УДК 621.793.71

F. I. Panteleenko, a member- correspondent. NAN B, Ph. D., Professor,
V. A. Okovity, Ph. D**., O. G. Devoino**, Ph. D., Professor, **A. S. Volodko,**
V. A. Sidorov, Ph. D., associate Professor, **V. V. Okovity, A. A Litvinko**
Belarusian National Technical University, Minsk, Belarus
Tel. / Fax:*+375 17 293-95-99,* ***E-mail****: niil_svarka@bntu.by*
V. M. Astashinsky, a member- correspondent NAS B, D. Phys. - math. n., prof.
A. V. Lykov Institute of Heat and Mass Transfer of the National Academy of Sciences of Belarus, Minsk, Belarus
Tel. / Fax: *+375 17 284-24-91,* ***E-mail****:ast@hmti.ac.by*

INVESTIGATION OF THE IMPACT OF COMPRESSION PLASMA FLOWS ON MULTILAYER COATINGS

The article presents the results of studying the impact of compression plasma flows, which are generated by quasi-stationary plasma accelerators, on multilayer protective coatings obtained using plasma spraying in air. Under shock and wave effects of pulses of the compression plasma flow, plastic deformation and significant compaction of the treated layer of the applied plasma coating occur. Ultrafast cooling and corresponding heat removal to the substrate, after melting of the formed layer with a thickness of about 20-30 microns, is the result of the thermal effect of compression plasma pulses. There are significant structural-phase changes in the modified area. The impact of high-temperature plasma pulses on the "base-coating" system leads to the melting of the resulting coating and the base layer and the subsequent liquid-phase mixing of these components under the influence of the pressure of the plasma flow. The action of plasma flows on the surface of the resulting material leads to significant changes in morphology. The degree of short-term melting in compositions containing various phases affects the number of centers of passing crystallization, leading to strengthening of structures during ultra-rapid cooling.
Keywords: *ceramic-metal plasma coatings, compression plasma flows, treatment distance, formed structures, surface layers, formed wear-resistant coatings.*

Ф. И. Пантелеенко, В. А. Оковитый, О. Г. Девойно, А. С. Володько, В. А. Сидоров, **В. В. Оковитый, А. А. Литвинко, В. М. Асташинский**

ИССЛЕДОВАНИЕ ВОЗДЕЙСТВИЯ ПОТОКОВ КОМПРЕССИОННОЙ ПЛАЗМЫ НА МНОГОСЛОЙНЫЕ ПОКРЫТИЯ

В статье представлены результаты исследования воздействия потоков компрессионной плазмы, генерируемых квазистационарными плазменными ускорителями, на многослойные защитные покрытия, полученные с помощью плазменного напыления на воздухе. При ударно-волновом воздействии импульсов компрессионного плазменного потока происходит пластическая деформация и значительное уплотнение обрабатываемого слоя нанесенного плазменного покрытия. Сверхбыстрое охлаждение и соответствующий отвод тепла к подложке, после расплавления сформированного слоя толщиной порядка 20-30 мкм, является результатом теплового воздействия компрессионных плазменных импульсов. В измененной области наблюдаются значительные структурно-фазовые изменения. Воздействие импульсов высокотемпературной плазмы на систему «основа-покрытие» приводит к расплавлению полученного покрытия и слоя основы и последующему жидкофазному смешению этих компонентов под действием давления плазменного потока. Воздействие потоков плазмы на поверхность полученного материала приводит к существенным изменениям морфологии. Степень кратковременного плавления в композициях, содержащих различные фазы, влияет на количество проходящих центров кристаллизации, приводя к упрочнению структур при сверхбыстром охлаждении.
Ключевые слова*: металлокерамические плазменные покрытия, компрессионные плазменные потоки, дистанция обработки, сформованные структуры, поверхностные слои, формованные износостойкие покрытия.*

1. Introduction.

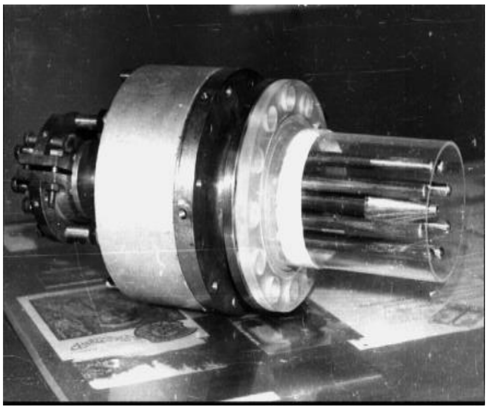
It is known [1–10] that the processing of multilayer plasma coatings by intense high-energy flows: electron, ion, laser, and plasma is accompanied by heating of the treated surface (sometimes above the melting point of the initial material) followed by rapid overcooling of the surface layer of the coating at a rate, reaching values of 10^{10} K/s. The resulting temperature gradients and alloying of the source material during the processing often lead to structural and phase transformations in the surface layers of the deposited materials and, accordingly, to a change in their technological properties: hardness, wear resistance, heat resistance, adhesion strength [1-7]. Completely new opportunities for the ongoing modification of the properties of coatings and a significant improvement in the resulting operational characteristics are provided by the use of compression plasma flows, which are generated by quasi-stationary plasma accelerators [1, 3]. This method has a number of advantages over other methods of high-energy processing: a short exposure time (of the order of ~ 100 μs), the possibility of additional doping of the resulting coating layers with elements of a pre-applied coating, the use of the gas used not only for heating the coating, but also for its doping. Joint mixing by compression plasma flows of the base-coated system makes it possible to obtain a near-surface layer containing elements of both the coating and the base. The purpose of our research was to study plasma coatings under high-energy exposure to a compressive plasma flow, to study changes in the elemental composition of the coating, structural and phase transformations and technological properties of the modified layer, to create scientific foundations for new methods for significantly improving the properties of plasma wear-resistant coatings, widely used in a number of industries.

2. Technological characteristics of the process of processing by pulses of compression plasma. It is known that under shock and wave impacts of compression plasma flow pulses, plastic deformation and significant compaction of the processed layer of the applied plasma coating occur. Ultrafast cooling and the corresponding heat removal to the substrate, after melting the formed layer with a thickness of about 20-30 microns, is the result of the thermal effect of compression plasma pulses. There are significant structural-phase changes in the modified area. The impact of high-temperature plasma pulses on the "base-coating" system leads to the melting of the resulting coating and the base layer and the subsequent liquid-phase mixing of these components under the influence of the pressure of the plasma flow. The action of plasma flows on the surface of the resulting material leads to significant changes in morphology. The degree of short-term melting in compositions containing various phases affects the number of centers of passing crystallization, leading to strengthening of structures during ultra-rapid cooling. In structures, there is a change in their short-range order, the material in the formed coating comes to a state similar to an amorphous one [1]. The degree of plastic deformation significantly affects the probability of formation of amorphous structures. Accordingly, when Al_2O_3-TiO_2-NiCrAlITa and Al_2O_3-TiO_2-Mo coatings are exposed to compression plasma flows, the main sign of optimization is the maximum melting at the minimum possible exposure distances with a corresponding increase in the levels of thermal, shock and wave effects of pulses. The possible minimum is limited by the appearance of signs of fault detection of the formed coating (large pores and a network of cracks on the surface, chips). An assessment of the degree of melting and compaction obtained, as well as signs of destruction, is carried out. In the study of thin sections treated with compression plasma, the evaluation of flashing options was carried out on a metallographic microscope (MeF-3) and on analyzers (MOP-AMO3, AutoScan). Together with the study of the properties formed during optimization, we studied the average parameters of microhardness, a characteristic of the formed coatings correlated with the degree of amorphization (microhardness tester "Micromet-II").

Coatings created using a magnetoplasma compressor (MPC) - a gas-discharge quasi-stationary accelerator (Figure 1 a), including an energy unit, a vacuum unit (a chamber with the necessary systems for pumping and puffing the working gas (hydrogen)), a diagnostic complex, a control and measuring a block that synchronizes all units of the installation. Vacuum chamber 150 cm long, at the end there is an MPC discharge device. The working gas supply system allows the use of any gases, as well as their mixture in any ratio. A general view of the discharge device used to create a compression plasma is shown in Figure 1b.

The energy accumulator structurally looks like a complex of a capacitor bank for supplying power to the MPC and capacitor banks that support the operation of the electrodynamic valve, it inlets the working gas. The main advantage of the MPC is the high stability of the compression flow with the possibility of correlation of the control parameters, compositions and flow sizes, the duration of the discharge, which makes it possible to carry out practical applications [2]. The MPC operated in the so-called "residual gas" mode - a previously evacuated vacuum chamber was filled with working gas (nitrogen or hydrogen) to the required pressure (it is possible to operate in the range of 133-1330 Pa). Modes of operation MPC-discharge duration - 140 μs, amplitude indicators of the discharge current - 50 to 100 kA (depending on the initial parameters of the discharge). As a result, a compression plasma flow is formed with indicators - length 10 cm, diameter 1-2 cm (in the region of maximum compression). In accordance with the initial parameters of the accelerator, the plasma velocity of the obtained compression flow is on the order of $(2\text{-}7).10^6$ cm/s. The resulting concentration of charged particles in the region of maximum compression in this case reaches the order of $(5\text{-}10).10^{17}$ cm-3, and the temperature is 1-3 eV. The treatment of the coatings under study on the samples was carried out when the surface was exposed to one or a series of compression plasma flow pulses, the number of which varied from 10 to 17 in different experiments. bit device MPK, presented in Figure 2.

a



b

Figure 1. General view of the research stand – magnetoplasma compressor (a); general view of the MPC discharge device (b)

The energy density [8] absorbed by the coated sample varied from 3 to 40 J/cm2 per pulse by changing the distance from the cutoff of the discharge device to the sample, as well as by changing the initial voltage on the MPC energy storage. The resulting dependence of the energy density absorbed by the surface, on the distance to the MPC discharge device when operating in a nitrogen atmosphere at parameters P_0=665 and 1330 Pa and the initial voltage on the accelerator energy storage device U_0=3.5 kV, is shown in Figure 3. The values of the absorbed surface energy density of the target, when the distance from the cathode cutoff to the sample changes from 8 to 16 cm, it decreases by almost 5 times at P_0=665 Pa.

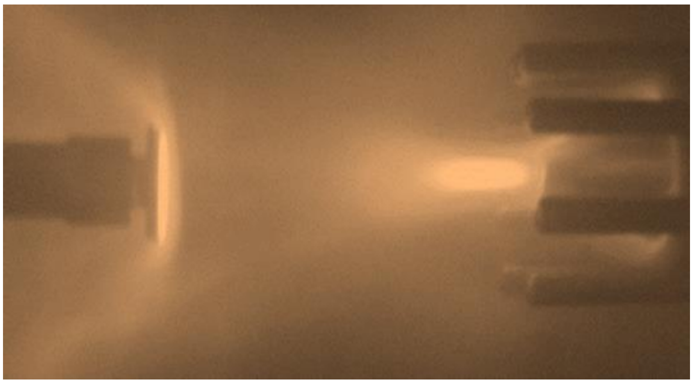


Figure 2. The process of modification under the influence of impulses compressive plasma flow on a sample coated plasma coated

Using the accepted technique, changing the used technological characteristics of the process of processing by pulses of the compression plasma flow, both the distance under the influences and their number were changed [7-11]. The number of pulses significantly affects the thickness of the treated layers. The total number of pulses must create a melted coating with high strength characteristics throughout the entire thickness of the coating. According to the optimization data (Tables 1 and 2), the optimum distances for the formation of hardened structures for NiCrAlITa-Al_2O_3-TiO_2 are 0.13 m; for Mo-Al_2O_3-TiO_2 - 0.14 m. This is confirmed by the stabilization of the total porosity, at distances below 0.13 and 0.14 m there is no decrease due to the instantaneous dynamic and thermal effects (about 200 μs), and also the maximum content of the refractory phase, which reduces the degree of melting. At distances below 0.11 m for NiCrAlITa-Al_2O_3-TiO_2 and 0.12 m for Mo-Al_2O_3-TiO_2, defects with the development of macro-cracks are noticeable.

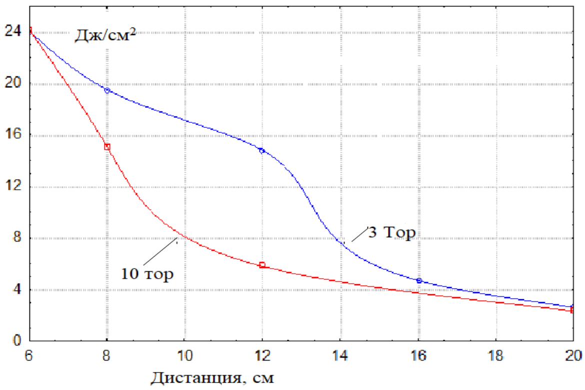


Figure 3. Dependence of the energy density absorbed by the treated surface of the sample on the used distance to the discharge device of the magnetoplasma compressor.

We also optimized the total number of pulses in the compression plasma. When the system is treated with a small amount of pulse, incomplete melting and partial mixing of the system components are observed. Processing with a large number of pulses is characterized by more uniform mixing. An increase in microhardness can also be due to the effects of rapid quenching: the sample experiences sharp heating up to the melting of the surface layer, followed by heat removal into the depth of the sample and rapid recrystallization. It was revealed as a result of research for the complete processing of the formed coatings for NiCrAlITa-Al_2O_3-TiO_2, 14-15 impacts are necessary, for Mo-Al_2O_3-TiO_2 - 12-13. A further increase is not necessary, the geometry of the created surface of the coating and the technological characteristics of the coating deteriorate due to remelting.

Table 1. Obtained values for optimizing the processing distance compression plasma pulses

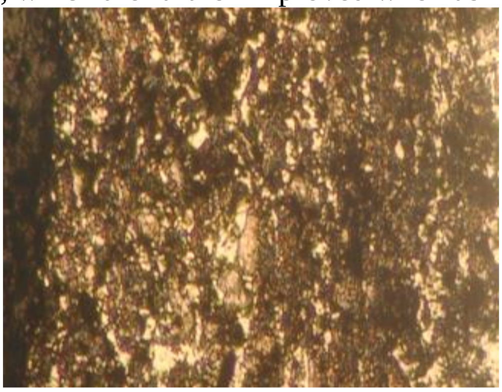
Coating	Distance of treatment with compression plasma pulses, m	Index of obtained porosity, %	Index microhardness, MP
Al_2O_3-TiO_2-Mo	0,17	4,9-6,1	5433-7989
	0,16	4,5 – 5,9	5948-8074 (4960-6731)
	0,15	3,8 – 5,1	6349-8565 (5292-7131)
	0,14	3,1 – 4,6	7240-9380 (6035-7821)
	0,13	3,4-4,9	6813-8522 (5681-7100)
	0,12	Destruction coatings	-
Al_2O_3-TiO_2-NiCrAlITa	0,17	4,5-5,8	5775-8644 (4621-6910)
	0,16	4,0-5,3	6286-9033 (5025-7227)
	0,15	3,7 – 4,9	7312-9350 (5850-7482)
	0,14	2,8 – 4,5	7414-9695 (5931-7761)
	0,13	2,6 – 3,9	7775-9914 (6221-7934)
	0,12	3,4-4,3	6286-8033 (5032-6429)
	0,11	Destruction coatings	-

Table 2. Obtained values for optimizing the number of pulses compression plasma

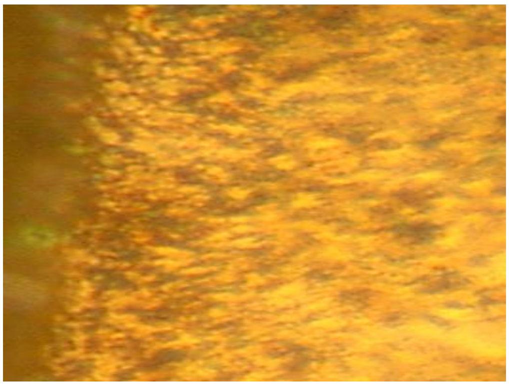
Formed coating	Total number of compression plasma pulse	Index of obtained porosity, %	Index of microhardness, MPa
Al_2O_3-TiO_2-Mo Distance processing (0,14 м)	10	5,9-6,6	5443-7798
	11	4,2 – 5,3	6189-8004
	12	3,2 – 4,7	6940-9089
	13	3,1 – 4,6	7240-9380
	14	4,5-6,3	6581-8442
	15	4,9-6,7	6335-7994
Al_2O_3-TiO_2-NiCrAlITa Distance processing (0,13 м)	11	4,5-5,8	6357-8394
	12	3,0-4,11	7148-9193
	13	3,2 – 4,4	7381-9495
	14	2,6 – 3,9	7775-9914
	15	2,8 – 4,1	7976-10199
	16	3,6-4,9	7621-9103
	17	4,5-5,4	7109-8998

The total number of pulses for powder materials NiCrAlITa-Al2O3-TiO2 than for Mo-Al2O3-TiO2. This follows from the mechanism of layer-by-layer processing, in which the dimensions of the formed zone from a single pulse directly depend on the conditions of heat transfer to the depth of the created coating. When the heat transfer conditions deteriorate, for example, when creating a high total porosity or heterogeneity, a larger zone for energy concentration and the thickness of the coating layer obtained as a result of processing by a single pulse are needed. This is typical for Al2O3-TiO2-Mo powders, since they are characterized by a structure with developed porosity and lower density compared to Al2O3-TiO2-NiCrAlITa powder materials.

With reduced values of heat transfer and an increase in the thickness of the layer formed by a single pulse, the sum of pulses for the final processing of the entire coating becomes smaller. The structures of wear-resistant coatings formed on optimized processing modes are shown in Figure 4. In the melted metal-ceramic material, a fairly homogeneous distribution of structural elements contributes to an increase in the wear resistance parameters of the formed powder compositions. Traces of Mo particles and nickel alloys are visible on the structures as characteristic light shells. Significant changes in the morphology of the created surface are caused by the effects of plasma flows. The fact that the composition of the powder materials used changed slightly during the formation of coatings is evidenced by the preserved structure of composite particles after their collision with the substrate and exposure to plasma pulses. This is a qualitative indicator for creating the necessary performance properties, which are further improved when using the next modification.



a)



b)

Figure 4. Structures of the developed wear-resistant: (a) Mo-Al_2O_3-TiO_2; (b) NiCrAlITa-Al_2O_3-TiO_2 after modification (×500)

3. Conclusion. Our studies allowed us to state that when the resulting wear-resistant plasma coatings are exposed to compression plasma flows, the following processes take place. The high amount of energy transferred by the plasma flow to the coating contributes to the melting of the surface layer with a thickness of 10–70 μm, depending on the coating material being processed. When exposed to a plasma flow, a certain part of the coating material can be removed due to the ablation effect. Moreover, the amount of material removed will increase with an increase in the energy transferred to the coating by the plasma flow. Under the influence of the pressure of the plasma flow, liquid-phase mixing will occur in the molten coating layer. At the last stage, the surface layer of the coating hardens under conditions of ultrafast cooling. It turns out that the phase and elemental composition of the surface layer of the coating changes significantly. A layer is formed in the coating, which contains elements of the coating and plasma-forming gas.

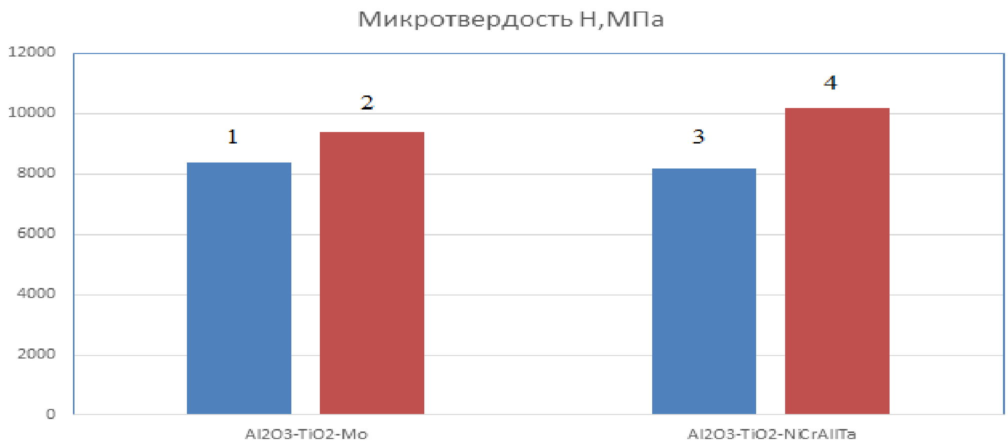


Figure 5. Indicators of microhardness of the formed coatings Mo-Al_2O_3-TiO_2 (1, 2) and NiCrAlITa-Al_2O_3-TiO_2 (3, 4) (1, 3 – process of plasma coating formation; 2, 4 – after modification by compression plasma)

And in the case of multi-stage processing of the "coating-base" system, a layer is formed that contains elements and coatings, and bases, and plasma-forming gas. With an increase in the energy absorbed by the coating due to a decrease in the distance from the electrodes to the part or an increase in the number of input processing pulses, the concentration of elements alloying the coating in the surface layer decreases, which in turn leads to a decrease in the concentration of intermetallic compounds in it. This is due to both an increase in the intensity of the ablation process and an increase in the thickness of the mixed coating layer (deeper penetration of the coating elements into the base). The resulting thickness of the mixed layer depends both on the processing modes and on the coating and base materials. Using the accepted technique, changing the used technological characteristics of the process of processing by pulses of the compression plasma flow, both the distance under the influences and their number were changed. The number of pulses significantly affects the thickness of the treated layers. The total number of pulses must create a melted coating with high strength characteristics throughout the entire thickness of the coating. According to the optimization data, the optimum distances for the formation of hardened structures for NiCrAlITa-Al_2O_3-TiO_2 are 0.13 m; for Mo-Al_2O_3-TiO_2 - 0.14 m. This is confirmed by the stabilization of the total porosity, at distances below 0.13 and 0.14 m there is no decrease due to the instantaneous dynamic and thermal effects (about 200 μs) , as well as the maximum content of the refractory phase, which reduces the degree of melting. At distances below 0.11 m for NiCrAlITa-Al_2O_3-TiO_2 and 0.12 m for Mo-Al_2O_3-TiO_2, defects with the development of macro-cracks are noticeable. We also optimized the total number of pulses in the compression plasma. When the system is treated with a small amount of pulse, incomplete melting and partial mixing of the system components are observed. Processing with a large number of pulses is characterized by more uniform mixing. An increase in microhardness can also be due to the effects of rapid quenching: the sample experiences sharp heating up to the melting of the surface layer, followed by heat removal into the depth of the sample and rapid recrystallization. It was revealed as a result of research for the complete processing of the formed coatings for NiCrAlITa-Al_2O_3-TiO_2, 14-15 impacts are necessary, for Mo-Al_2O_3-TiO_2 - 12-13. A further increase is not necessary, the geometry of the created surface of the coating and the technological characteristics of the coating deteriorate due to remelting. The structure of wear-resistant coatings formed on optimized processing modes is a melted metal-ceramic material with a fairly homogeneous distribution of structural elements that contribute to an increase in the wear resistance parameters of the formed powder compositions. Traces of Mo particles and nickel alloys are visible on the structures as characteristic light shells. Significant changes in the morphology of the created surface are caused by the effects of plasma flows. The fact that the composition of the powder materials used changed slightly during the formation of coatings is evidenced by the preserved structure of composite particles after their collision with the substrate and exposure to plasma pulses. This is a qualitative indicator for creating the necessary performance properties, which are further improved when using subsequent modifications. When studying the obtained properties of the formed coatings, the change in the average microhardness of the deposited compositions was analyzed. The microhardness increased by 1.15–1.25 times after the application of the modification, which is explained by the more efficient formation of phases with increased strength and amorphous structure during local melting of coatings with a thickness of approximately 30–50 μm, followed by instantaneous cooling, and the ability to ignore the recrystallization process.

LITERATURE:

1. Ilyushchenko, A. F. High-energy processing of plasma coatings / A. F. Ilyushchenko, V. A. Okovity, A. I. Shevtsov. – Minsk: Besprint, 2007. – 246 p.

2. Okovity, V. A. Formation and study of multilayer composite oxide plasma coatings on elements of screen anti-meteor protection ”for an international scientific and technical journal / Okovity V. A., Panteleenko F. I., Devoino O. G., Okovity V. V., Astashinsky V. M., Khramtsov P. P., Chernik M. Yu., Uglov V. V., Sobolevsky S. B. // “Science and technology” BNTU, 2016. – Issue 5. – P.357-364.

3. Panteleenko, F. I. Investigation of plasma two-layer composite coatings zirconium dioxide - nichrome / Panteleenko F. I., Okovity V. A., Panteleenko E. F. // “Actual problems in mechanical engineering”, NSTU – Novosibirsk- 2017. Volume 4. No. 3. – P. 100-105.

4. Okovity, V. A. Multilayer composite oxide plasma coatings on screen protection elements based on zirconium dioxide. / Okovity V. A., Panteleenko F. I., Okovity V. V., Astashinsky V. M., Khramtsov P. P., Chernik M. Yu., Uglov V. V., Sobolevsky S. B. // "Science and technology", BNTU – Minsk. – 2017. Issue 5. – P. 422-4311.

5. Okovity, V. A. Formation and study of plasma two-layer composite coatings (viscous NiCr metal layer and solid ZrO2) / Okovity V. A., Panteleenko F. I., Okovity V. V., Astashinsky V. M., Khramtsov P. P., Chernik M. Yu., Uglov V. V., Sobolevsky S. B. // Science and technology, BNTU – Minsk. – 2018. – Issue. 1. – S. 21-28.

6. Ilyuschenko, A. Ph. Laser processing of plasma spraying coatings /A. Ph. Ilyuschenko, V. A. Okovity, N. K. Tolochko // Materals and manufacturing processes. – New York (USA) – 2002. – vol.17. – No. 2. – P. 157-167.

7. Wang, Yu. Laser remelting of the surface of nanostructured Al2O3-13 wt.% TiO2 coatings deposited by plasma spraying on a titanium alloy / Yu. Wang, G. Li, V. Tian, Yu. Yang // Applied Surface Science. – 2009. – T. 255. – S. 8603–8610.

8. Laser remelting of plasma nanostructured Al2O3-TiO2 coatings at different laser power / Yu. Wang [et al.] // Technology of Surfaces and Coatings. – 2010. – T. 204. – S. 3559-3566.

9. Dubur, L. Properties of alumina-titanium coatings obtained by laser deposition in air plasma / L. Dubur, R. S. Lima, K. Moro // Technology of surfaces and coatings. – 2007. – T. 201. – S. 6278-6284.

10. Development of the microstructure of laser-remelted coatings Al2O3-13 wt. % TiO2 / S. G. Li [et al.] // Journal of alloys and compounds. – 2013. – T. 576. – S. 187-194.

Received by the editors 27.01.2023.