}, \tag{4}$$

where:

F_{oi} - total area of the sprayed surface, sm^2;

t_i - coating thickness, sm;

f_{oi} - spraying performance, sm^3/min.

$$S_{ci} = \frac{F_{oi} t_i}{f_{oi} \cdot 60 \cdot \eta_{oi}} \left(\frac{K_i}{T_n \cdot n_{oi} \cdot \gamma_{oi} \cdot \gamma_{ki}} + C_{oi} \right) \tag{5}$$

The expression for calculating the criterion of economic efficiency of spraying coatings without regard to their geometric characteristics will be as follows:

$$S_{gi} = \frac{V_i}{f_{oi} \cdot 60 \cdot \eta_{oi}} \left(\frac{K_i}{T_n \cdot n_{oi} \cdot \gamma_{oi} \cdot \gamma_{ki}} + C_{oi} \right) \tag{6}$$

Eq. (6) is a multi-parameter technical and economic model that calculates the cost of obtaining a unit volume of plasma coatings.

Minimum values of S_{gi} mean a high level of economic efficiency in the technological process. The most cost-effective option (technological process) cannot consistently achieve productivity and reliability. Therefore, selecting the optimal technological process requires a comprehensive criterion based on the technical and economic model and focusing on the indicators of reliability and productivity. Such a criterion can be represented as:

$$Q = \frac{f_{oi} \cdot \eta_{oi}}{S_{gi}}. \tag{7}$$

By expression (6), you can analyze and calculate the technical and economic parameters of the deposition process.

3. RESULTS AND DISCUSSION

Fig. 1 shows the algorithm of the software package, which allows us to select a rational deposition method.

With the help of this software package it is possible to change the initial parameters online. It consists of several steps, which are presented below.

Step 1. Analytical comparison of the developed technological process with existing ones. After analyzing the part characteristic, the database (DB) of existing technological processes (TP) is used. The possibility of using the developed TP and the data of similar developments are evaluated.

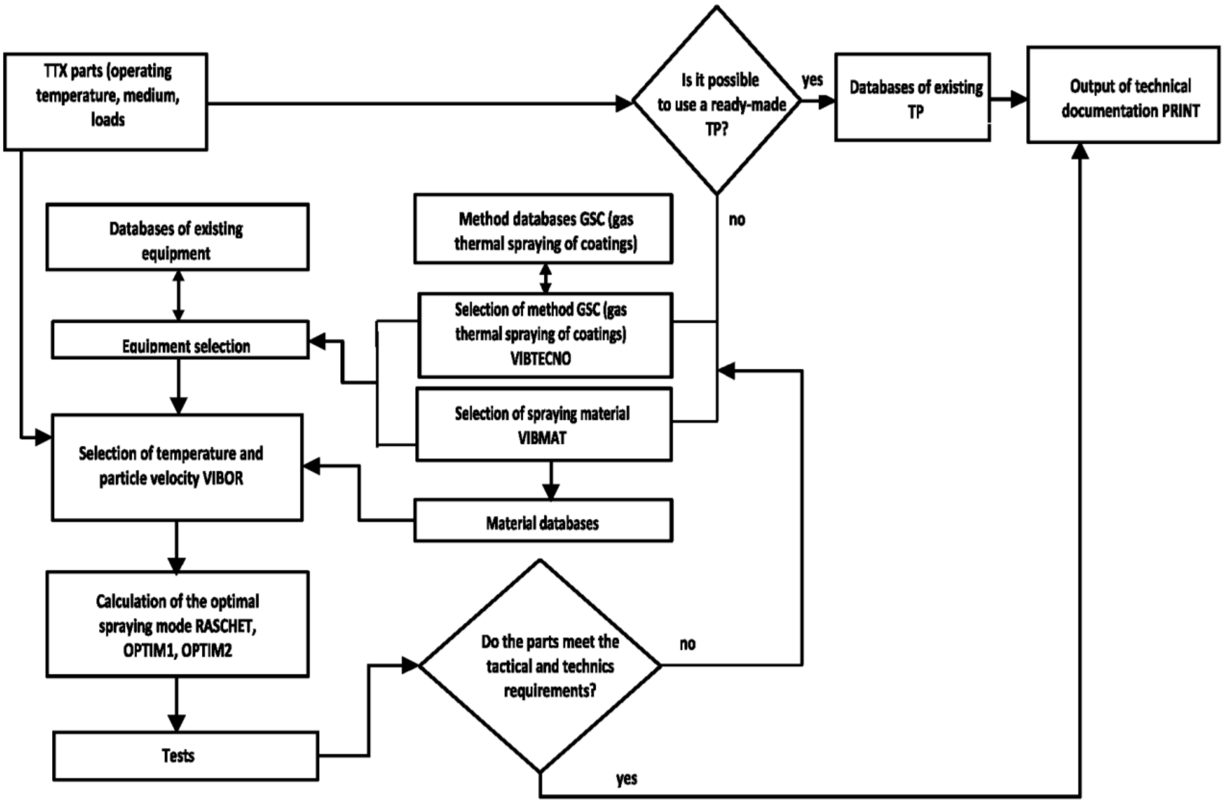


Fig. 1. Algorithm for selecting a rational deposition method

When a suitable TP is found, the system outputs data on the typical TP, including the material grade, the deposition method and the parameters to be obtained. Without a suitable technological process, the system proceeds to synthesize a new one.

Step 2. Material selection (module "VIBMAT"). The selection of the optimal material is carried out using existing databases (Fig. 2*a* and Fig. 2*b*).

The coating material selection is also made according to the possible operating medium (Fig. 2*c*). The program allows selecting the select the material under the condition of $T_c \le 0{,}8T_{mp}$, where T_c – coating operating temperature; T_{mp} – the melting point of coating material.

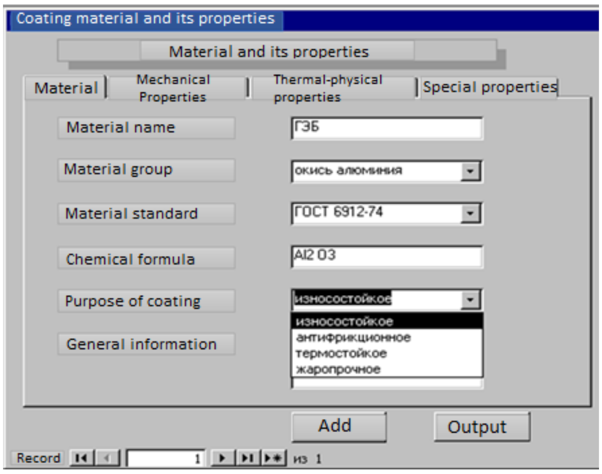
Step 3. Selection of deposition method (module "VIBTECHNO"). The selection of the deposition method is based on the technological feasibility and economic cost of manufacturing a coated part (Fig. 2*d*). To evaluate the methods, the criterion of unit costs S_{gi} for *i*-th option is minimized using a calculation model.

Step 4. Selection of spraying modes (modules "OPTIM 1", "OPTIM 2", "RASHET"). The target function is used for modes selection $F_{v,T}$, which should be minimal at modes that provide the specified coating properties:

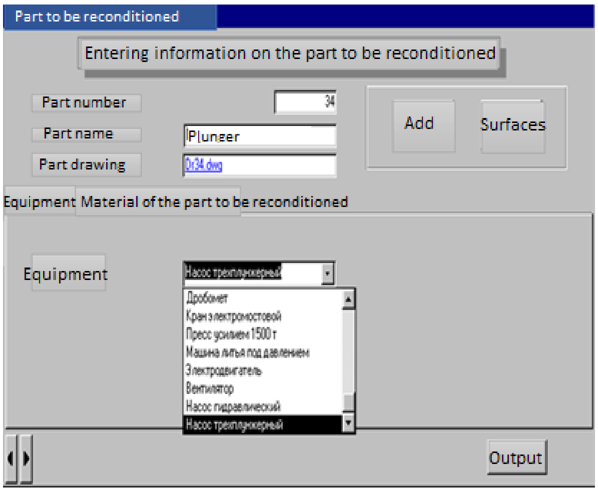
$$F_{v,T} = F(T - T_{giv}, v - v_{giv}) = \begin{cases} 0 \; if \; T = T_{giv} \; and \; v = v_{giv} \\ > 0 \; for \; other \; cases \end{cases} \quad (8)$$

where:

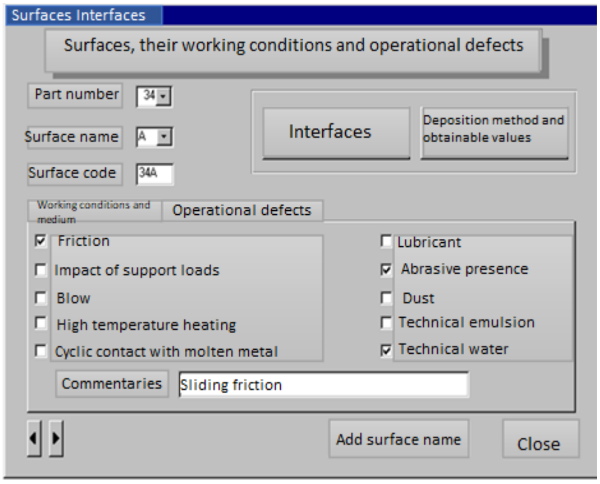
T_{giv}, v_{giv} - respectively temperature and particle velocity, at which the desired coating properties are provided.



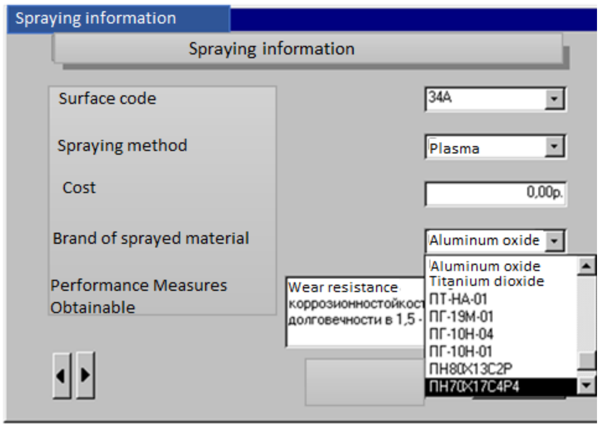
a)



b)



c)



d)

Fig. 2. Database forms: a) by coating materials; b) by parts; c) by surfaces of reconditioned parts and their working conditions; d) by typical technological processes

When searching for plasma deposition modes that satisfy condition (7), the following constraints are taken into account:

$$\begin{cases} I_H \le I \le I_B \\ G_{1H} \le G_1 \le G_{1H} \\ G_{2H} \le G_2 \le G_{2B} \end{cases}. \quad (9)$$

The constraints in (8) on technological parameters are taken into account by functions defined by the following expressions:

$$D_1 = \begin{cases} I_H \le I \le I_B \\ I\langle I_H; I\rangle I_B \end{cases};$$

$$D_{G1} = \begin{cases} G_{1H} \le G_1 \le G_{1B} \\ G_1\langle G_{1H}; G_1\rangle G_{1B} \end{cases};$$

$$D_{G2} = \begin{cases} G_{2H} \le G_2 \le G_{2B} \\ G_2\langle G_{2H}; G_2\rangle G_{2B} \end{cases}. \quad (10)$$

Minimizing expression (8) with an account of (10) is reduced to finding the minimum of the function:

$$\tilde{F} = \left|T_{giv} - T_{set}\right|/T_{giv} + D_1 + D_{G1} + D_{G2}. \quad (11)$$

Outside the admissible region of mode changes, the functions (9) considerably exceed the value of the expression (7), so the minimum of the target function (10) will be in the region of admissible values of current and gas and powder flow rate. The particle temperature that provides the specified coating properties is calculated to select the modes. Then the arc current, gas and powder flow rate at which the material particles are heated to the specified temperature are determined.

When searching for values of arc current, gas and powder flow rates that provide a given set of temperatures of the sprayed particles, the possibility of realizing the minimum T_{min} and maximum T_{max} temperatures is checked. If there is no such possibility, then modes for intermediate values of particle temperatures are selected. If not, then it is concluded that the specified conditions are not realizable.

Optimization of the technological process can be carried out using other requirements, which are rewritten using such functions as minimum plasmatron wear F_w, using the plasmatron at the highest efficiency F_e, minimum spraying distance F_{minx}, etc.

In this case, the general target function can be represented as

$$F_t = F + \lambda_w F_w + \lambda_e F_e + \lambda_{minx} F_{minx}, \quad (12)$$

where:

λ_w, λ_e, λ_{minx} - are 0, if not used, and are 1 - if used.

The "RASHET" program provides the calculation of temperature and particle velocity.

Step 5. The coating is tested to verify the correctness of the calculation results and their refinement to obtain the best possible performance.

Step 6. Data Retention (module "PRINT"). The program saves information in the database and prints flow charts for selected or developed technological processes. In this case, the calculation results can be presented in the form of specific numerical values, the required parameters or factors, functional relationships, tables, graphs, charts, etc.

4. CONCLUSION

In the course of this research, restrictive factors that have a significant influence on the design of new technological processes of plasma spraying have been established. The possibility of increasing the efficiency of using plasma spraying by developing methods and means of automation and computerization of this process has been substantiated.

A mathematical model describing the influence of statistically significant parameters of plasma deposition processes on the optimization criterion was obtained. The implemented software package (CAE-system) allows effective computational experiments for comprehensive research and prediction of the obtained coatings of various functional purposes with improved physical-mechanical and functional properties.

REFERENCES

[1] M. Guptaa, N. Markocsana, X.-H.Lib, B. Kjellmanc, Development of Bondcoats for High Lifetime Suspension Plasma Sprayed Thermal Barrier Coatings. *Surface and Coatings Technology*, 371, 2019: 366-377, 2019. https://doi.org/10.1016/j.surfcoat.2018.11.013

[2] S.M. Muneer, M. Nadeera, Wear Characterization and Microstructure Evaluation of Silicon Carbide Based Nano composite Coating Using Plasma Spraying. *Materials Today: Proceedings*, 5(11), 2018: 23834-23843. https://doi.org/10.1016/j.matpr.2018.10.175

[3] Z. Shi, J. Wang, Z. Wang, Y. Qiao, T. Xiong, Y. Zheng, Cavitation Erosion and Jet Impingement Erosion Behavior of the NiTi Coating Produced by Air Plasma Spraying. *Coatings*, 8(10), 2018: 346. https://doi.org/10.3390/coatings8100346

[4] H. Dong, Y. Han, Y. Zhou, X. Li, J-T. Yao, Y. Li, The Temperature Distribution in Plasma-Sprayed Thermal-Barrier Coatings During Crack Propagation and Coalescence. *Coatings*, 8(9), 2018: 311. https://doi.org/10.3390/coatings8090311

[5] N. Zhang, N. Zhang, S. Guan, S. Li, G. Zhang, Y. Zhang, Composition versus Wear Behaviour of Air Plasma Sprayed NiCr-TiB_2-ZrB_2 Composite Coating. *Coatings*, 8(8), 2018: 273. https://doi.org/10.3390/coatings8080273

[6] P.G. Grützmacher, M. Schranz, C.-J. Hsu, J. Bernardi, A. Steiger-Thirsfeld, L. Hensgen, M.R. Ripoll, C. Gachot, Solid lubricity of WS_2 and Bi_2S_3 coatings deposited by plasma spraying and air spraying. *Surface and Coatings Technology*, 446, 2022: 128772. https://doi.org/10.1016/j.surfcoat.2022.128772

[7] Z. Li, Y. He, T. Liu, B. Yang, P. Gao, J. Wang, Q. Wang, Structural modifications induced by ultrasonic vibration during plasma spray deposition Ni coating on Al substrate. *Surface and Coatings Technology*, 441, 2022: 128600. https://doi.org/10.1016/j.surfcoat.2022.128600

[8] I.N. Kravchenko, S.V. Kartsev, Y.A. Kuznetsov, S.A. Velichko, Optimization of Plasma Deposition and Coating Plasma Fusion Parameters and Regimes. *Refractories and Industrial Ceramics*, 62, 2021: 51-56. https://doi.org/10.1007/s11148-021-00557-w

[9] I.P. Gulyaev, V.I. Kuzmin, O.B. Kovalev, Highly hydrophobic ceramic coatings obtained by plasma spraying of powder materials. *Thermophysics and Aeromechanics*, 27, 2020: 585-594 https://doi.org/10.1134/S0869864320040113

[10] R.A. Zhilin, P.V. Strunkin, Additive Technologies with Application of the Plasma Dusting. *High Technologies in Construction Complex*, 1, 2020: 190-192.

[11] S. Goel, S. Björklund, N. Curry, S. Govindarajan, U. Wiklund, C. Gaudiuso, S. Joshi, Axial Plasma Spraying of Mixed Suspensions: A Case Study on Processing, Characteristics, and Tribological Behavior of Al_2O_3-YSZ Coatings. *Applied Sciences*, 10(15), 2020: 5140. https://doi.org/10.3390/app10155140

[12] G.I. Trifonov, Investigating the relationship between the thermophysical and physico-mechanical parameters of plasma spraying and the travel rate of the plasmatron. *Mechanical equipment of metallurgical plants*, 1(12), 2019: 76-80. (In Russian)

[13] F.I. Panteleenko, V.A. Okovity, A.F. Panteleenko, Materials for Gas-Thermal Spraying, Obtained by Diffusion Alloying from Powders Based on Austenitic Steels. *Science & Technique,* 18(5), 2019: 380-385. https://doi.org/10.21122/2227-1031-2019-18-5-380-385

[14] V.V. Ivancivsky, V.Y. Skeeba, E.A. Zverev, N.V. Vakhrushev, K.A. Parts, Increase in wear resistance of nickel plasma coatings under traditional and combined treatment conditions. *IOP Conference Series: Earth and Environmental Science*, 194, 2018: 042006. https://doi.org/10.1088/1755-1315/194/4/042006

[15] O.K. Yatskevich, O.G. Devoyno, M.A. Kardapolova, Technology of modifying of aluminum oxide powder for plasma spraying. *Progressive technologies and systems of mechanical engineering*, 4 (63), 2018: 134-143. (In Russian)

[16] K. Sirozhev, Analysis of methods of application of metal-composite powder layers on metals. *Scientific researches of the XXI century*, 2(10), 2021: 139-143.

[17] S.A. Sidorov, V.P. Lyalyakin, D.A. Mironov, Selection of modes of plasma spray coating deposition on flat working surfaces. *Machine Building Technology*, 5, 2020: 5-8. (In Russian)

[18] I.N. Kravchenko, S.V. Kartsev, Yu.A. Kuznetsov, A.L. Galinovsky, Assessment of the Heat Balance and Effective Power of Plasma Spraying with After-Melting. *Electrometallurgy*, 7, 2021: 19-24. (In Russian)

[19] V.A. Okovity, F.I. Panteleenko, V.V. Okovity, V.M. Astashinsky, Formation of Plasma Powder Coatings from Cermet with Subsequent High-Energy Modification. *Science and Technique*, 19(6), 2020: 469-474. https://doi.org/10.21122/2227-1031-2019-18-5-380-385

[20] S.Yu. Zhachkin, G.I. Trifonov, N.A. Penkov, A.V. Biryukov, On the question of

mathematical modeling of the plasma deposition process in the restoration of the agricultural machinery parts. *Reinforcing Technologies and Coatings*, 17(4), 2021: 162-165. https://doi.org/10.36652/1813-1336-2021-17-4-162-165

[21] G. Mauer, M.O. Jarligo, D.E. Mack, and R. Vaßen, Plasma-sprayed thermal barrier coatings: new materials, processing issues, and solutions. *Journal of Thermal Spray Technology,* 22, 2013: 646-658. https://doi.org/10.1007/s11666-013-9889-8

[22] S.-W. Yao, J.-J. Tian, C.-J. Li, G.-J. Yang, and C.-X. Li, Understanding the Formation of Limited Interlamellar Bonding in Plasma Sprayed Ceramic Coatings Cased on the Concept of Intrinsic Bonding Temperature. *Journal of Thermal Spray Technology*, 25(8), 2016: 1617-1630. https://doi.org/10.1007/s11666-016-0464-y

[23] V.A. Okovity, F.I. Panteleenko, V.V. Okovity, V.M. Astashinsky, Plasmatron for coatings. *Science and Technique*, 18(1), 2019: 5-10. https://doi.org/10.21122/2227-1031-2019-18-1-5-10

[24] A.S. Baev, Plasma technologies for restoration and hardening of shipboard equipment parts. *Shipbuilding*, 1(842), 2019: 38-42. (In Russian)

[25] I.O. Yakubovich, T.G. Oreshenko, Tasks and prospects of improving the quality of coatings obtained by plasma spraying. *Actual problems of aviation and cosmonautics*, 1(12), 2016: 344-345.

[26] Yu.Yu. Balashov, M.S. Rudenko, M.N. Volochaev, A.V. Girn, The research of dependence between the input parameters of plasma spraying and microstructure of the obtained coatings. *Siberian Journal of Science and Technology,* 20(3), 2019: 384-389.

[27] G.I. Trifonov, Development of an automated design system for the application of functional coatings. *Mechanical equipment of metallurgical plants*, 2(15), 2020: 43-48. (In Russian)

[28] I.S. Syundyukov, A.Yu. Ryabikin, G.V. Ivanova, M.A. Skotnikova, Increasing the wear resistance of crankshafts by plasma spraying. *Modern mechanical engineering. Science and education*, 11, 2022: 196-209. (In Russian)

[29] V.P. Singh, A. Sil, R. Jayaganthan, Wear of Plasma Sprayed Conventional and Nanostructured Al_2O_3 and Cr_2O_3, Based Coatings. *Transactions of the Indian Institute of Metals*, 65, 2012: 1-12. https://doi.org/10.1007/s12666-011-0070-0

[30] I.N. Kravchenko, S.V. Kartsev, S.A. Velichko, Yu.A. Kuznetsov, O.A. Sharaya, M.A. Markov, A.D. Bykova, Metallographic studies of the structure and physical and mechanical properties of coatings obtained by plasma methods. *Metallurg*, 8, 2021: 69-76. https://doi.org/10.52351/00260827_2021_08_69

[31] V.N. Sokolov, M. S. Chernov, V. I. Kalita, D. I. Komlev, A. A. Raduk, The structure of porosity of plasma coatings. *Physics and chemistry of materials teatment*, 5, 2020: 33-43. https://doi.org/10.30791/0015-3214-2020-5-33-43