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RESEARCH OF PLASMA COMPOSITE COATINGS FROM OXIDE AND NICKEL BASE ALLOY

The results of a study of the influence of plasma jet parameters and the fractional composition of the initial powder on the characteristics of two-layer composite coatings based on nickel-chrome and zirconium dioxide on elements of protective screens are presented. Optimization was carried out based on obtaining the maximum powder utilization rate. A comparative analysis of the dependence of the powder utilization coefficient of viscous metal layers of nickel-chromium and nickel-aluminum on the spraying distance shows that with a similar nature of the curves of the presented dependences in absolute value, the values of the powder utilization coefficient are greater under optimal conditions for nickel-chromium powder. This can be explained by the high plasticity of the latter and, accordingly, less rebound of particles colliding with the substrate. The results of studies of the microstructure of cross sections of the formed coatings, carried out using scanning electron microscopy, are presented. The microstructures of the cross sections of the ZrO₂ coating and the Ni-Cr intermediate layer are considered. From the presented data it is clear that in the initial state the coating is characterized by porosity, with the average pore size being several micrometers and in some areas reaching 20 microns. The microstructure of the Ni-Cr layer is characterized by lower porosity. The effect of compression plasma flows on the sprayed coating leads to the formation of a remelted oxide layer 12–15 μm thick, promotes smoothing of the surface topography and the formation of cracks on the surface, propagating mainly into the depth of the coating. Treatment of oxide coatings with compression plasma also leads to a decrease in their porosity.

Keywords: plasma jet, coatings, shielding elements, ratio of powder use, plasma flows, cubic modification, zirconium dioxide

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ИССЛЕДОВАНИЕ ПЛАЗМЕННЫХ КОМПОЗИЦИОННЫХ ПОКРЫТИЙ ИЗ ОКСИДА И СПЛАВА НА ОСНОВЕ НИКЕЛЯ

Приведены результаты исследования влияния параметров плазменной струи и фракционного состава исходного порошка на характеристики двухслойных композиционных покрытий на основе никель-хрома и диоксида циркония на элементах защитных экранов. Проведена оптимизация на основании получения максимального коэффициента использования порошка. Сравнительный анализ зависимости коэффициента использования порошка вязких металлических слоев никель-хрома и никель-алюминия от дистанции напыления показывает, что при аналогичном характере кривых представленных зависимостей по абсолютной величине значения коэффициента использования порошка больше при оптимальных режимах для порошка никель-хрома. Это можно объяснить высокой пластичностью последнего и соответственно меньшим отскоком соударяющихся с подложкой частиц. Приведены результаты исследований микроструктуры поперечных сечений сформированных покрытий, выполненных с использованием растровой электронной микроскопии. Рассмотрены микроструктуры поперечных сечений покрытия ZrO₂ и промежуточного слоя Ni-Cr. Из представленных данных видно, что в исходном состоянии покрытие характеризуется пористостью, причем средний размер пор составляет несколько микрометров и в некоторых областях достигает 20 мкм. Микроструктура слоя

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Ni–Cr характеризуется меньшей пористостью. Воздействие на напыленное покрытие компрессионных плазменных потоков приводит к формированию переплавленного слоя оксида толщиной 12–15 мкм, способствует сглаживанию рельефа поверхности и образованию на поверхности трещин, распространяющихся преимущественно в глубину покрытия. Обработка оксидных покрытий компрессионной плазмой приводит также к снижению их пористости.

Ключевые слова: плазменная струя, покрытия, элементы защитных экранов, коэффициент использования порошка, плазменные потоки, кубическая модификация, диоксид циркония.

1 Introduction

When considering the performance characteristics of screen coatings that protect objects from damage under high-energy impacts, one of the most important indicators is the level of absorption of the kinetic energy of meteoric particles by the coating material. Without touching on all the mechanisms of energy absorption, we point out that a significant part of it is spent on elastic and plastic deformation of the coating material. Significant factors influencing the increase in the durability of such coatings are high ductility and viscosity. An increase in hardness sharply reduces ductility and toughness, leading to brittle fracture. The most commonly used structural materials for anti-meteor screens are aluminum alloys, titanium, and steel. Multilayer structures with a hard ceramic front layer and a sublayer of viscous metal material exhibit higher impact resistance. To obtain the front ceramic layer of antimeteorite coatings, oxide compositions, including those based on zirconium dioxide, are most often used [1-5]. This is due to a number of its properties: a relatively high coefficient of linear thermal expansion and the ability to provide high mechanical properties of strengthened ceramics, in particular impact strength. The main requirement for ensuring the effective operation of such protective elements is that they allow a significant reduction in the kinetic energy of incoming microparticles, while maintaining the stability of their structure. Based on this, it is proposed to form composite coatings based on zirconium oxide with the preliminary deposition of a transitional viscous sublayer based on metals, firstly, which increases the adhesive strength of the formed coating to the substrate, and secondly, which has visco-plastic properties different from those of the external coating [6-11], which leads to a significant slowdown of passing microparticles. At the same time, to increase the strength of the surface layer of the coating, which primarily interacts with the incident microparticle, it is proposed to treat it with compression plasma flows with energies that ensure melting of the surface layer. In this case, due to processes associated with rapid crystallization of the melt, the formation of a fine-crystalline structure with enhanced mechanical properties is expected. The structural-phase state of the near-surface modified layer can also be controlled by the parameters of the compression-plasma effect itself, in particular the absorbed energy density, the gas pressure of the residual atmosphere, the number of successive impact pulses, etc. To identify the features of the redistribution of elements in the coating and changes in their phase composition after exposure to compression plasma flows, the methods of X-ray spectral microanalysis and X-ray structural analysis were used. To study the microstructure of coatings after exposure to compression plasma flows, the method of scanning electron microscopy was used.

2 Methodology

In order to increase the strength of the surface ceramic layer of the coating, which primarily interacts with the incident microparticle, the work proposes to treat it with compression plasma flows with energies that ensure melting of the near-surface layer. It is assumed that as a result of such modification, due to processes associated with high-speed crystallization of the melt, a fine-crystalline structure with enhanced mechanical properties will be formed. The structural-phase state of the near-surface modified layer was regulated by

the parameters of the compression-plasma effect itself, in particular, the absorbed energy density, the gas pressure of the residual atmosphere, the number of successive impact pulses, etc. Optimization of sputtering of the NiCr-based sublayer was carried out according to the method described in the sources [12]. Studies of the microstructure of the cross sections of the formed coatings were carried out using scanning electron microscopy (SEM).

3 Results and discussion

During the plasma spraying process, a large number of factors influence the properties of the resulting coatings. The most important of them, all other things being equal, are: the flow rate of the plasma-forming and transport gases, the flow rate of the sprayed powder, the electric arc current (input power), the spraying distance, and the speed of the substrate [12]. At the first stage, the process of deposition of a viscous metal layer based on nickel-chromium was optimized based on obtaining the maximum utilization rate of the material. Initially, the powder utilization factor (PUF) was determined at different current values (300 - 650 A, with an interval of 50 A) and plasma gas (nitrogen) flow rates R_{N_2} (45; 50; 55) l/min, but with a constant spraying distance $L = 110$ mm (Figure 1). At the next stage, the optimal values of the spraying distance were determined with constant current values and plasma gas flow rates ($I=550$ A; $R_{N_2}=50$ l/min) for different powder fractions (Figure 2). It is obvious that an increase in the current strength and the flow rate of the plasma-forming gas (Figure 1) to certain values leads to an increase in the instrumentation factor, because these parameters affect the degree of powder penetration [1-4]. Their further increase leads to the fact that the particles overheat and when they hit the substrate, they splash, therefore, the instrumentation factor decreases. As the N_2 flow rate increases, the current values for the maximum instrumentation decrease. A similar trend persists when changing the spraying distance (Fig. 2) when optimizing the flow rate N_2 and current (in our case, $R_{N_2} = 50$ l/min, $I = 550$ A). At short deposition distances, the particle does not have time to heat up sufficiently and reaches the substrate with a temperature $<tra$. The maximum PUF is observed at $L = 110$ mm; a further increase in the spraying distance leads to the fact that the particle, due to its long stay in the jet, melts and splashes when it hits the substrate, and accordingly the PI drops [5]. Thus, at optimal conditions for NiCr (nitrogen plasma gas flow rate - 50 l/min, current strength - 550A, spraying distance -110 mm, powder fraction 40-63 microns, powder consumption 4.5 kg/hour) coatings with maximum Instrumentation and control - 85%.

The next step was to optimize the process of applying a hard layer based on zirconium dioxide. Figures 3-4 show the dependences of the utilization factor of the sprayed powder (UCP, %) based on zirconium dioxide during plasma spraying onto a nickel-chrome sublayer from the above spraying conditions. The dependence of the instrumentation factor, % on the spraying distance is shown in Figure 3.

At short deposition distances, the particle does not have time to heat up sufficiently and reaches the substrate with a temperature $<tra$. In our case, the IPC increases to $L=100$ mm for ZrO_2 powders with a fraction <50 μm and to $L=110$ mm with a fraction of 50-63 μm ; a further increase in the spraying distance leads to the fact that the particle melts due to its long stay in the jet and when it hits the substrate, it splashes, and accordingly the instrument falls [5]. An increase in the current and flow rate of the plasma-forming gas to certain values (Figure 4) leads to an increase in the instrumentation factor, because these parameters affect the degree of powder penetration [1-4]. Their further increase leads to the fact that the particles overheat and when they hit the substrate, they splash, therefore, the instrumentation factor decreases. As the N_2 flow rate increases, the current values for the maximum instrumentation decrease.

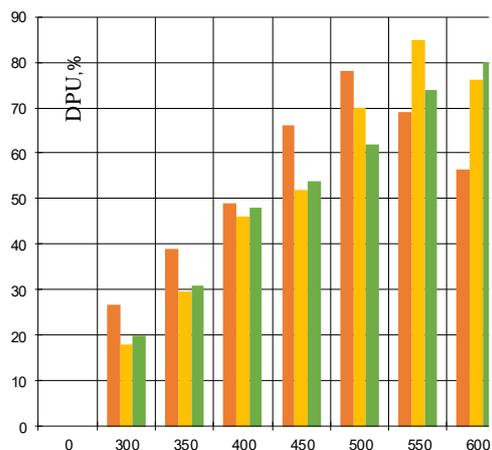


Figure 1. Dependence of the powder utilization coefficient on the electric arc current for NiCr powders with different flow rates of plasma-forming gas R_{N2}, l/min: 1 – 55; 2 – 50; 3 – 45 (L = 110 mm; R_{pore} = 4.5 kg/h; powder fraction 40–63 μm)

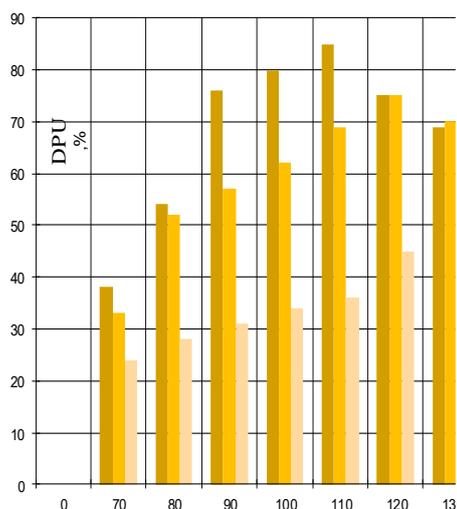


Figure 2. Dependence of the powder utilization coefficient on the spraying distance for NiCr powders with fraction: 1 – 40–63 μm; 2 – 63–100 μm; 3 – 100–160 μm (I = 550 A; R_{N2} = 50 l/min; R_{pore} = 4.5 kg/h)

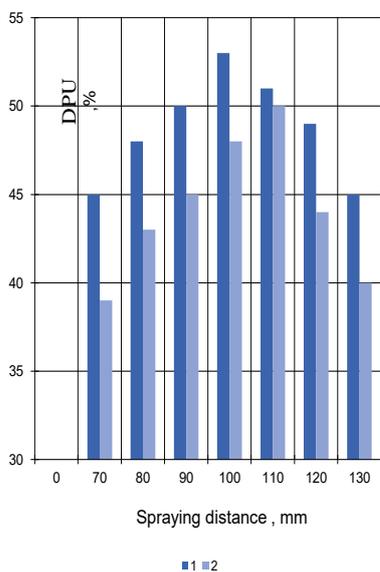


Figure 3. Dependence of the powder utilization coefficient on the spraying distance for ZrO₂ powders with fraction: 1 – less than 50 microns; 2 – 50–63 μm (I=500 A; R_{N2}=50 l/min; R_{pore}=4.5 kg/h)

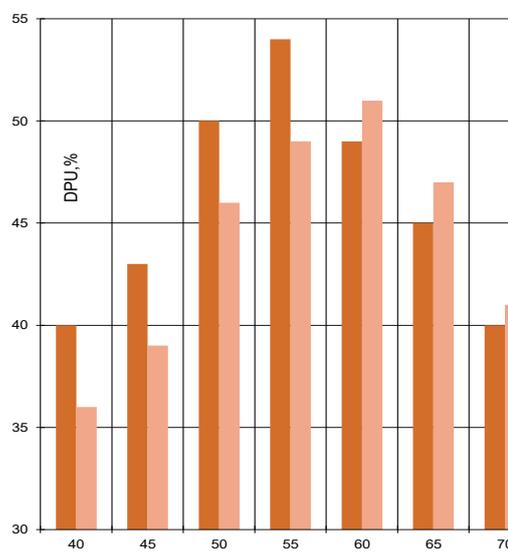


Figure 4. Dependence of the powder utilization factor on the consumption of plasma-forming gas N₂ for ZrO₂ powders with a fraction: 1 – less than 50 microns; 2 – 50–63 μm (L=100 mm; I=500 A; R_{pore}=4.5 kg/h)

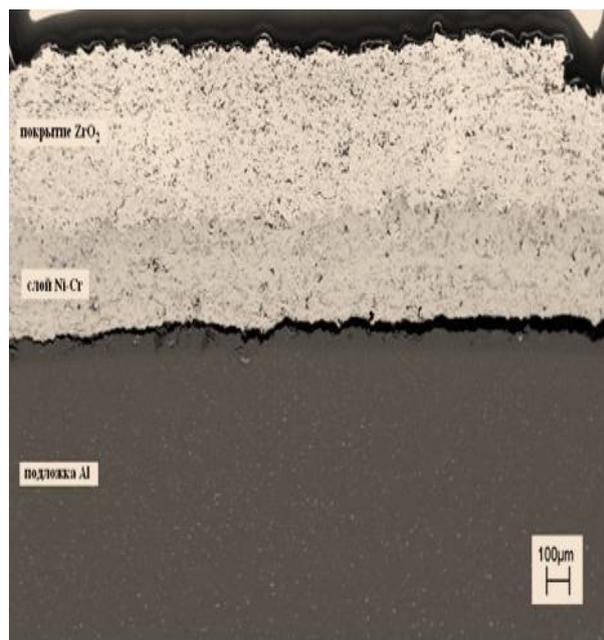


Figure 5. Scanning electron microscopy (SEM) image of a cross-section of the coating before exposure to compression plasma flows

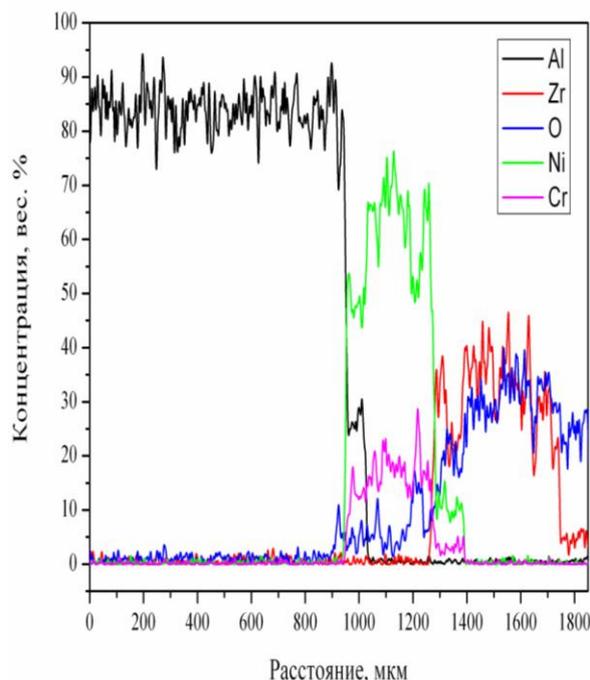
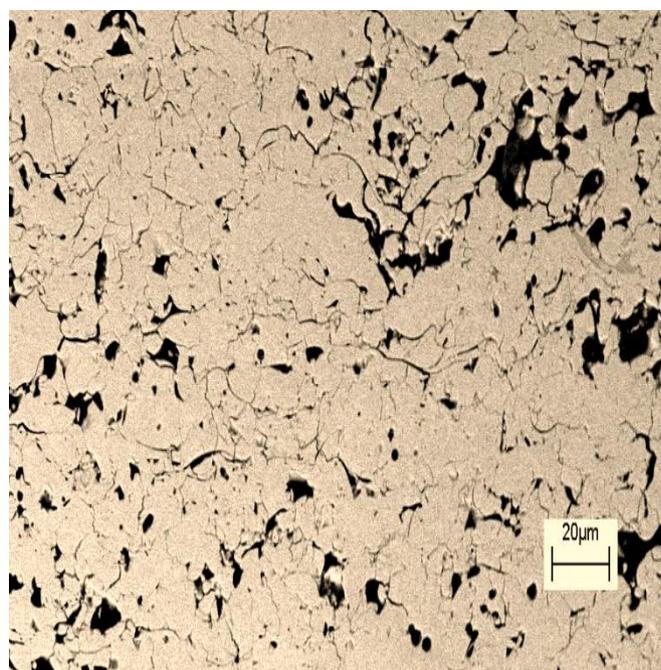
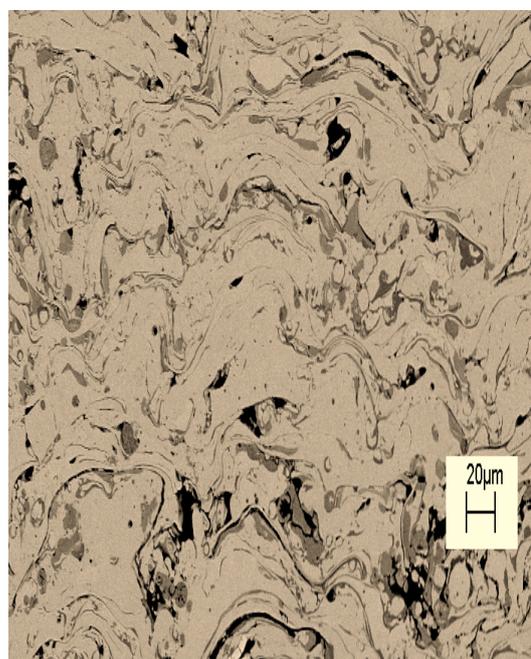


Figure 6. SEM image and distribution of characteristic X-ray radiation of elements along a selected line on a transverse section of the coating



a



b

Figure 7. SEM image of the microstructure of the zirconium dioxide coating (a) and the Ni-Cr intermediate layer (b) on a transverse section

For $RN2=55$ l/min, maximum instrumentation factor=56% corresponds to $I=600$ A, for $RN2=50$ l/min maximum instrumentation factor=54% corresponds to $I=650$ A. The results

of studying the microstructure of the cross sections of the formed coatings are presented in Figure 5. From the presented data it can be seen that the thickness of the ZrO₂ coating is about 800 μm. Between the coating based on zirconium oxide ZrO₂, the image revealed the presence of an intermediate sublayer, the thickness and elemental composition of which were studied using X-ray microanalysis. The results presented in Figure 6 indicate that the sublayer thickness is about 450 μm. Elemental analysis revealed that the sublayer consists of nickel and chromium. Figure 7 shows SEM images of the microstructure of cross sections of the ZrO₂ coating and the Ni-Cr intermediate layer. From the presented data it is clear that in the initial state the coating is characterized by porosity, with the average pore size being several micrometers, and in some areas reaching 20 microns. The microstructure of the Ni-Cr layer is characterized by less porosity.

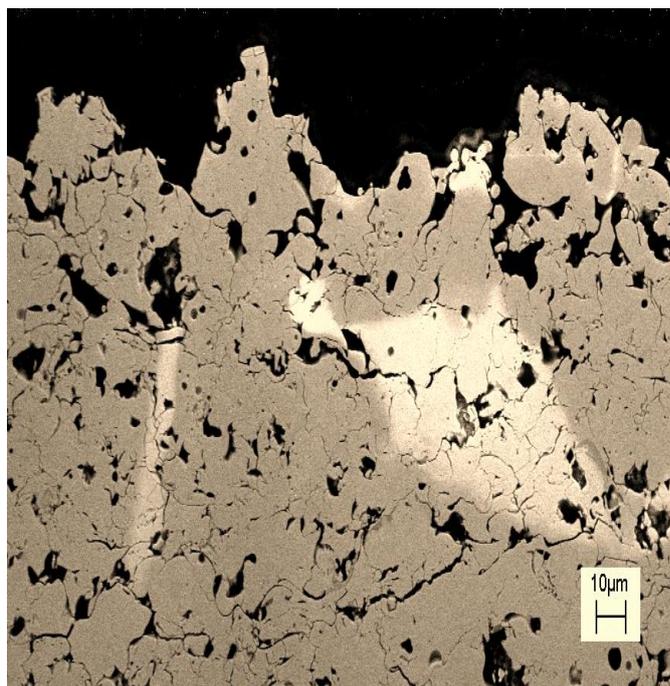


Figure 8. SEM image of the surface layer of the coating before exposure to compression plasma flows (cross section)

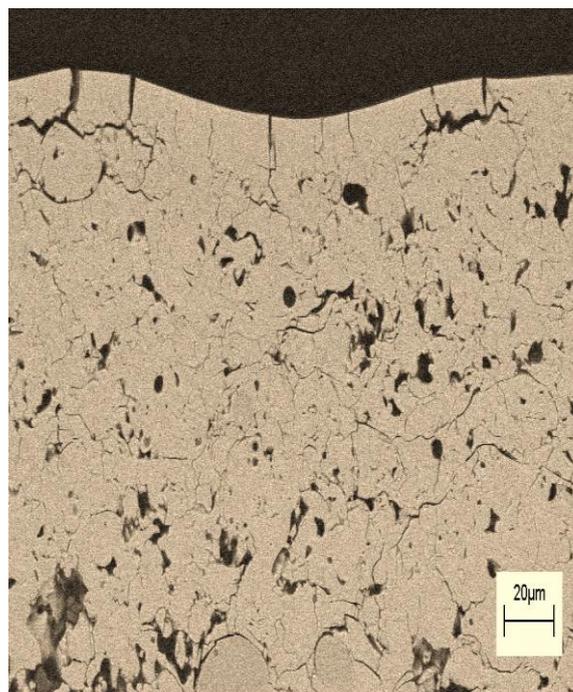


Figure 9. SEM images of a cross-section of the coating after exposure to compression plasma flows at different magnifications

Figure 8 shows a SEM image of the surface layer of the coatings obtained on a transverse section before exposure to compression plasma flows. The data obtained show that in the initial state, the near-surface layer is characterized by the presence of a large number of microcracks extending both along the surface and in depth. After exposure of the coating to compression plasma flows, the surface is smoothed, as evidenced by the SEM image of the transverse section shown in Figure 9. Analysis of the obtained SEM images showed that the number of microcracks and pores in the near-surface modified layer of the coatings is significantly reduced. This may result in melting of the near-surface layer and its crystallization from the melt. Nevertheless, some number of microcracks are present due to high-speed cooling of the crystallized layer. However, these microcracks extend mainly into the depth of the coating, which may prevent peeling off of parts of the coatings during mechanical action. Based on the presence of cracks extending into the sample, it is possible to determine the thickness of the molten layer, which is 12–15 μm.

4 Conclusion

1. Optimization of plasma spraying of two-layer composite coatings based on nickel-chromium and zirconium dioxide on elements of protective screens was carried out based on obtaining the maximum coefficient of powder utilization. Studies have been carried out of the influence of plasma jet parameters (current, spraying distance, consumption of plasma-forming gas nitrogen), the fractional composition of the initial powder on the characteristics of coatings. A comparative analysis of the dependence of the powder utilization coefficient of viscous metal layers of nickel-chromium and nickel-aluminum on the spraying distance shows that with a similar nature of the curves of the presented dependences in absolute value, the values of the powder utilization coefficient are greater under optimal conditions for nickel-chromium powder. This can be explained by the higher plasticity of the latter and, accordingly, less rebound of particles colliding with the substrate.

2. The results of studies of the microstructure of the cross sections of the formed coatings, carried out using scanning electron microscopy, showed that the sprayed structure is a coating based on zirconium dioxide ZrO_2 with a coating thickness of approximately 800 microns. Between the coating and the aluminum alloy substrate there is a transitional viscous layer of Ni-Cr transition metals, the thickness of which is 450 μm . The effect of compression plasma flows on the coating leads to the formation of a remelted oxide layer with a thickness of about 12–15 microns, promotes smoothing of the surface topography and the formation of cracks on the surface, propagating mainly into the depth of the coating. Treatment of oxide coatings with compression plasma also leads to a decrease in their porosity.

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