***ISSN 2079-1372 Problems of Tribology**, V. 31, No 2/120-2026, 34-43*

Problems of Tribology
Website: http://tribology.khnu.km.ua/index.php/ProbTrib
E-mail: tribosenator@gmail.com

DOI: https://doi.org/10.31891/2079-1372-2026-120-2-34-43

Effect of composition modification and heat treatment on the microstructure and wear resistance of plasma-sprayed nickel-based coatings for engine valves

O.V. Dykha*0000-0003-3020-9625, **A.A. Vychavka**0009-0009-1467-9337, **O.P. Babak** 0000-0002-1068-0631,
M.O. Dykha0000-0002-6075-1549, **V.O. Dytyniuk**0000-0001-6377-524X

[1]Khmelnytskyi national University, Ukraine
**E-mail: tribosenator@gmail.com*

Received: 04 April 2026: Revised 05 May 2026: Accept: 10 May 2026

Abstract

The work investigated the microstructure, phase composition and wear resistance of plasma coatings based on self-fluxing nickel alloys obtained from PG-10N-01 powder and intended for strengthening internal combustion engine valves. It was established that due to high heating and cooling rates during plasma spraying, a lamellar structure with the presence of amorphous and crystalline phases, oxide inclusions and pores is formed. It was shown that heat treatment provides partial crystallization of the amorphous phase, a decrease in porosity and an increase in the microhardness of the coating. The distribution of microhardness along the depth of the layer was studied, which is characterized by relative stability within the coating and a gradual decrease in the transition zone to the base. The effect of composition modification (introduction of ferrosilicon) on the structure formation and porosity of the coating was established. According to the results of tribological tests, an increase in wear resistance and a decrease in the coefficient of friction after heat treatment were determined. The adhesive wear mechanism caused by the structural heterogeneity of the coating is substantiated.

Keywords: plasma spraying, NiCrBSi, microstructure, wear resistance, microhardness, heat treatment, phase composition, porosity, friction coefficient, internal combustion engine valve

Introduction

Increasing the durability and reliability of machine parts operating under conditions of intense friction and wear is one of the key tasks of modern mechanical engineering and materials science. This problem is of particular relevance for friction units of vehicles, energy and technological equipment, where the combination of high contact loads, temperature effects and aggressive environments leads to accelerated destruction of surface layers. Such critical elements include valves of internal combustion engines, which operate under conditions of cyclic thermomechanical loads, elevated temperatures, gas corrosion and intensive wear of contact surfaces. Destruction or premature wear of valves leads to a decrease in the efficiency of the engine and a reduction in its resource.

In this regard, technologies for forming protective coatings are becoming widely used, among which plasma spraying occupies a leading place due to its high versatility, productivity and the ability to obtain coatings with specified functional properties. The use of plasma coatings to strengthen the working surfaces of valves allows to increase their wear resistance, heat resistance and corrosion resistance, which directly affects the operational characteristics of the engine.

Plasma coatings based on self-fluxing nickel alloys are characterized by high hardness, resistance to corrosion and abrasive wear and the ability to form dense protective layers with good adhesion to the base. The formation of the microstructure of such coatings occurs under conditions of extremely high heating and cooling rates of powder particles, which leads to the formation of a lamellar structure with the presence of amorphous and crystalline phases, oxide inclusions, pores and interparticle boundaries. It is these structural features that determine the mechanical and tribological characteristics of the coatings, in particular their hardness, wear resistance and resistance to fracture under contact interaction conditions.

Analysis of modern research shows that improving the operational properties of plasma coatings is achieved by optimizing their phase composition, reducing porosity, forming strengthening carbide and boride phases, as well as using additional technological operations, in particular heat treatment or remelting. Thermal stabilization of the structure contributes to the transition of the amorphous component to a more stable crystalline state, reducing residual stresses and increasing the cohesive strength of the coating. Another promising direction is the modification of the composition of powder materials, which allows for targeted influence on the formation of the structure and properties of coatings.

However, despite a significant amount of scientific research in this area, the relationship between the microstructure of plasma coatings, their phase composition and wear mechanisms remains poorly understood, especially for coatings used to restore and strengthen internal combustion engine valves. The influence of technological parameters of spraying, heat treatment and modification of the powder composition on the formation of structural heterogeneity and its role in the processes of friction and fracture needs to be clarified.

In this regard, the purpose of this work is to study the microstructure and wear resistance of plasma coatings based on self-fluxing nickel alloys, establish the regularities of the formation of their structural state, and evaluate the influence of composition modification and heat treatment on the performance characteristics of coatings intended for strengthening internal combustion engine valves.

Literature review

The microstructure of plasma coatings is formed as a result of the impact of molten or semi-molten powder particles on the surface of the substrate, their rapid cooling, deformation and layering. As a result, a typical lamellar structure is formed from individual flattened particles, interlamellar boundaries, pores, oxide inclusions and local areas of incomplete fusion. It is this heterogeneity that largely determines the hardness, wear resistance and corrosion behavior of coatings. NiCrBSi coatings are characterized by a combination of a hard metal matrix with boride, carbide and silicide phases, which increase microhardness and resistance to abrasive wear [2], [5], [7]. At the same time, excessive porosity or weak interlamellar bonding can reduce the cohesive strength of the coating and contribute to fracture under contact loads [7], [8].

An important way to improve the structure of plasma coatings is heat treatment or remelting. Short-term heat treatment of NiCrBSi coatings promotes relaxation of residual stresses, partial compaction of the structure, formation of more stable crystalline phases and increase of microhardness, which positively affects wear resistance [6], [8]. Laser or automatic remelting provides a denser structure with fewer pores and cracks, improves metallurgical bond with the base and increases the mechanical characteristics of the coatings [2], [9]. Such changes are especially important for self-fluxing NiCrBSi alloys, since boron and silicon lower the melting point, facilitate surface wetting and promote the formation of a dense wear-resistant layer [11].

Increasing the wear resistance of plasma coatings is often achieved by introducing hard reinforcing phases, in particular WC–Co. With an increase in the WC–Co content in NiCrBSi-composite coatings, the proportion of hard carbide inclusions increases, which counteract microcutting and plastic deformation of the surface during friction [3], [10]. However, excessive content of hard particles can increase the brittleness of the coating, promote the formation of microcracks and worsen the uniformity of the structure. Therefore, optimal wear resistance is ensured not only by high hardness, but also by a balanced combination of hard phases, a plastic matrix, low porosity and sufficient adhesion to the base [3], [10].

Amorphous and nanocrystalline coatings based on Fe and Ni alloys are characterized by increased structural homogeneity, the absence of large crystal grains, and high hardness, which contributes to increased resistance to wear and corrosion failure [1], [5], [6]. Nanocrystallization of amorphous NiCrBSi alloy after spraying can improve operational properties due to the formation of finely dispersed strengthening phases [5]. However, the corrosion resistance and durability of such coatings depend on the condition of the substrate surface, the quality of preparation before spraying, the coating density, and the presence of defects that can be penetration paths for aggressive media [1], [4], [12].

Thus, the analysis of literature sources shows that the wear resistance of plasma coatings is determined by a complex of structural factors: lamellar structure, porosity, phase composition, the presence of solid boride and carbide phases, the quality of interparticle bonding and the state of the “coating–base” interface. The most effective directions for increasing their performance are optimization of spraying parameters, use of composite powders, heat treatment, laser remelting and formation of a dense finely dispersed or nanocrystalline structure [2], [6], [8], [9].

Purpose and objectives of the study

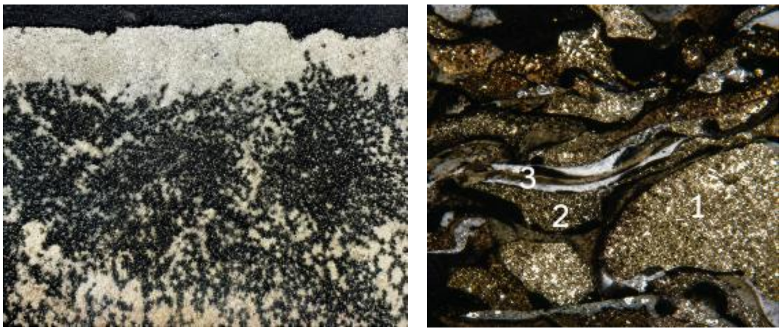
The purpose of this work is to establish the regularities of microstructure formation and study the wear resistance of plasma coatings based on self-fluxing nickel alloys, as well as to assess the influence of powder composition modification and heat treatment on their physicomechanical and tribological properties.

To achieve the goal, the work performed a microstructural analysis of plasma coatings, determined their phase composition and features of structure formation depending on the deposition conditions, investigated the distribution of microhardness across the coating cross-section, and established the effect of heat treatment on its structural state and mechanical properties. Special attention was paid to assessing the effect of modifying the powder composition, in particular the introduction of ferrosilicon, on the porosity and structural characteristics of the coating, as well as conducting tribological tests to establish wear patterns and determine the mechanisms of surface destruction under friction conditions.

Analysis of the structure of plasma coatings

During plasma spraying of PG-10N-01 powder on 40X steel, a hardened layer is formed, which evenly covers the surface of the part. The coating thickness is 300–350 μm and is characterized by uniformity over the entire area (Fig. 1a). The average hardness of the coating does not exceed HV 550. The resulting layer is characterized by a fine-grained structure and uniform distribution of structural components after melting with the formation of a transition zone between the coating and the base.

The formation of the coating structure occurs under conditions of high rates of heating and cooling of particles (10^6–10^8 K/s), which is accompanied by their complete or partial melting. The starting powder contains nickel, chromium, boron, silicon, iron and carbon, which causes the formation of a significant proportion of the amorphous phase in the coating. During the deposition process, the molten and semi-molten particles are deformed and form a lamellar (plate-like) structure of the surface layer, which determines the main physical, mechanical and tribological properties of the coating.

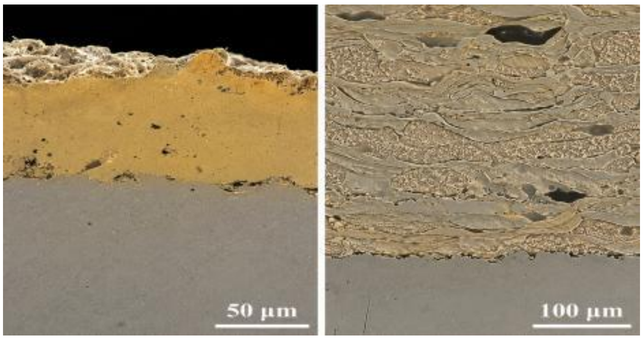


a) b)

Fig. 1. Microstructure of plasma coating and structural components of the deposited layer

The formed coatings are characterized by a complex heterogeneous structure (Fig. 1b), in which three main types of particles are distinguished: unmelted and undeformed (1), unmelted but plastically deformed (2), and completely molten particles (3). The proportion of unmelted particles is insignificant and does not exceed 10%. The main operational properties of the plasma coating are determined by particles of type 3, since it is they that form a dense structure with increased hardness, reaching 1000 HV, during crystallization.

It was found that the choice of spraying modes significantly affects the quality of the formed coating. High cooling rates of molten particles contribute to the occurrence of residual tensile stresses. If these stresses exceed the adhesion strength to the base, the coating may peel off. Important factors determining the morphology and specific surface area of the coating are the size and shape of the powder particles: a decrease in size and an increase in their irregularity lead to an increase in the specific surface area and affect the features of structure formation. The results of the analysis of the morphology of the coating obtained from the PG-10N-01 powder are shown in Fig. 2a.

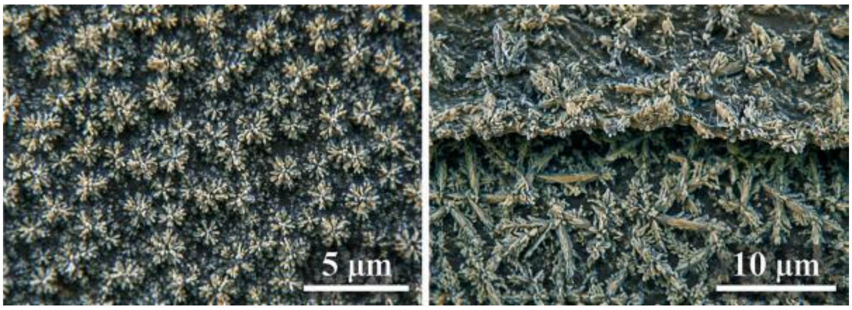


a) b)

Fig. 2. Morphology of the cross-section of the PG-10N-01 powder coating.

The coating is characterized by a uniform thickness without pronounced macrodefects, such as cavities or cracks, which indicates the stability of the deposition process and sufficient adhesion to the substrate. At the same time, individual spherical inclusions are detected in the structure, which correspond to semi-molten or unmolten particles of the starting powder that have not undergone full thermal action in the plasma jet. The reason for their formation is insufficient thermal input or limited duration of the particles in the high-temperature zone, which makes it impossible to form an amorphous phase. Such solid inclusions are evenly distributed in the amorphous-crystalline matrix of the coating (Fig. 2b) and can act as local stress concentrators.

Microstructural analysis showed that the vast majority of structural elements of the coating have sizes up to 200 μm, while the fine component is represented by grains with a size of 3–8 μm. The morphology of the grains is heterogeneous and includes leaf-like and dendritic forms (Fig. 3), which indicates non-equilibrium crystallization conditions. The formation of such a structure is due to high cooling rates of molten particles, which leads to the development of dendritic growth and the formation of fine phases, which determine the mechanical and tribological properties of the coating.



a) b)

Fig. 3. Grain structure of the applied coating from PG-10N–01 powder

During spraying, a significant number of sprayed particles are produced, which settle on the surface of the part in a semi-molten or molten state, cool and deform into flat particles. As a result, a layered coating surface is formed. The surface roughness Ra is 0.224 μm.Stabilization of the structure of the resulting coating occurs during the following heat treatment, which involves annealing at temperatures below the Trek temperature (recrystallization) to convert the amorphous structure into a crystalline one. Annealing was carried out at a temperature of 863 K (590 °C) with a holding time of 1 hour. Heat treatment improves the functional properties of the coating: the structure is stabilized due to the transition of the amorphous component to a crystalline one, crystals of the strengthening phases CrNi3 and Fe3Ni appear; the cohesive forces of adhesion of the coating to the base increase and porosity decreases. In the X-ray diffraction pattern taken after heat treatment [1-5], a wide peak indicates the transition of the amorphous phase to a crystalline one Fig. 4.

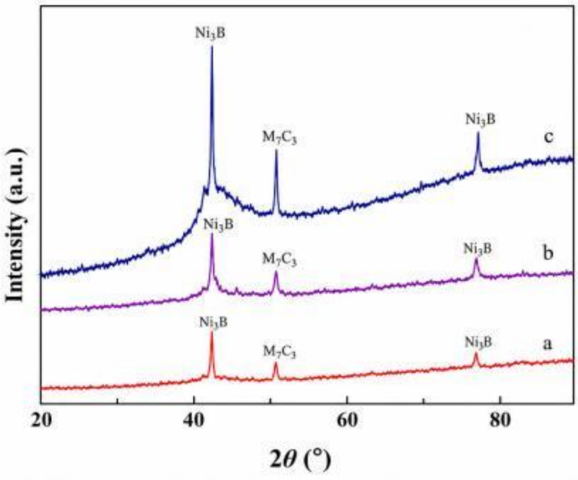


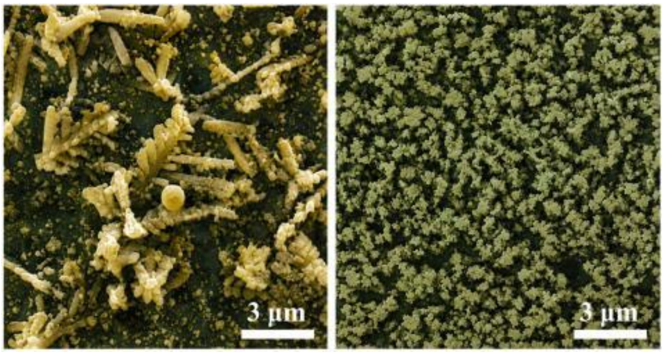
Fig. 4. X-ray diffraction patterns of NiCrBSi powder: a – in the initial state; b – powder after sputtering; c – powder after sputtering and heat treatment

The X-ray diffraction patterns of the NiCrBSi powder (Fig. 4) indicate phase transformations occurring during spraying and subsequent heat treatment.

In the as-received condition (curve a), the diffraction pattern is characterized by pronounced peaks corresponding to the Ni_3B phase (in the regions of ~2θ = 40–45° and ~75–80°), which is typical for boride constituents in self-fluxing nickel-based powders. In addition, a peak of the carbide phase M_7C_3 (~2θ ≈ 50°) is observed, indicating the presence of chromium-rich carbides in the structure. After spraying (curve b), a decrease in intensity and noticeable broadening of the Ni_3B peaks are observed, suggesting partial dissolution or amorphization of the boride phase due to rapid solidification of the molten material. The M_7C_3 peaks are still present but become less pronounced, indicating dispersion and refinement of the carbide phase. Following spraying and heat treatment (curve c), recrystallization of the structure occurs, as evidenced by the increased intensity and sharper peaks of Ni_3B. At the same time, the carbide phases M_7C_3 become more clearly defined, and additional carbides (such as those of the $M_{23}C_6$ type) may also be detected based on peak positions in the corresponding 2θ ranges. This suggests the formation of a more equilibrium and strengthened microstructure with a higher fraction of hard phases.

Thus, the analysis of the diffraction patterns (Ni_3B, M_7C_3) demonstrates that spraying leads to partial amorphization and phase dispersion, whereas heat treatment promotes recrystallization and phase stabilization, which are key factors contributing to increased hardness and wear resistance of the coating.

Fig. 5 shows that the sputtered surface has two types of grains (Fig. 5, a and b): larger crystals in the form of dendrites (a) – Ni3B, smaller (b) – grains up to 1 μm in size, almost spherical in shape, which corresponds to chromium carbides Cr7C3, Cr7C23.



a) b)

Fig. 5. Morphology of two types of grains in the cross-section of the PG-10N-01 powder coating.

The results of spectral analysis showed that after heat treatment, the content of the chromium carbide phase in the coating structure increases, and the content of the Ni3B phase decreases.

Microhardness study of the deposited layer

Hardness is one of the important operational characteristics of the material. The analysis of microhardness along the cross-section of the coating was carried out to assess the mechanical properties of the formed microstructure. The features of the plasma spraying technological process (high powder heating temperature, high cooling rate of the applied coatings) cause an uneven distribution of the components of the powder material over the surface of the part, as a result of which the applied coating has a heterogeneous chemical composition and structure, as well as a different number of pores and oxides. Usually, a significant proportion of the amorphous phase with a special structure and properties is found in the structure of plasma coatings. All this provides an ambiguous nature of the change in hardness along the cross-section of the coating. The microhardness of the coating applied to the surface of the part and the coating, which after application was subjected to stabilizing heat treatment - annealing at 590°C, was determined. The results are presented in Fig. 6.The average hardness of the coating is within 500 - 550 MPa, the thickness of the coating does not exceed 300 - 350 microns. Between the hardness of the coating and the hardness of the base, there is a fairly smooth decrease in values to the average values of the hardness of the base. As can be seen from the graphs, the microhardness varies depending on the distance from the surface of the part, but within the applied layer it does not change significantly.

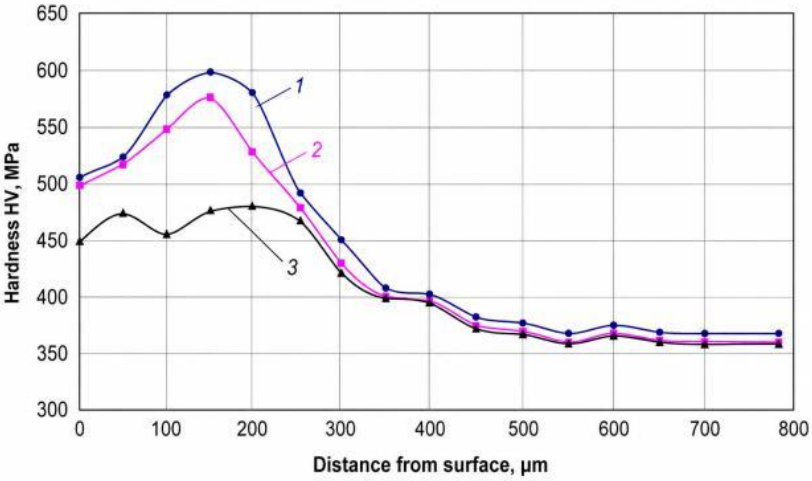
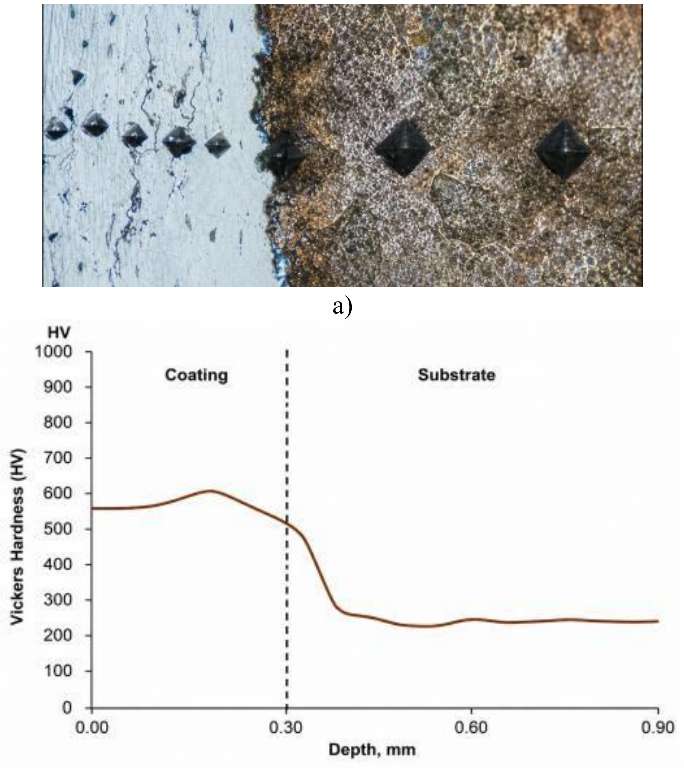


Fig. 6. Microhardness of plasma coatings of the Ni-Cr-B-Si system: 1 - coating of the Ni-Cr-B-Si system from PG-10N-01 powder after heat treatment; 2 - coating without annealing; 3 - Steel 40X without coating.

Fluctuations in microhardness values are due to the heterogeneous structure of the applied coating.

The presence of hard phases such as boron nitrides or chromium carbides in individual zones increases the hardness of these zones. Areas of the coating where an amorphous structure has formed have lower hardness values. Heat treatment contributes to the formation of a more uniform and stable structure, increasing the hardness of the applied coating (up to HV 600) due to the separation of the carbide phase – Cr3C7 and intermetallics Fe3Ni from the γ-solid solution (Fig. 6).



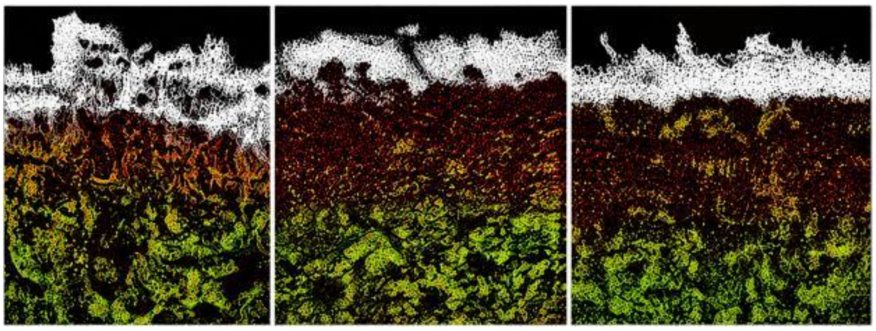
a)

b)

Fig. 7. Hardness along the depth of the plasma coating: a) impressions from the indentation of a tetrahedral pyramid; b) hardness distribution along the depth of the coating [3-8]

The Vickers microhardness profile versus depth clearly reveals the interface between the coating and the substrate, as well as the variation of mechanical properties across these regions (fig. 7). In the near-surface region (0–0.25 mm), corresponding to the coating, the hardness remains high and relatively stable at ~550–600 HV, with a slight maximum (~600 HV) in the middle of the layer. This indicates the formation of a strengthened structure due to the presence of hard phases (borides and carbides) and rapid solidification during spraying. Near the coating–substrate interface (~0.30 mm), a noticeable drop in hardness to ~500 HV is observed, indicating a transition (diffusion) zone characterized by gradual changes in phase composition and microstructure. Within the substrate (beyond 0.30 mm), the hardness decreases sharply to ~250–300 HV and then stabilizes at ~230–250 HV with minor fluctuations. These values correspond to the base material without strengthening phases. Thus, the hardness profile exhibits a gradient behavior: high hardness in the coating, a sharp transition at the interface, and consistently lower values in the substrate, confirming the effectiveness of the coating as a strengthening layer.

Adding ferrosilicon (from 2 to 5%) to PG-10N-01 powder contributes to the formation of a greater thickness of the applied layer and its porosity (Fig. 8).



a) b) c)

Fig. 8. Microstructure of the valve surface: a - - coating of PG-10N-01 powder with the addition of 5% ferrosilicon; b - coating of PG-10N-01 powder with the addition of 2% ferrosilicon, c) - coating of PG-10N-01 powder without the addition of ferrosilicon.

Table 1

Dependence of coating porosity on ferrosilicon content

Powder composition	Layer depth, µm	Porosity, %
PG-10N-01	290	0…1
PG-10N–01 + 2% ferrosilicon	330	10…15
PG-10N–01 + 5% ferrosilicon	350	20…30

When ferrosilicon is added to the powder, macrovoids are formed on the surface (Fig. 8, a, b). An increase in the amount of silicon in the composition of the PG powder contributes to the formation of chromium silicides (Cr3Si, Cr5Si3), which contribute to an increase in the hardness of the resulting layer. An increase in porosity when forming a coating with the addition of ferrosilicon has almost no effect on the microhardness, since chromium silicides appear in the structure, the hardness of which is not inferior to the hardness of chromium carbides (HV 1600). The porosity of the surface layer of the part significantly affects its oil capacity and lubricating properties, therefore determining the durability of the friction surface under conditions of insufficient lubrication. The changes that occur after the introduction of the powder into the coating significantly affect the formation and growth of transition layers. This, in turn, leads to changes in the mechanical properties of composite materials. Due to the short duration of the reflow process, the transition zone has an insignificant length of 10–15 µm. However, this length is sufficient to remove residual stresses, increase density and ensure fusion of the coating with the base, which is manifested in the penetration of the applied material into the surface layers. As a result of coagulation processes, the shape of the pores in the coating becomes rounded. Results of microanalysis of the chemical composition of molten plasma coatings of the Ni-Cr-B-Si system from PG-10N-01 powder with the addition of ferrosilicon, carried out using a microanalyzer PEM 106 i.

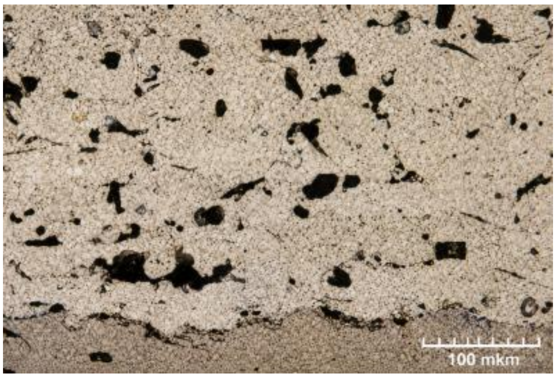


Fig. 9. Microstructure of the Ni-Cr-B-Si system coating

Table 2

Chemical composition of Ni-Cr-B-Si powder coating

Elements	Mass fraction in volume percent, %					
	Transition zone	1	2	3	4	5
Ni		83.7	48.3	64.4	87.7	71.9
Cr	5.49	12.4	33.3	20.2	7.36	20.6
Fe	94.00	2.8	16.4	12.1	4.58	4.3
Yes	0.33	0.9	0.75	1.64	0.26	1.06

As a result of chemical analysis of the distribution of elements in the structural coating, it can be concluded that silicon inclusions are mainly concentrated in dark areas of the coating (Fig. 9).

Study of wear resistance of valves after plasma spraying

The study of the wear resistance of valves was carried out on the friction machine SMC-2 according to the roller-flat counterbody scheme, which made it possible to establish the influence of nanodispersed inclusions on the level of increase in the wear resistance of self-flux coatings of the Ni-Cr-B-Si system (PG-10N-01) (Fig. 10). The dependencies that were obtained as a result of laboratory studies made it possible to analyze the kinetics of wear of self-flux coatings, as well as the level of their wear resistance. The composition of the Ni-Cr-B-Si system powder allows, after spraying onto the steel surface of a part made of Steel 40X, to obtain an increase in microhardness and bond strength due to physicochemical processes that ensure an increase in operational indicators (wear resistance, corrosion resistance). Wear tests conducted on SMC-2 showed that samples with a coating that was subjected to heat treatment have higher wear resistance.

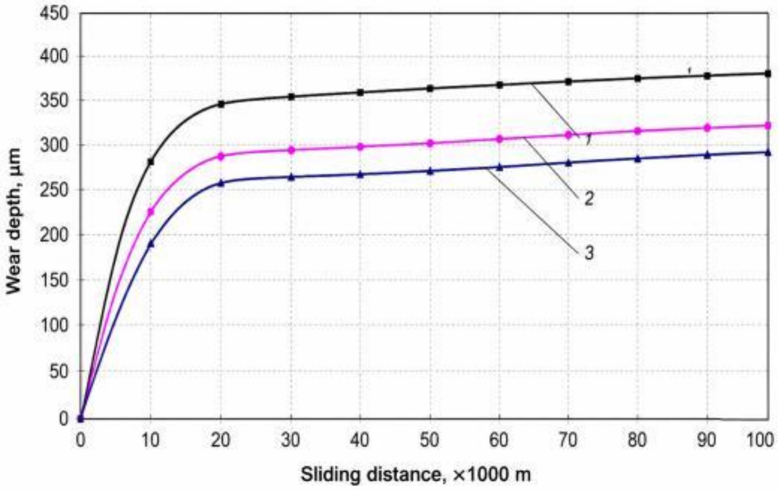


Fig. 10. Wear resistance of plasma coatings from Ni-Cr-B-Si powder system: 1 – Steel 40X without coating; 2 – Ni-Cr-B-Si coating from PG-10N-01 powder without annealing; 3 – coating after heat treatment.

Heat treatment has a positive effect on the tribological characteristics of the coating: it contributes to a decrease in the friction coefficient and its greater stability during friction [2-7] (Fig. 10).

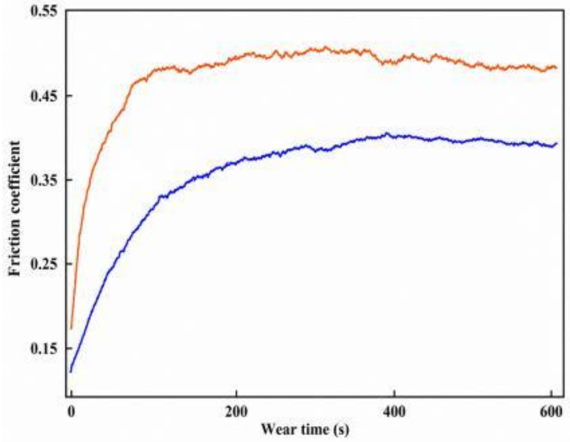


Fig. 11. Character of change in the friction coefficient of the NiCrBSi coating after application to the surface of the part (red curve) and after heat treatment (blue curve)[2-7]

Fig. 11 shows a comparison of the friction coefficient between the sprayed coating and the coating that was subjected to heat treatment. The friction coefficient of the sprayed coating gradually stabilizes, starting from 60 s, reaching values of 0.45. The friction coefficient fluctuated greatly, which negatively affects the wear resistance of the material. For the coating that was subjected to heat treatment, the stabilization of the friction coefficient was detected later - after 250 s, but its values are lower - 0.38. The higher values of the friction coefficient for the applied coating are explained by the rather inhomogeneous structure that was formed during spraying and the rather high surface roughness. The coating that was subjected to heat treatment has a more homogeneous structure, so the friction coefficient undergoes smaller fluctuations. To describe the wear mechanism of the sprayed coating, the morphology of the wear surface of the coating that was subjected to heat treatment was investigated. The worn surface consists of both relatively smooth particles, with a small number of cracks and an almost round shape, and areas where cracks have expanded due to friction, the particles are displaced relative to each other and overlap. Amorphous nickel-based coating is a typical brittle material with a large number of protruding particles on the surface, so the friction force and compressive stresses cause cracks in the defects under the oxide layer during wear. The boundaries of flat particles have a high content of oxides, which are prone to wear and delamination. The reciprocating motion causes fatigue damage to the surface structure of the coating and creates fatigue cracks. Under the action of a periodic tangential force, the fatigue crack expands and causes volume delamination. The presence of multiple cracks in the middle and surrounding areas of an individual particle also indicates that particles with poor flattening or insufficient fusion exist independently in the coating. A significant amount of wear products was found in the friction zone (Fig. 12)

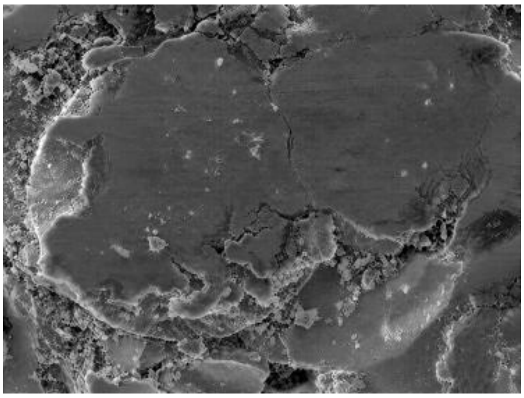


Fig. 12. The coating surface is contaminated with wear products

In Fig. 11, a large amount of fine debris adhering to the coating surface can be seen. This indicates that, unlike the wear mechanism of amorphous material, the wear mechanism of nanocrystals is predominantly adhesive. Debris that accumulates on the surface of the part can significantly increase wear. Cracks occur during friction, which are mainly caused by the presence of pores and oxides. The crack nuclei are powder particles with a defective surface (incompletely melted particles).

Conclusions

1. The effectiveness of the use of plasma coatings based on self-fluxing nickel alloys to increase the wear resistance of heavily loaded parts, in particular internal combustion engine valves, is shown. Based on the planning of a factorial experiment, the optimal spraying parameters were determined according to the microhardness criterion: current strength 244 A, distance 100 mm, powder consumption 0.48 g/s.

2. It was found that the microstructure of the coatings is heterogeneous and includes amorphous and crystalline phases. Heat treatment (annealing at 590 °C) promotes crystallization of the amorphous component, formation of strengthening phases (Cr_7C_3, Ni_3B, Cr_3Si) and increase of the microhardness of the coating by 100–120 HV.

3. According to the results of microstructural and tribological analysis, it was established that the wear of the coating is predominantly adhesive in nature and is caused by its structural heterogeneity, the presence of pores and oxide inclusions, which act as stress concentrators and centers of crack initiation.

4. It has been proven that modification of the coating composition by introducing up to 5% ferrosilicon has a positive effect on its operational properties: the porosity and oil capacity of the surface increase, which contributes to a decrease in the intensity of wear under friction conditions.

References

1. Jiang, C., Liu, W., Wang, G., Chen, Y., Xing, Y., Zhang, C., & Dargusch, M. (2017). The corrosion behaviors of plasma-sprayed Fe-based amorphous coatings. Surface Engineering, 34, 634–639.https://doi.org/10.1080/02670844.2017.1319647

2. Serres, N., Hlawka, F., Costil, S. et al. Microstructures of Metallic NiCrBSi Coatings Manufactured via Hybrid Plasma Spray and In Situ Laser Remelting Process. J Therm Spray Tech 20, 336–343 (2011). https://doi.org/10.1007/s11666-010-9565-1

3. Guo, H., Li, B., Lu, C., Zhou, Q., & Jia, J. (2019). Effect of WC–Co content on the microstructure and properties of NiCrBSi composite coatings fabricated by supersonic plasma spraying. Journal of Alloys and Compounds, 789, 966–975.https://doi.org/10.1016/j.jallcom.2019.02.290

4. Ghaziof, S., Raeissi, K., & Golozar, MA (2010). Improving the corrosion performance of Cr–C amorphous coatings on steel substrate by modifying the steel surface preparation. Surface and Coatings Technology, 205, 2174–2183.https://doi.org/10.1016/j.surfcoat.2010.08.082

5. Li, C.-J., Wang, Y.-Y., & Li, H. (2004). Effect of nano-crystallization of high velocity oxy-fuel-sprayed amorphous NiCrBSi alloy on properties of the coatings. Journal of Vacuum Science & Technology A, 22, 2000–2004.https://doi.org/10.1116/1.1776183

6. Bacha, N.-E. (2003). Characterization of amorphous plasma sprayed coatings of FeCrPC and NiCrBSi. Journal of Metastable and Nanocrystalline Materials, 18, 1–8.https://www.scientific.net/JMNM.18.1

7. Chen, L.-Y., Xu, T., Lu, S., Wang, Z.-X., Chen, S., & Zhang, L.-C. (2018). Improved hardness and wear resistance of plasma sprayed nanostructured NiCrBSi coating via short-time heat treatment. Surface and Coatings Technology, 350, 436–444.https://doi.org/10.1016/j.surfcoat.2018.07.037

8. Planche, MP, Liao, H., Normand, B., & Coddet, C. (2005). Relationships between NiCrBSi particle characteristics and corresponding coating properties using different thermal spraying processes. Surface and Coatings Technology, 200, 2465–2473. https://doi.org/10.1016/j.surfcoat.2004.08.224

9. Liu, L., Xu, H., Xiao, J., Wei, X., Zhang, G., & Zhang, C. (2017). Effect of heat treatment on structure and property evolutions of atmospheric plasma sprayed NiCrBSi coatings. Surface and Coatings Technology, 325, 548–554.https://doi.org/10.1016/j.surfcoat.2017.07.011

10. Chen, L.-Y., Wang, H., Zhao, C., Lu, S., Wang, Z.-X., Sha, J., Chen, S., & Zhang, L.-C. (2019). Automatic remelting and enhanced mechanical performance of a plasma sprayed NiCrBSi coating. Surface and Coatings Technology, 369, 31–43.https://doi.org/10.1016/j.surfcoat.2019.04.052

11. Shieh, Y.-H., Wang, J.-T., Shih, HC, & Wu, S.-T. (1993). Alloying and post-heat treatment of thermal sprayed coatings of self-fluxing alloys. Surface and Coatings Technology, 58, 73–84.https://doi.org/10.1016/0257-8972(93)90176-O

12. Cha, SC, Gudenau, HW, & Bayer, GT (2002). Comparison of corrosion behavior of thermal sprayed and diffusion-coated materials. Materials and Corrosion, 53, 195–205. https://doi.org/10.1002/1521-4176(200203)53:33.0.CO;2-G

Диха О.В., Вичавка А.А., Бабак О.П., Диха М.О., Дитинюк В.О. Вплив модифікації складу та термічної обробки на мікроструктуру і зносостійкість нікелевих плазмових покриттів для клапанів ДВЗ

У роботі досліджено мікроструктуру, фазовий склад і зносостійкість плазмових покриттів на основі самофлюсівних нікелевих сплавів, отриманих із порошку ПГ-10Н-01 та призначених для зміцнення клапанів двигунів внутрішнього згоряння. Встановлено, що внаслідок високих швидкостей нагріву і охолодження під час плазмового напилення формується ламелярна структура з наявністю аморфних і кристалічних фаз, оксидних включень і пор. Показано, що термічна обробка забезпечує часткову кристалізацію аморфної фази, зниження пористості та підвищення мікротвердості покриття. Досліджено розподіл мікротвердості по глибині шару, який характеризується відносною стабільністю в межах покриття та поступовим зменшенням у зоні переходу до основи. Встановлено вплив модифікації складу (введення феросиліцію) на структуроутворення та пористість покриття. За результатами трибологічних випробувань визначено підвищення зносостійкості та зниження коефіцієнта тертя після термічної обробки. Обґрунтовано адгезійний механізм зношування, зумовлений структурною неоднорідністю покриття.

Ключові слова: плазмове напилення, NiCrBSi, мікроструктура, зносостійкість, мікротвердість, термічна обробка, фазовий склад, пористість, коефіцієнт тертя, клапан ДВЗ