

STRUCTURE AND PROPERTIES OF POWDER GAS-PLASMA COATINGS BASED ON NICKEL

*D.B. Hlushkova¹, V.A. Bagrov¹, S.V. Demchenko¹,
V.M. Volchuk², O.V. Kalinin², N.E. Kalinina³*

¹Kharkiv National Automobile and Highway University, Kharkiv, Ukraine

E-mail: diana@khadi.kharkov.ua;

*²Prydniprovsk State Academy of Civil Engineering and Architecture,
Dnipro, Ukraine;*

³Oles Honchar Dnipro National University, Dnipro, Ukraine

E-mail: diana.borisovna@gmail.com

The development of modern technology requires a constant increase in reliability and durability of products. Widely used in the practice of domestic and foreign engineering coatings from electrolytic chromium for several hundred hours are triggered, they are unsatisfactorily working on friction and wear at high temperatures. The subject of the study were powder materials based on nickel PG-SR3 and PG-SR4. The work is devoted to the study of the formation of gas-plasma coatings on parts of the cylinder-piston group of internal combustion engines using self-fluxing powders based on nickel, as well as the structure and properties change after coating sputtering, its reflow, subsequent hardening. The purpose of this work is to study powder materials applied to the working surfaces of piston rings by gas-thermal spraying. The object of the study are processes of formation of the structure and properties of coatings from powder materials. The presence in the deposited layer of a solid solution based on nickel, carbide phase, borides of chromium and nickel, chromium silicides is established. The greatest macro- and microhardness is possessed by fused layers containing the greatest number of strengthening phases. The conducted researches and industrial tests allowed to introduce the coating into production.

INTRODUCTION

A significant place in the production of parts for various purposes is taken by the manufacture of piston rings of internal combustion engines, the main reason for the decommissioning of which is wear and tear of working surfaces. Therefore, much attention is paid to the problems of wear resistance increase of the friction pairs of the piston ring-sleeve and actual piston rings.

Creating a combination of high hardness and high ductility in one material is possible only in heterogeneous metal.

As of this date, there are virtually no reliable criteria for optimizing the composition and structure of coatings obtained during high-energy operations, and predicting their performance and durability under friction. Due to the dependence of the strength and wear resistance of coatings on numerous factors related to the properties of the substrate and coating materials and the parameters of the technology of their application, it has been necessary to undertake a research study. Setting theoretical and technological bases of formation of the forecasted structures and properties of the parts under at high-energy influence for the purpose of increase of their durability is an important and most pressing problem. Solving this problem provides great opportunities in predicting and managing the functional characteristics of piston rings in a wide range of operating conditions.

PROBLEM OVERVIEW

High reliability and engine life largely depends on the parts of the cylinder-piston group. This is because forcing the internal combustion engine leads to a significant

increase in specific loads and temperature of the parts of the cylinder-piston group, which causes cracking and destruction of parts. As the specified details operate in the conditions of intensive friction and wear, it is necessary to provide high wear resistance of a surface [1].

Piston ring breakage is observed in almost all types of engines. Electrolytic chromium coatings, which are widely used in the practice of domestic and foreign mechanical engineering, sometimes comply with requirements of piston rings quite well. But a porous layer of chromium with a thickness of 40...50 μm is triggered within a few hours of operation, and then the solid base begins to wear [1-4]. Electrolytic chromium works poor on friction and wear at high temperatures, which leads to softening.

Covering compound systems have a set of properties that comply with the operating conditions of forced diesels. But the process of applying such coatings is very time consuming and efficient only in special cases [3-5].

In modern practice, instead of traditional methods of chemo-thermal reprocessing to strengthen the surface, high-temperature treatment methods are widely used, in particular gas-plasma spraying. The process is characterized by high productivity, simplicity, the possibility of automation while ensuring sufficient surface quality [1-3, 6].

For gas-plasma and other types of spraying the most effective use of powders PG-SR3, PG-SR4 on the basis of nickel with the addition of chromium, silicon, boron and others. (Ni-Cr-Si-B system alloys) [1, 3]. They provide high hardness and wear resistance of the surface. There are no specific data in the literature on the structure of the studied powders when they interact with the cast

iron base. It is noted only [3–5] that the high hardness and wear resistance due to the presence of carbides, borides, carboborides.

The purpose of this work is to study powder materials applied to the working surfaces of piston rings by gas-thermal spraying.

The object of the study is processes of formation of the structure and properties of coatings from powder materials.

OBJECTIVES OF THE STUDY

1. To analyze the change in the structure and properties of coatings of PG-SR powders (Ni-Cr-Si-B alloy systems).

2. To determine the feasibility of heat treatment for coatings of test powders.

3. To determine the effect of coatings of PG-SR powders on the wear resistance of parts operating in abrasive wear and corrosion.

MATERIAL AND METHODS OF THE STUDY

Nickel-based powder materials are taken as materials for strengthening piston rings, which can provide the necessary properties for the operating conditions of the selected parts and comply with the requirements for sprayed materials (Table 1).

Coatings made of self-flux alloys such as PNHSR are recommended based on literature [5–7] to create resistance to abrasive and erosion wear in conditions of corrosion and cavitation.

Therefore, powder materials from PN73H16S3R3, PN70H17S4R4 alloys were taken as a basis in finding ways to increase the resistance to abrasive wear in corrosion of parts made of gray cast iron (Table 2).

Table 1

Chemical composition of powder materials

Powder manufacturer	Chemical composition, %					
	Cr	Si	B	Fe	C	Ni
PG-SR4 type PN70H17S4R4	16.0...18.0	3.8...4.5	2.9...4.0	5.0	0.8...1.2	basis
PG-SR3 type PN73H16S3R3	15.0...17.0	2.7...3.7	2.2...3.0	5.0	0.6...0.9	-"

Table 2

Chemical composition of gray iron

Gray iron SCh 25	Content of elements, %					
	C	Si	Mn	Cr	Ni	P
	3.2...3.4	1.4...1.7	0.6...0.9	–	–	up to 0.3

The coating process includes the following operations: preliminary preparation of the surface of the product for coating, the actual coating process, further processing if necessary (fusing, heat treatment, etc.) [8–11]. The performance properties of coatings are formed in all operations of their production, so we studied the impact of these operations on the structure and properties of the coating.

Shot blasting was used to clean the sprayed surface and bring it out of the state of thermodynamic

equilibrium with the medium. We used a fraction of 0.5...1.5 mm (GOST 11964-66) as an abrasive material. Blowing was carried out at a compressed air pressure of at least 0.4 MPa. The area of shot blasting is not less than 3 mm larger than the spray area. Another way to activate the sprayed surface during plasma spraying is to heat it to 50...130 °C depending on the material of the part. Preheating was performed directly with a plasma torch (Table 3).

Table 3

Preheating modes

Plasma gas	Plasmatron current, A	Arc voltage, V	Heating distance, mm	Consumption of plasma gas, l/min	Plasmatron movement speed, mm/min
Argon + nitrogen (23...35%)	325...350	50...55	130...150	35...40	400...600

Plasma spraying modes shown in Table 4 were carried out at the following constant parameters:

– speed of rotation of the samples – 45 rpm, linear speed of movement of the samples relative to the plasma jet – 18.4 m/min;

– the diameter of the charge line in the nozzle of the anode – 2 mm;

– distance from the place of introduction of powder to a cut of a nozzle – 4 mm;

– the axis of the plasma jet is perpendicular to the axis of rotation of the sample.

The fusing of the layer was carried out under conditions of accelerated gas-plasma surface heating with relatively slow cooling (Fig. 1 and Table 4). In such

conditions, some approximation of the structure to equilibrium is expected. In the initial powder and

especially in the layer after spraying the structures are formed in nonequilibrium conditions [12, 13].

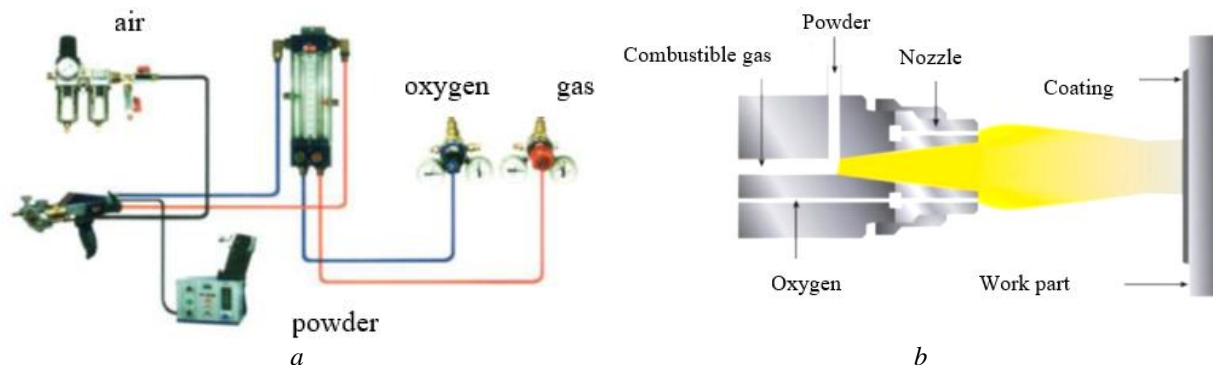


Fig. 1. Scheme of coating of powder materials by gas-plasma method: a – supply of powder and gas; b – own spraying [7]

Table 4

Modes of plasma spraying

Sprayed material	Fractions, μm	Spray mode settings						
		Plasma-tron current, A	Arc voltage, V	Spray distance, mm	Plasma-forming gas mixture	Consumption of plasma-forming gas, l/min	Consumption of transporting gas, l/min	Powder consumption, kg/h
PRHSR	45...100	280...300	40...45	100...120	5...10	35...40	6.0...9.0	2.5...3.3

The structure of the powder shows crystals, as well as a dispersed mixture of phases between them (Fig. 2).

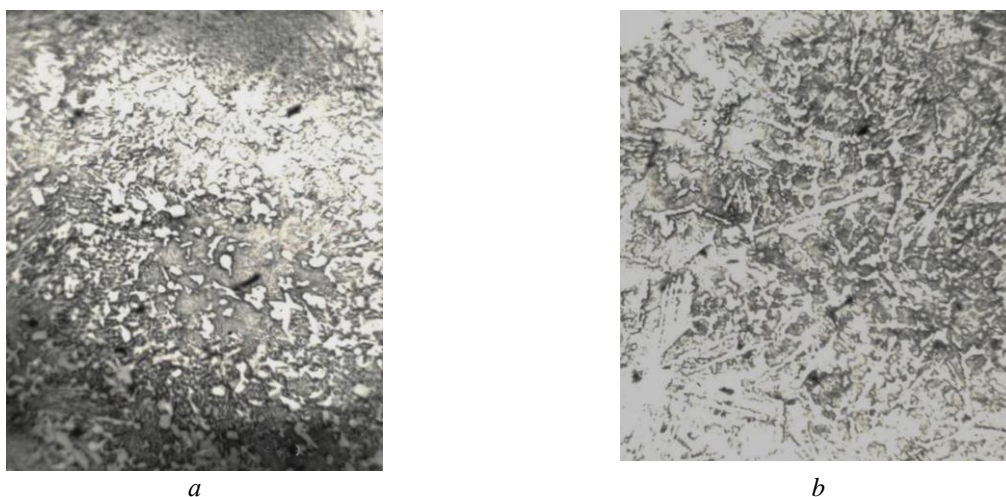


Fig. 2. Structure of powders for spraying PG-SR4 coatings

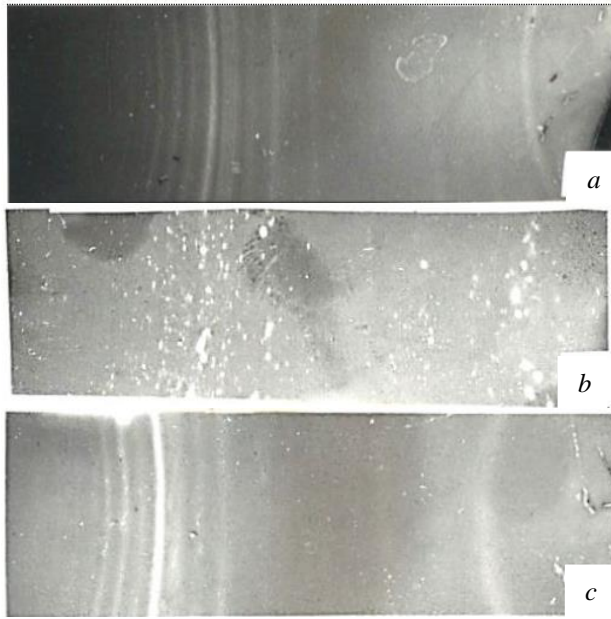
When X-raying, a multiphase structure is registered in the source powder. The most fully represented lines of solid solution are based on nickel and carbide phase of Cr_{23}C_6 type (Fig. 3,a). But many lines cannot be unambiguously identified. We can find a match with the main lines of chromium and nickel borides, chromium silicides. The radiograph of the molten layer (see Fig. 3,b) is quite identical to the radiograph of the powder. The radiograph of the unfused layer (see Fig. 3,c) preserves the lines of chromium carbides and the strongest lines of other phases. Preservation of the phase lines in the spray layer without fusing and the layer after quenching indicates that these phases are formed during the primary crystallization. This is confirmed by the metallography of the source powder and the source layer.

A similar structure is in the molten layer (Fig. 4): the components are uniformly distributed in its volume.

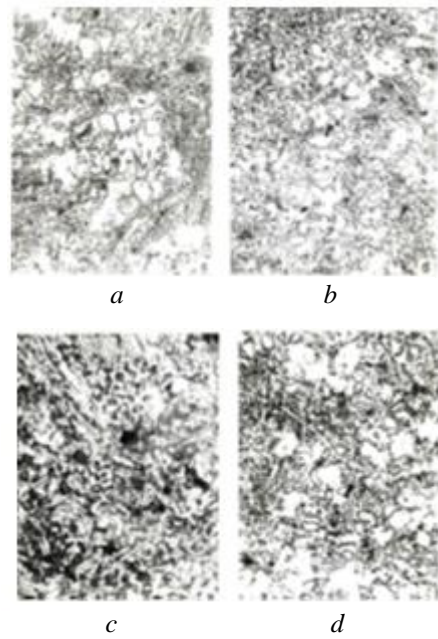
Electron microscopic studies show that in the area of coarse mixtures there are oriented areas, in the area of small mixtures – non-oriented, less dispersed. It can be assumed that the phase registered as rounded particles is chromium carbide. Particles are stored when heating the layer under hardening (see Fig. 4,d). Microhardness measurements confirm this.

The multiphase layer revealed by X-raying is confirmed by microscopic studies.

A similar phase and structural composition has a coating of PG-SR3, a distinctive feature of the layer is a smaller amount of coarse mixture of phases, which is associated with changes in the content of the carbon alloy.



*Fig. 3. X-rays of PG-SR4 alloys:
a – PG-SR4 powder, λCr ;
b – unfused layer; c – fuse layer*



*Fig. 4. Structure of the fuse layer PG-SR4:
a, b – coarse and fine mixtures; c – structure after
etching; d – structure after volumetric hardening*

Fusing of the layers leads to partial fusing of the base metal and activation of diffusion processes in the border zone heated to high temperatures. This causes the base material to mix with the layer material and form a new alloy different in structure from the base and layer.

When sprayed with PG-SR metals in the structure of the base metal in the border areas there are no changes, because the total heating of the base metal is insignificant, its interaction with the coating particles is very weak (Fig. 5).

In the case of fusing of the obtained coatings, we observe significant changes in the structure of cast iron at the boundary with the layer and the layer at the boundary with cast iron due to the intensification of diffusion processes. At the boundary of the layer there is an increase in the amount of coarse mixture of phases (see Fig. 5), which can be explained by the diffusion of carbon and iron from cast iron in the PG-SR4 and PG-SR3 layer. A thin layer of single-phase alloy is formed at the boundary with the molten metal. In the cast iron, a layer with increased ferrite content is formed at the boundary,

which may be the result of diffusion into the nickel base, which promotes graphitization.

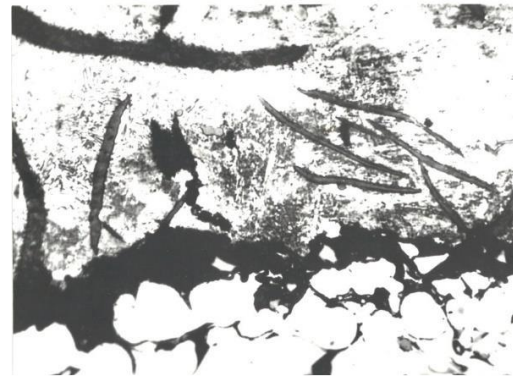


Fig. 5. The structure of the boundary of the substrate (gray cast iron) and the layer with unfused coating PG-SR4

The structure of the PG-SR4 molten coating layer is shown in Fig. 6.

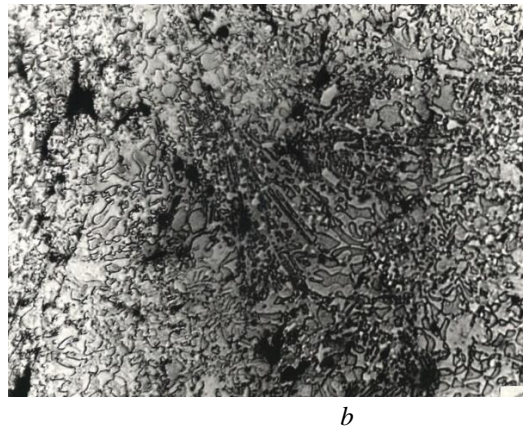
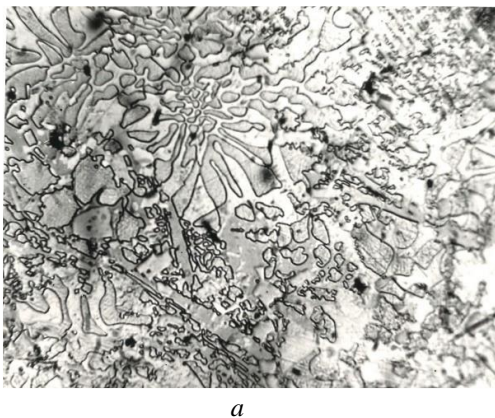


Fig. 6. The structure of the PG-SR4 molten coating layer: a – coarse mixtures; b – thin mixtures

These structural features of coatings from PG-SR alloys and changes in the structure during further treatments are reflected in changes in macro- and microhardness (Fig. 7).

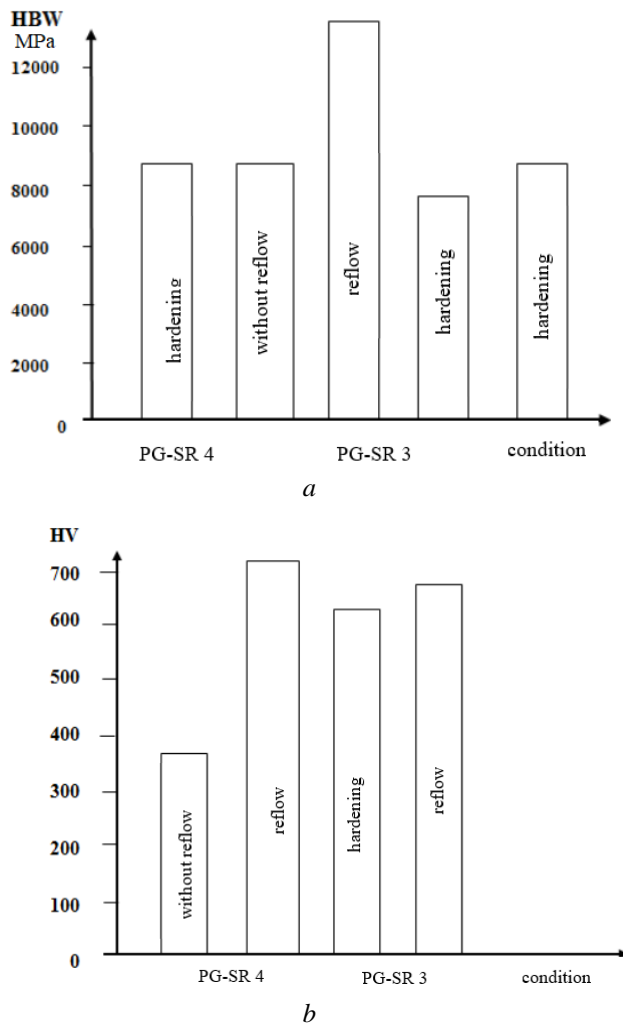


Fig. 7. Histogram of the influence of the PG-SR4 molten coating layer on a – macro- and b – microhardness indicators

In the studied parts of the cylinder-piston group of internal combustion engines the fuse layers with the greatest macro- and microhardness, are characterized by the most complete set of strengthening phases. The smallest microhardness in the layer after the volume hardening as a result of dissolving at heating under the hardening of a significant number of strengthening phases and noticeable coagulation of the phases preserved. High average microhardness of the unfused layer, obviously, is connected with the specificity of super-speed crystallization of particles at a peak, which leads to the formation of a small grain of particles. The strengthening effect of fine grains probably compensates for the decrease in microhardness due to changes in phase composition, which is observed when X-raying.

Evidence can be determined by comparing the microhardness of the source powder and the particles of the layer. The microhardness of the source powder is characterized by a wide range of values: 5.700...8.900 MPa, which is associated with both the structural composition of the particles and the possible

differences in composition. Particles with a smaller number of detected strengthening phases (see Fig. 1,a) have a lower hardness (5.700...8.250 MPa), and particles with a structure shown in Fig.1,b have a higher hardness (see Fig. 1,a).

In the sprayed unfused layer of piston ring parts, non-fusing particles practically retain their hardness (5.700...8.250 MPa), molten particles are characterized by a smaller difference in microhardness values and an even higher average level, approximately 7.300...8.500 MPa. Reduced macrohardness of the unfused layer is due to its high porosity. The lower hardness of the molten coating of PG-SRZ (HV = 700...760), compared with PG-SR4 (HV = 760...820) is also associated mainly with a decrease in the number of reinforcing phases.

Thus, the analysis of changes in the structure and properties of coatings of PG-SR powders after spraying and fusing showed that the best properties should have fuse coatings.

Subsequent heat treatment associated with prolonged high-temperature heating is undesirable, as it degrades the structure and properties of the coating. It is advisable to apply the coating on the part after finishing.

The possibility of using PG-SR4 coating to increase the wear resistance of cast iron was tested in industrial conditions. After grinding, the depth of the layer was 1.200 μm, the surface roughness Ra was not more than 2.5 μm.

In the studied operating conditions, the piston rings fail after a month of operation due to intensive and very uneven wear of the outer surface. The sprayed rings were removed for inspection after three months of operation. The surface of the sleeve after operation took the form of a polished product (Ra not more than 0.32 μm) without any local surface violations.

The conducted studies allow concluding that the coating of products with PG-SR powders (alloys of the Ni-Cr-Si-B system) is a reliable method of increasing the wear resistance of parts operating in abrasive wear conditions together with corrosion. Piston rings with developed coatings were installed on the paired blocks of the cylinder-piston group of the 10-cylinder locomotive engine for operational tests. Serial chrome-plated rings were installed on the odd-numbered units. After 100.000 km (corresponding to 4.000 h of operation), sets of 4 rings from units 4, 8, and 7 were removed from the locomotive for complex research. Analysis of the data shows that the rings with the developed coating wear less and wear the sleeve less than the serial rings with hard and porous chrome coating.

CONCLUSIONS

1. Analysis of changes in the structure and properties of coatings of PG-SR powders showed that the best properties should have fuse coatings.

2. For coatings of PG-SR powders, heat treatment is undesirable because it degrades the structure and properties of the coating.

3. Coating of products with PG-SR powders (alloys of the Ni-Cr-Si-B system) is a reliable method of increasing the wear resistance of parts operating in

abrasive wear together with the corrosive effects of the environment.

4. The obtained results were introduced at the Malyshev Factory for parts of the cylinder-piston group.

REFERENCES

1. C. Navas, R. Colaço, J. de Damborenea, R. Vilar. Abrasive wear behaviour of laser clad and flame sprayed-fuse NiCrBSi coatings // *Surface and Coatings Technology*. 2016, v. 200, N 24, p. 6854-6862.
2. B.N. Chapman. Thin-Film Adhesion // *J. Vac. Sci. Technol.* 1974, v. 11, N 1, p. 106-110.
3. D.B. Hlushkova, O.D. Hrinchenko, L.L. Kostina, A.P. Cholodov. The Choice of Material Strengthening of Leading Edges of Working Blades of Turbines // *Problems of Atomic Science and Technology*. 2018, N 1(113), p. 181-188.
4. <http://www.plasmacentre.ru/produkcziya/poroshki-provoloka-elektrodi/pgsr4/>
5. L.I. Gladkikh, S.V. Malykhyn, D.B. Glushkova, S.S. D'yachenko, G.P. Kovtun. Residual Stresses and Structure of Titanium and Chromium Nitride Coatings Obtained by a Method of an Ion-Plasma-Enhanced Deposition // *Metallofizika i Noveishie Tekhnologii*. 2003, v. 25(6), p. 763-776 (in Russian).
6. N.D. Nikitin, A.Ya. Kulik, N.I. Zakharov. *Heat-shielding and wear-resistant coatings*. L.: "Mashinostroenie", 1999, 198 p.
7. E. Zenz, D. Pnueli, and Z. Rozeann. The effect of a thin coating of insulation material on the performance of cutting tools // *J. Vac. Sci. Technol.* 2013, v. 53, p. 337-344.
8. D.B. Hlushkova, Y.V. Ryzhkov, L.L. Kostina, S.V. Demchenko. Increase of wear resistance of the critical parts of hydraulic hammer by means of ionplasma treatment // *Problems of Atomic Science and Technology*. 2018, N 1(113), p. 208-211.
9. R.H. Duolley. A Survey of Vacuum Deposition Technology // *SC Pand Solid State Technology*. 1999, v. 10, N 12, p. 39-44.
10. D. Leontiev, O.I. Voronkov, V. Korohodskiy, D. Hlushkova, I. Nikitchenko, E. Teslenko, O. Lykhodii. Mathematical Modelling of Operating Processes in the Pneumatic Engine of the Car: SAE Technical Paper 2020-01-2222, 2020. ISSN: 0148-7191; doi:10.4271/2020-01-2222.
11. N.E. Kalinina, D.B. Hlushkova, O.D. Hrinchenko, T.V. Nosova, A.A. Reznikov. Hardening of leading edges of turbine blades by electrospark alloying // *Problems of Atomic Science and Technology*. 2019, N 2(120), p. 151-154.
12. W. Moeller, W. Enssinger. *Nastasi yon implantation and thin – film deposition: Handbook of plasma immersion, ion implantation and deposition / Edited by A. Anders*. N. Y. USA, 2000, 736 p.
13. Y. Gap, Sh. Kitahara. Some contributions on adhesive mechanism and composition of boundary between sprayed coating and substrate // *Weld Soc.* 2003, v. 42, N 2, p. 91-99.

Article received 28.06.2022

СТРУКТУРА І ВЛАСТИВОСТІ ПОРОШКОВИХ ГАЗОПЛАЗМОВИХ ПОКРИТТІВ НА ОСНОВІ НІКЕЛЮ

Д.Б. Глушкова, В.А. Багров, С.В. Демченко, В.М. Волчук, О.В. Калінін, Н.С. Калініна

Розвиток сучасної техніки потребує постійного підвищення надійності та довговічності виробів. Широко застосовувані в практиці вітчизняного та зарубіжного машинобудування покриття з електролітичного хрому за кілька сотень годин спрацьовуються, вони незадовільно працюють на тертя та зношування за високих температур. Предметом дослідження були порошкові матеріали на основі нікелю ПГ-СР3 та ПГ-СР4. Робота присвячена дослідженню формування газоплазмових покриттів на деталях циліндропоршневої групи двигунів внутрішнього згорання з використанням самофлюсованих порошоків на основі нікелю, а також зміні структури та властивостей після напилення покриття, його оплавлення, наступного загартування. Мета роботи – дослідження порошкових матеріалів, які нанесені на робочі поверхні поршневих кілець газотермічним напиленням. Об'єктом дослідження є процеси формування структури та властивостей покриттів із порошкових матеріалів. Встановлено наявність у напиленому шарі твердого розчину на основі нікелю, карбідної фази, боридів хрому та нікелю, силцидів хрому. Найбільшу макро- і мікротвердість мають оплавлені шари, що містять найбільшу кількість зміцнювальних фаз. Проведені дослідження та промислові випробування дозволили впровадити покриття у виробництво.