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## ENVIRONMENTAL COMPONENT OF THE PROBLEM OF INCREASING THE DURABILITY OF PISTON RINGS<sup>5</sup>

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**Abstract.** *The work is devoted to the actual problem: Increasing the durability of piston rings using a modern method of surface treatment. Solving this problem with the help of traditional methods of chemical and thermal treatment does not give stable industrial results, therefore, the development of the technology of using modern methods and the methodology of their testing is an important urgent task.*

**Keywords:** *piston, steel, durability, structure.*

## ЕКОЛОГІЧНА СКЛАДОВА ПРОБЛЕМИ ПІДВИЩЕННЯ ДОВГОВІЧНОСТІ ПОРШНЕВИХ КІЛЕЦЬ

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**Анотація.** *Робота присвячена актуальній проблемі - підвищенню довговічності поршневих кілець сучасними методами обробки поверхні. Вирішення цієї проблеми за допомогою традиційних методів хіміко-термічної обробки не дає стабільних промислових результатів, тому розробка технології використання сучасних методів та методик їх апробації є важливим актуальним завданням.*

**Ключові слова:** *поршень, сталь, довговічність, структура.*

### Introduction

The development of modern agricultural machinery presents ever-increasing requirements for the performance characteristics of structural materials, the reduction of the metal content of parts, and the increase of their efficiency and quality. In the complex of problems of increasing the reliability and durability of machines, the issue of wear resistance of parts occupies a special place [1].

The research conducted in Ukraine and abroad in this area, as well as the positive results of their use in industry in the manufacture and restoration of parts of the cylinder-piston group (CPG), allow, at present, to widely implement these progressive methods .

Currently, one of the problems of mechanical engineering is increasing the wear resistance of piston rings made of high-strength cast iron.

Coatings used in the practice of domestic and foreign mechanical engineering for piston rings in some cases do not sufficiently meet the requirements for piston rings.

In this regard, the development of highly effective piston ring coatings is quite important and relevant.

### Relevance of development

Piston ring failure is observed in almost all types of engines [1]. Electrolytic chromium coatings, widely used in the practice of domestic and foreign engineering, in a number of cases do not meet the requirements for piston rings well enough. A porous layer of chromium with a thickness of 40-50 μm is activated in a few hundred hours, and then the solid base begins to activate. Electrolytic

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<sup>5</sup> Робота виконана під керівництвом професора Глушкової Д.Б.

chromium does not work satisfactorily for friction and activation at high temperatures, which leads to strengthening under certain conditions, it can undergo corrosion.

Progressive methods of strengthening parts of the cylinder-piston group include gas plasma spraying. The working conditions of piston rings require a different approach to the selection of coatings [1, 2].

Although the basic provisions of the general theory of obtaining coatings have been developed, the effectiveness of each method and the possibility of using specific coatings always depends on information about the change in the properties and structure of materials during sputtering. For alloys, it is not always possible to know the structure and properties of coatings in advance. Extensive experimental work is necessary investigation of the structure and properties after sputtering.

Therefore, the presented work is timely and relevant [3-5].

### Material and research methodology

Material of piston rings. Strengthening piston rings made of high-strength cast iron, the composition of which is given in table 1.

Table 1 - Chemical composition of gray and high-strength cast iron

cast iron	C	Si	Mn	Cr	No	Mo	Cu	Mg	P
SC 25	3.2-3.4	1.4-1.7	0.6-0.9		-	-	-	-	≤0.3
HF 42	3.4-3.7	2.1-2.5	0.85-1.3	0.15	1.2-1.5	0.6-0.9	0.3-0.4	0.03-0.1	≤0.1

Methodology of friction and wear tests . Testing of new materials and technologies in the conditions of real production is associated with significant costs of material resources and time. Therefore, in order to evaluate the effectiveness of the use of materials, methods of their processing, structural changes of parts and other measures, laboratory and bench tests simulating the maximum approximation to real operating conditions were carried out. Tribotechnical characteristics are the main criteria for assessing the workability of materials for volumetric hydraulic drive parts and the effectiveness of their surface treatment .

In this regard, test methods were chosen for the work, which allow simulating the main processes of friction and wear of real parts.

The tests were carried out on the SMC-2 friction machine, which allows you to compare the tested materials in terms of wear resistance, anti-friction properties and properties in the process side jobs according to the "roller-pad" scheme (fig. 1).

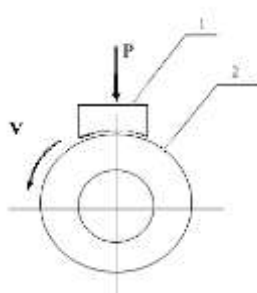


Fig. 1. Scheme «roller-pad»

Metallographic, electron microscopic and X-ray studies.

The structures were studied and photographed on a MIM-7 microscope at a magnification of (70 - 1000) times. Electron microscopic and X- ray microspectral studies were conducted to establish

the relationship between the conditions of recovery through worn layers, their microstructure and operational characteristics .

Electron microscopic studies were performed on a UEM 100 ML microscope using varnish replicas made according to standard methods.

The structure of the surface before and after operation was studied using a SEM scanning electron microscope at an accelerating voltage of 30 kV in a wide range of magnifications from 20 to 10 thousand times. To analyze the phase composition of the base metal and coating, X-ray structural phase analysis was performed on the URS-50 unit.

The amount of residual stresses in the near-surface layers was determined on the DRON-2 installation by the method of repeated oblique surveys in the radiation of a copper anode with a graphite monochromator.

Radiographs for qualitative and quantitative analysis and measurement of lattice parameters were taken on URS-55, URS-60 devices in Debye chambers using iron and chromium radiation

### **Study of the wear resistance of parts strengthened by gas thermal spraying**

#### **Operating conditions of piston rings of parts of the cylinder-piston group**

The piston rings of the parts of the cylinder-piston group work in stressful conditions, which are characterized by high temperatures (up to 1900 °C of the combustible mixture, up to 600 °C on the surface of the sleeve and up to 450 C on the piston skirt), pressures (up to 15 MPa) and an extremely unfavorable nature friction from liquid to dry during reciprocating motion .

Combustion of fuel with a high sulfur content in the cylinders of diesel engines increases the intensity of wear of piston rings (fig. 2).



Fig. 2. Piston rings

Such rings are used in agricultural machinery, for example, in engines of MTZ tractors (fig. 3).



Fig. 3. Tractor MTZ\_80 "Belarus"

Wheeled tractors of the Belarusian Tractor Plant of the MTZ series (MTZ-80, MTZ-80L, MTZ-82, MTZ-82L) are universal agricultural tractors of the 1.4 t class.

MTZ-80, MTZ-82 (MTZ-80L, MTZ-82L) tractors are equipped with a four-cylinder, four-stroke D-240 diesel engine with a rated power of 59 kW (80 hp) with an electric starter (D-240L with a starting motor).

### Research of the structure and properties of gas - plasma coatings from powder materials

As materials for strengthening piston rings, a number of powder materials were taken, which can provide the necessary properties for the operating conditions of the selected parts and satisfy the requirements for sprayed materials (table. 2).

Coatings made of self-fluxing alloys, such as PNHSR, are recommended according to the literature to create resistance to abrasive and erosive wear under corrosion conditions

Table 2 - Chemical composition of powder materials from system alloys, %

Material	No	C	Cr	Si	B	Fe
PGSR3 (PN73X16S3R3)	basis	0.6-0.9	15-17	2.7-3.7	2.2-3.0	5
PGSR4 (ПН70Х17СХР4)	basis	0.8-1.2	16-18	3.8-4.5	2.9-4.0	5

Therefore, powder materials from PN73X16C3P3, PN70X17CXP4 alloys in their pure form and in combination with chromium carbides were taken as a basis when searching for ways to increase the resistance to abrasive wear under corrosion conditions of piston rings made of gray cast iron (fig. 4.). The operational properties of such coatings are formed in the process of carrying out various operations of obtaining the coating: dusting, melting, subsequent treatments. Therefore, there is a need to study the impact of these operations on the structure and properties of the coating.

### Modes of gas-thermal spraying

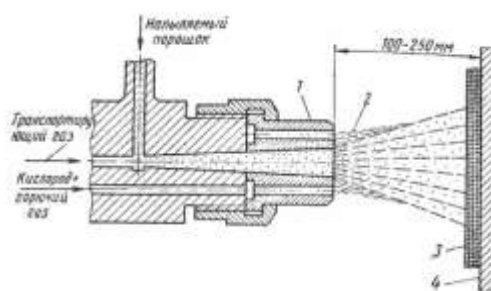


Fig. 4. Scheme of gas thermal application spraying

The plasma sputtering modes listed in table 3 were processed with the following constant parameters:

- speed of sample rotation – 45 rpm, linear speed of movement of samples relative to the plasma jet – 18.4 m/min;
- the diameter of the charge pipe in the anode nozzle - 2 mm;
- the distance from the place of introduction of the powder to the section of the nozzle - 4 mm;
- the axis of the plasma jet is perpendicular to the axis of rotation of the sample

Table 3 - Preheating modes

Plasma-forming gas	Plasmatron current, A	Arc voltage, V	Heating distance, mm	Consumption of plasma-forming gas, d/ min	Speed movement of the plasmatron, mm/min
Argon + nitrogen (23-35 %)	325-350	50-55	130-150	35-40	400-600

### Structure and properties of self-fluxing alloy coating

Coatings from these alloys are recommended for creating high resistance to abrasive and erosive wear in conditions of corrosion and cavitation at low and high (up to 600-800°C) temperatures. Therefore, coatings (PN73X16C3P3 – PGSRZ, PN70X17C4P4 – PGSR4, PN70X17C4P4 + 40% Cr<sub>3</sub>) were studied in connection with the search for a way to increase resistance to abrasive wear under corrosion conditions of a number of cast iron parts.

The operational properties of such coatings are formed in the process of operations of obtaining the coating: dusting, melting, subsequent treatments. This requires studying the impact of these operations on the structure and properties of coatings.

The structure of the particles of the layer indicates that they were formed by molten particles. particles that did not melt differ, as a rule, in larger sizes and are most often collected in groups (fig. 5).

The described experimental data may indicate that the low density of chromium-nickel coatings is due to the physical and mechanical properties of the alloy itself in the liquid and solid states.

The connection of the unmelted coating layer with the cast iron is unsatisfactory. Alternating areas of good and bad contact can be observed at the boundary between the coating and the substrate (fig. 6, a, c), and in some places the connection of the layer with cast iron is completely absent.

A significant increase in density, excellent connection with the substrate characterizes the fused coating. Calculations fix the porosity of the fused coating at approximately 1.3%.

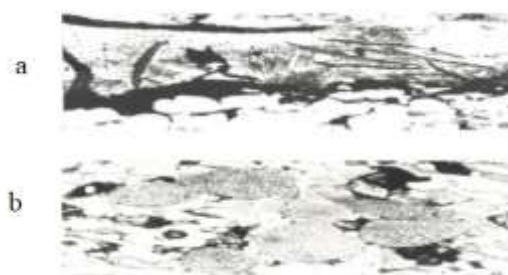


Fig. 5. Structure of unmelted PGSR4: a - agar contact with the substrate; b – bad contact, ×100

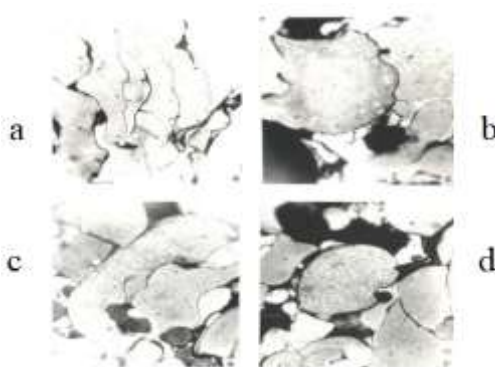


Fig. 6. Structural elements of the non-melted coating of PGSR 4  
a, c – deformed particles, ×100;  
b, d – undeformed particles, ×1000

In general, the structure of the fused coating is characterized by uniformity in the volume of the layer, but the structure of the alloy differs in microvolumes .

Structure and properties of gas-plasma coatings in the PGSR type, there are no specific data on the structure of the studied alloys of the system Ni - Si - Si - B with carbon and iron. It is noted only

that their high hardness and wear resistance are due to the presence of carbides, borides, carboborides in the structure .

In order to find out possible interactions, it follows that chromium, nickel and iron in the amount included in the investigated alloys should form solid solutions among themselves. Silicon up to 5 % dissolves in nickel, up to 1 % - in chromium, and with a higher content forms a number of chromium silicides ( $\text{Cr}_2\text{Si}$ ) in the composition of eutectics, for example,  $\text{Ni}_2\text{B}$ ,  $\text{Cr}_2\text{B}$  (fig. 7). Carbon, most likely, should interact with chromium and boron, because nickel and silicon are non-carbide-forming elements. With chromium, carbon can form a number of carbides:  $\text{Cr}_{23}\text{O}_6$ ,  $\text{Cr}_7\text{O}_3$ ,  $\text{Cr}_3\text{O}_2$  in the composition of eutectics and peritectics.

Of course, the nature of the transformations in a multicomponent system is a function of many parameters and cannot be specifically determined by double interactions, but it can be expected that the main structure of the considered alloys should be a multicomponent nickel-based solid solution.

The work studied the structure and properties of such an alloy in a layer and their changes during some technological operations.

Radiographically, the multiphase structure of the original powder is recorded. The most fully presented solid solution lines based on nickel and the carbide phase of the  $\text{Cr}_{23}\text{O}_6$  type (fig. 8). But many lines do not lend themselves to unambiguous identification. One can find a coincidence with the main lines of chromium and nickel borides, chromium silicides. Many main lines of different phases overlap each other, and some do not fit into the lattice of any system, which does not allow specifying the phase composition of the alloy.

Radiograph of the melted layer quite completely coincide with the X-ray pattern of the powder.

Chromium carbide lines and the strongest lines of other phases are preserved on the radiograph of the unmelted layer. Preservation of phase lines in the sputtered layer without melting and the layer after quenching indicate that these phases are formed as a result of primary crystallization, this is confirmed by the metallography of the original powder and the original layer. Crystals are visible in the structure of the powder, as well as a dispersed mixture of phases between them. The molten layer has a similar structure, the components are uniformly distributed throughout the layer. Electron microscopic studies show that in the area of coarse mixtures oriented areas are observed, in the area of fine mixtures - non-oriented, which are less dispersed. The multiphasic nature of the layer determined by X-ray analysis is confirmed by microscopic studies (fig. 9).

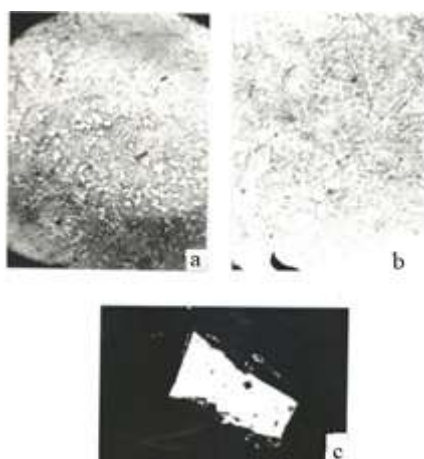


Fig. 7. Structure of the coating for sputtering PGSR coatings  
a, b – structure of PGSR4 powder; c - is the structure of  $\text{Cr}_3\text{O}_2$  carbides, which additionally introduced during sputtering  $\text{PNSR4}+40\% \text{Cr}_3\text{PRO}_2$ , a, b -  $\times 1000$ , c -  $\times 400$

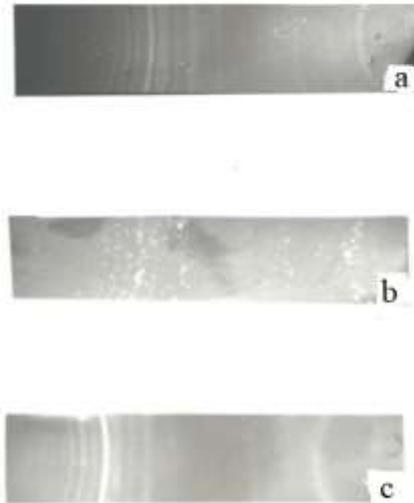


Fig. 8. X-ray patterns of PGSR 4 alloys  
a – PGSR4 powder ; b – unmelted layer, c – melted layer

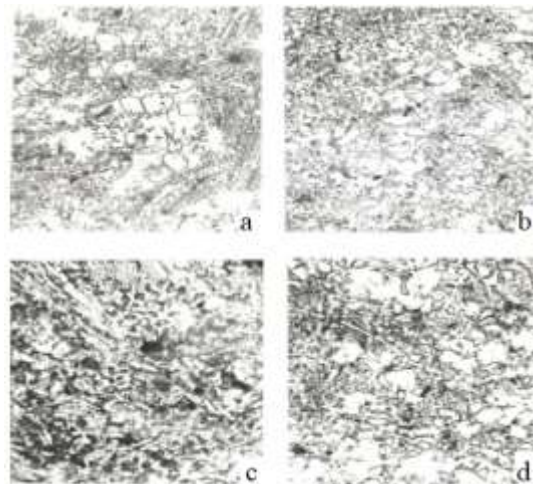


Fig. 9. The structure of the molten layer of PGSR 4  
a, b – coarse and fine mixtures; c – structure after etching,  
d – structure after volume hardening,  $\times 100$

It can be suggested that the phase in the form of rounded particles is chromium carbide. They are stored when the layer is heated for hardening. Microhardness measurements indicate the same.

The structure of the undeformed particles coincides with the structure of the original powder.

A coating with PGSR3 has a similar phase and structural composition, a distinctive feature of the layer is a smaller amount of a coarse mixture of phases, which is associated with a change in the composition of the alloy (in terms of carbon).

#### **Structure of the boundary regions of the sprayed layer**

When sputtering with PGSR alloys, no changes occur in the structure of the base metal and border regions, due to this total heating of the base metal and a sharp temperature difference at the point of contact of each particle with the base (fig. 9) the structure of cast iron at the boundary with the layer does not differ from the original structure. When layers are melted, a change in the structure of cast iron is observed at the boundary with the layer and in the layer at the boundary with the base.

The changes are associated with the partial melting of the base metal and the activation of diffusion processes in the boundary zone heated to a high temperature.

Melting of the base metal causes its mixing with the material of the layer and the formation of a new alloy different in structure from the base and layer.

Increase at the boundary of the layer of a coarse mixture of phases (fig. 10, 11) can be explained by the diffusion of carbon and iron into the layer of cast iron and steel in the case of PGSR4 and PGSR3. A thin layer of a single-phase alloy is formed at the boundary with unmolten metal.

A change in the structure of cast iron, a layer with an increased content of ferrite is formed at the border, which can be explained by the diffusion of the graphitizing element nickel in the cast iron.

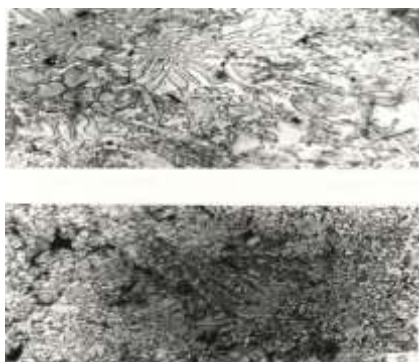


Fig. 10. Structure of the molten layer of PGSR 4  
a – coarse mixtures; b - thin mixtures,  $\times 1000$

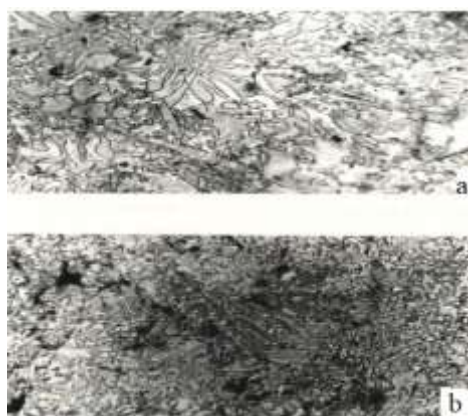


Fig. 11. Structure of the boundary zone of the molten layer  
a – coverage of PGSR4; b – coverage of PGSR3,  $\times 1000$

#### **Structure and properties of coatings from PGSR 4 + 40% Cr<sub>3</sub>PRO<sub>2</sub>**

The structure and hardness of coatings in the molten state, as well as after annealing and after hardening, were studied. Fused coatings are generally characterized by good density, although slightly less than PGSR coatings without chromium carbides.

The increase in porosity is due to the fact that single large pores or even their accumulation are observed in some areas at the boundary of the layer and the base metal. Obviously, these are areas that had a poor connection with the matrix in the filed state. Larger accumulations of gases in such places do not have time to diffuse to the surface and coagulate in place.

The structure of the molten layer is presented in (fig. 12) In all coatings, the structure of the layer is heterogeneous in depth and two zones are observed: in one, connected to the substrate, there is a clearly defined oriented columnar dendritic structure of the cast metal: in the other, the structure is more homogeneous, without noticeable orientation. After etching, three zones with different metallographic structures are defined in the layer:

I – the zone of the layer reaching the surface is characterized by a uniform distribution of homogeneous secretions;

II – the middle zone, which is characterized by non-homogeneous allocations in size;

III – the zone of the layer adjacent to the substrate has a dendritic structure.

We assume that the noted structure of the layer is due to the peculiarities of its melting by surface gas-plasma heating.



Fig. 12. General type of coating layer of PGSR +40% Cr<sub>3</sub>PRO<sub>2</sub>, ×400

Surface heating is characterized by a temperature gradient along the depth, which can be noticeably affected by the melting of such a heterogeneous structure, which must have a sputtered layer of PGSR4+40% Cr<sub>3</sub>O<sub>2</sub>.

The formation of the sputtered layer occurs by the sequential stacking of individual particles of PGSR4 and Cr<sub>3</sub>O<sub>2</sub> carbide. Chromium carbide has a melting point significantly higher than the alloy of the Ni-Cr-Si-B system (the melting point of Cr<sub>3</sub>O<sub>2</sub> is 1830 ... 1895 °C) [8]. Therefore, it can be assumed that the carbide particles will not completely melt in the plasma and enter the layer semi-melted, keeping the monocrystalline structure in the main volume. The metallographic and X-ray structural analysis of the original powder mixture testifies to the polycrystalline structure of the original Cr<sub>3</sub>O<sub>2</sub> carbide powder. PGSR4 powder consists of spherical particles, while carbide particles have a polygonal shape and are single crystals. Even on an X-ray image taken from a rotating column, the carbide powder is represented by reflex lines. Particles of carbides have a high microhardness equal to 15800 ... 17800 MPa (table 4).

Table 4 - Wear resistance of PGSR4 coatings under conditions of hydroabrasive wear

Material	Hardness	Roller wear, g	Pad wear, g
Steel 38KHS TVC hardening	660	0.330	0.182
PGSR4	710	0.247	0.136
PGSR4+40% Cr <sub>3</sub> PRO	760	0.102	0.089
PGSR4+40% Cr <sub>3</sub> PRO <sub>2</sub> , hardening	640	0.164	0.096

#### **Wear resistance of coatings made of alloys of the Ni-Cr-Si-B system**

Wear resistance tests were carried out in connection with the goal of the task - to increase the wear resistance of piston rings operating in friction conditions with high shock loads and abrasive wear. For comparison, 38KHS steel, hardened by TVC, was tested.

It follows from the obtained experimental data that coatings with Ni-Cr-Si-B alloys significantly increase the wear resistance of products, while reducing the wear of the joint of the part. The addition of Cr<sub>3</sub>PRO<sub>2</sub> carbides increases the wear resistance of the coating by more than three times compared to steel 38KHS. Hardening of coatings with chromium carbide additives slightly reduces the wear resistance of the coating, but still leaves it at a fairly high level. This allows us to assume that if

there is a need, the product can undergo heat treatment together with the coating. The possibility of applying the PGSR4 coating to increase the wear resistance of cast iron was tested in industrial conditions. After grinding, the depth of the layer was 1200  $\mu\text{m}$ , the surface cleanliness was 6. Under the studied operating conditions, the piston rings fail after one month of operation due to intensive and very uneven wear of the outer surface. The filing rings were removed for control after three months of operation. After operation, the surface of the sleeve acquired the appearance of a polished product ( $\nabla 9$ ) without any local surface disturbances. The conducted studies allow us to say that the coating of products with alloys of the Ni-Cr - Si - B system is a reliable method of increasing the wear resistance of parts operating under conditions of abrasive wear together with the corrosive influence of the environment, and can be recommended for practical use.

### Conclusions

The conducted studies showed:

1. Ni - Cr - Si - B alloys significantly increases the wear resistance of piston rings, while reducing the wear of the connected part. The addition of carbides increases the wear resistance of the coating by more than three times compared to steel 38KHS.
2. Coating products with alloys of the Ni - Cr - Si - B system is a reliable method of increasing the wear resistance of parts operating in conditions of abrasive wear, compatible with corrosive effects on the environment, and implemented in industry.
3. Quenching of coatings with chromium carbide additives slightly reduces the wear resistance of the coating, but leaves it at a sufficiently high level. This allows us to assume that, if necessary, the product can be subjected to heat treatment together with the coating.
4. The possibility of applying PGSR4 coatings to increase the wear resistance of cast iron piston rings was tested under the conditions of operation of protective sleeves of water pumps. After grinding, the depth of the layer is 1200  $\mu\text{m}$ .
5. The work was implemented by the State Enterprise "Zavod named after Malyshev " with an economic effect of UAH 60,000. for a year.

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