doi: 10.18323/2782-4039-2023-2-64-4

The study of the structure and properties of a wear-resistant gas-thermal coating containing tungsten

Aleksey Yu. Plesovskikh*, postgraduate student
Svetlana E. Krylova[1], Doctor of Sciences (Engineering), Professor
Orenburg State University, Orenburg (Russia)

***E-mail: plesovskih@tehno-oren.ru**

[1]ORCID: https://orcid.org/0000-0002-5303-9780

Received 14.02.2023 *Accepted 08.05.2023*

Abstract: The paper presents the results of reverse engineering including metallographic, mechanical, and engineering-technical studies of used rods of a compressor produced by the Dresser-Rand company (Siemens, Germany). The study established that the original product is made of AISI 4140 steel with a working coating based on tungsten carbide applied to a depth of 0.2 mm by the HVOF method. The paper contains the results of the development of an import-substituting technological process for producing a wear-resistant powder coating of the Ni–Cr–B–WC system applied by cold gas flame spraying on the surface of a critical unit of compressor equipment in the oil and gas industry. Microanalysis identified that the sprayed spherical WC particles are evenly distributed in the nickel bond without the formation of free cavities at the lamella boundary, retain the size identical to the original powder composition upon the high-speed collision with the substrate, and minimize the level of residual mechanical stresses in the surface layer. The study shows that the sprayed coating has a high microhardness (the bases – 700 $HV_{0.1}$, WC – up to 2000 $HV_{0.1}$), which ensures high wear resistance during operation of the rod in a friction pair. A comparative analysis of the tribological properties of the coatings showed that when changing the shape, particle size distribution, and percentage ratio of tungsten carbide from 20 to 70 % in the nickel matrix, the overall wear resistance of the coating equivalently increases. The authors concluded on the possibility of manufacturing an import-substituting product using the gas flame spraying technology with metallurgical powder compositions containing tungsten. The authors developed an industrial technology for applying a wear-resistant coating on the working surface of a rod made of AISI 4140 steel. The paper presents the results of the analysis of the stress state of a material with a coating produced using the developed technology in comparison with the original product. In the product obtained by the experimental technology, in the process of applying the coating and its subsequent mechanical processing, uniform residual mechanical stresses are formed that do not exceed the value of the difference in the principal mechanical stresses. The paper presents the results of the study obtained both on standard samples and on a pilot part.

Keywords: reverse engineering; compressor rod; cold gas flame spraying; wear-resistant tungsten-based coating; tribological properties; residual mechanical stresses.

For citation: Plesovskikh A.Yu., Krylova S.E. The study of the structure and properties of a wear-resistant gas-thermal coating containing tungsten. *Frontier Materials & Technologies*, 2023, no. 2. DOI: 10.18323/2782-4039-2023-2-64-4.

INTRODUCTION

Currently, most of the critical parts of pumping and compressor equipment of the chemical and oil and gas processing industries of the Russian Federation are made according to the technologies of foreign manufacturers. Taking into account the existing external economic situation, the purchase and operation of components for this equipment, in particular heavy-duty rods of compressor units, is difficult, however, the need for these parts is very significant and amounts to 800–1500 thousand pieces per year within the state. Taking into account this fact, the companies of service maintenance and repair of the oil and gas industry objects are forced to quickly solve a number of scientific and technical issues related to the manufacture of import-substituting products.

Thus, within the repairing machine-building enterprise OOO Tekhnologiya, as a research and technological groundwork, metallurgical studies and re-engineering of used compressor equipment rods from the foreign manufacturer, the German company Dresser-Rand Group (Siemens, Germany), were carried out to determine the grade of the main material, as well as the technology of its surface and volume hardening.

Based on literature data, reference documentation for the compressor equipment parts and the available experience of industrial operation of products, the technology of applying protective coatings using gas-thermal spraying processes seemed to be the most likely method of surface hardening [1]. In this regard, the determination of the chemical composition, particle size distribution and geometric shape of the initial original materials for gas-thermal spraying, as well as the necessary analysis of the properties of coatings, has become an urgent task.

The work [2] shows that HVOF-deposited coatings of the WC–12Ni system containing additives of Cr_3C_2 carbides have a lower porosity than pure WC–10Ni coatings, and their mechanical properties depend not on the deposition rate and the composition of the carrier gas but on the percentage of dispersed chromium-based phases. The grain-size ratio of fine (up to 15 μm) and coarse (100–150 μm) WC grains exerts an important influence on the impact strength and elastic modulus of WC–Cr_3C_2–12Ni coatings.

The authors of [3] consider that, despite the corrosion resistance of tungsten coatings with a cobalt binder, the latter should be replaced by nickel to protect human health and the environment, as well as for economic reasons. At the same time, as alternative coatings, the authors propose using powder mixtures based on WC as a solid phase with a metal matrix based on Fe and Ni (WC–NiMoCrFeCo, WC–FeNiCrMoCu, WC–FeCrAl), indicating the corrosion resistance of such coatings in 3.5 % NaCl solution, their low porosity and hardness values (≈1200 HV) comparable to a conventional WC–CoCr coating, which makes them suitable for industrial applications.

Sprayed tungsten-containing composite coatings can reliably protect the working surface from wear [4; 5]. Tungsten-containing composite coatings, have increased contact strength, hardness, the ability to maintain durability and mechanical properties at elevated temperatures up to 700–800 °C, resistance to corrosive environments due to the addition of molybdenum and the formation of close interatomic bonds with the metal base of cobalt or nickel [6; 7]. This is particularly true since the parts of oil and gas and power equipment are often subject to thermal cycling, abrasion, erosion, and corrosion in the presence of a wearing and corrosive environment.

It is known that a decrease in the WC grain size leads to an increase in hardness and a decrease in the crack resistance of the coating [8–10]. In the work [11], the authors compared the micro-structure and mechanical properties of the WC coating. The authors noted that reducing the WC grain size significantly increases the coating hardness due to enhanced decarburisation of the WC grains. The sources [12; 13] analyze the influence of deposition kinematic parameters on the thickness, porosity, residual stresses, and micro-hardness. It is shown, that the parameters of gas-thermal spraying change in the interrelated way, determined by the geometry: the retraction distance, the spraying angle, and the burner displacement velocity. Changes in these technological factors, in turn, affect the conditions of particle collision, which largely determines the properties of the coating.

The analysis of the literature sources showed that thermally sprayed coatings with WC are widely used in industry, since they offer an effective and economical method for protecting the base material from environmental influences and provide wear resistance without compromising other properties of the component [14]. By now, a wide range of materials for applying coatings of this type have been developed and are being produced. Modern technological equipment has been created, numerous experimental studies have been carried out to determine the modes of coating deposition, and contact interactions of the applied coatings with the surface of the part and with each other have been studied.

However, the issue of the formation of a coating with a predictable structure still has a number of implementation difficulties associated with the lack of objective control of the strength, and porosity of the coating during the technological process, which does not allow introducing appropriate adjustments to the deposition parameters. In each specific case, the proposals for the choice of a material and a spraying technology are advisory, since even within the same chemical composition, coatings differ significantly in density, porosity, applied loads, and other subjective factors.

Residual stress control is a major problem in the coating application technology [15; 16], which can be especially crucial in cases where there is a large discrepancy between the thermal, structural, and mechanical properties of layers and substrates. Therefore, the aggregate influence of the structure, and properties of the sprayed material and spraying parameters on the structure and residual stresses for each specific case requires a detailed study.

An object of the study is a compressor rod with a working surface hardened by flame spraying of a powder composition containing tungsten carbide.

A subject of the research is the modes of gas-thermal spraying of coatings, which ensure the formation of the required structure and performance characteristics of the coating surface layer.

The purpose of the study is to develop and test a rational technology for obtaining a tungsten-containing surface coating, that provides the required combination of performance properties of the import-substituting product "a compressor plant rod" of the Dresser-Rand Group company (Siemens, Germany).

METHODS

In this work, the authors used spherical tungsten carbide with a fraction of 60–80 μm mixed with a binder of the Ni–Cr–B system as a strengthening carbide phase. One of the stages of planning and implementation of flame spraying technology was the development and preparation of a powder composition with 20–80 % WC content.

Gas-thermal spraying was carried out on a CastoDyn DS 8000 processing unit with a combustible gaseous mixture of acetylene C_2H_2 and oxygen O_2 in the ratio of 1:5 with a SSM 10 installed spraying module designed for work on the restoration and hardening of parts by metal powder compositions. Flame spraying was carried out in the mode of continuous linear displacement of the burner relative to the rotating part.

The authors performed spectral analysis of the chemical composition of the tested materials on a PMI-MASTER 13L0059 spectrometer in accordance with the GOST 18895 standard.

Electron microscope investigations were performed by the SEM method using a JEOL JCM-6000 microscope equipped with wave and energy-dispersive analyzers; scanning was performed by varying the accelerating voltage in the range of 5–15 kV. The coating elemental composition was determined by X-ray microanalysis of multiple individual zones of the surface layer.

The microhardness of the deposited layer (matrix and carbide inclusions) was determined by the imprint on an HVS-1000 microhardness tester according to the GOST 9450-76 standard at a load of 0.968 N. The authors performed measurements on transverse sections with a step of 0.05 mm. The measurement error did not exceed 1–3 %. The substrate material hardness was measured on a METOLAB 601 hardness tester using the Brinell method in accordance with the GOST 9012-59 standard.

Mechanical tensile tests of the base materials were carried out using a UTS 111.2-100 testing machine at room temperature in accordance with the GOST 1497-84 standard. For impact toughness testing, the authors used a Resil 300 pendulum impact machine; tests were carried out according to the GOST 9454-78 standard on samples with a U-shaped stress concentrator.

To analyse the stressed state of the coated material, the authors evaluated the distribution of the principal mechanical stress difference (PMSD) over the sprayed surface corresponding in geometry and length to the working area of the finished product. For this purpose, the authors carried out a comparative study of samples with experimental cold flame spraying of the developed composition on AISI 4140 steel and samples obtained from the original Dresser-Rand compressor rod made of the same steel. The stress state of the finished product was assessed by the obtained diagrams of stress in the coating using the STRESSVISION mechanical stress scanner operating based on the magneto-anisotropic method.

The PMSD measurement scheme is shown in Fig. 1. According to this scheme, a template was made and attached to the surface of the rod with a sprayed coating.

Coating porosity was determined according to ASTM E2109-01 on an Eclipse MA200 metallographic microscope at a temperature of 22.1 °C and a humidity of 55 %.

The adhesive strength tests of the coatings were carried out by the adhesive method according to ASTM C633-13 on a SHIMADZU AGS-X universal tensile testing machine at a temperature of 24.1 °C and a humidity of 54 %.

For a reasoned proposal of the developed coating for operation, it was necessary to evaluate its wear resistance. The authors evaluated the wear resistance of the resulting coating in comparison with the surface layer of the original product. To determine the resistance of the coating of the Ni–Cr–B–WC system to abrasive wear, the studied samples were subjected to friction tests under dry wear conditions at a load of 50 N, a rotation speed of 500 rpm, a temperature of 22 °C, and a humidity of 63 %. The tests were carried out on a SMTs-2 friction machine without lubricant to eliminate the modifying effect on the friction surface. During testing, the authors used a disc made of 9HS tool steel with a hardness of 60 HRC as a counter-body. The contact area during testing was 50 mm^2.

RESULTS

According to the established chemical composition (Table 1), the original product "compressor rod" is made of AISI 4140 steel.

The analysis of the microstructure of the original product templates showed that the working surface of the "compressor rod" has a surface layer 150–200 µm deep that essentially differs from the base material and does not have a transition heat-affected zone (Fig. 2), which confirmed the assumption that the coating was applied using the high-speed HVOF flame spraying method.

Considering that the mechanism for obtaining the coating provides for a high-speed impact of molten particles on the prepared metal substrate (degreasing, drying, surface activation, and heating up to 120–150 °C), the surface layer structure is formed due to the formation of layered lamellae 5–7 µm thick parallel to material base. As a rule, small pores and oxides crystallise between the lamellae. Such a heterogeneous layered structure, evidently, has lower strength characteristics than the original material; however, it has advantages at friction, which ensures long-term operation of the part in the "rod – stuffing box seal" coupling pair.

Fig. 3 shows a typical fragment of the studied coverage area and the spectrum composition corresponding to the selected area. The chemical composition of the spectrum area is given in Table 2.

According to the results of X-ray micro-analysis, the working surface layer contains about 86 % of tungsten, cobalt is present as a binder and amounts 6–8 %, and the presence of carbon, vanadium, chromium, and iron allows predicting the additional influence of the carbide and intermetallide hardening mechanism in the cobalt binder.

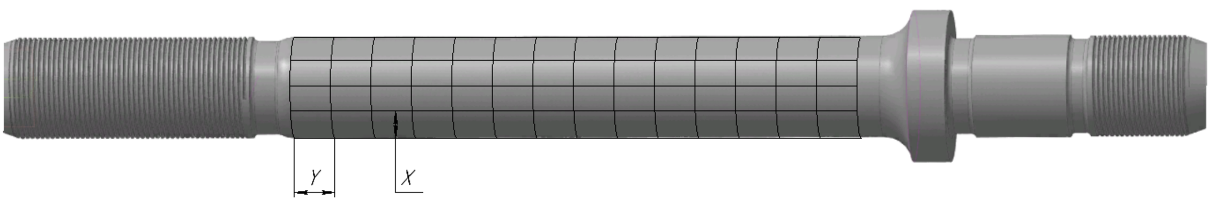
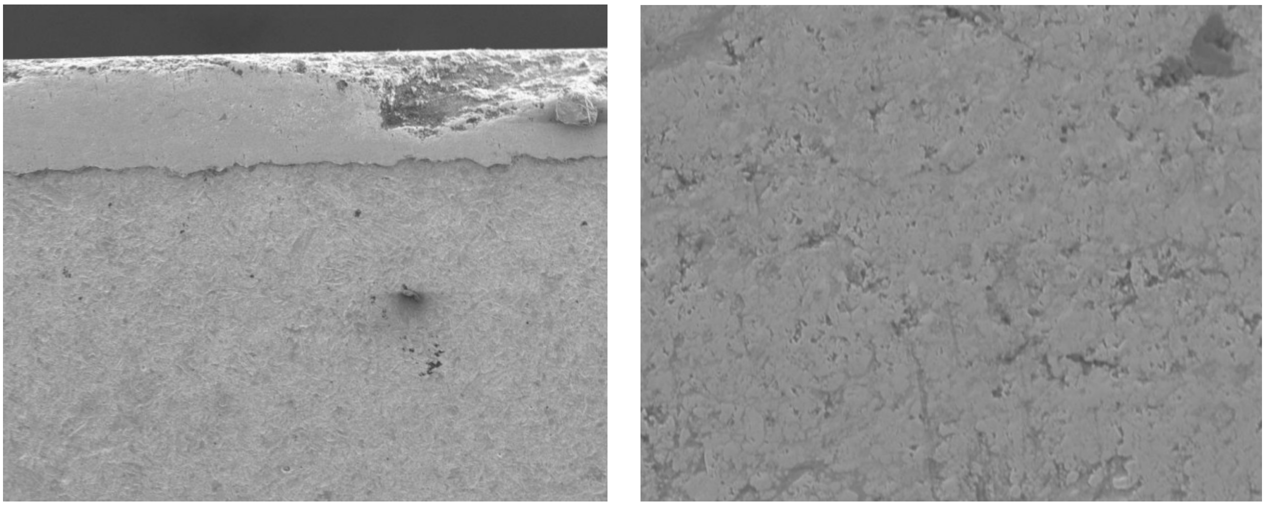


Fig. 1. *PMSD measurement diagram:*
X – measuring section length equal to 52 mm; Y – measuring section width equal to 16 mm

Table 1. *Chemical composition of the product base, % by weight*

	C	Si	Mn	Cr	Mo	Ni	Fe
Average value*	0.400	0.270	0.960	0.920	0.218	0.054	97.178
AISI 4140	0.430	0.300	1.000	1.100	0.250	–	96.920

* *The average value is obtained from the results of at least three measurements.*



a ***b***

Fig. 2. *The results of metallographic studies of the working surface:*
a *– surface general view (×100);* ***b*** *– structure type (×100)*

The porosity of the original coating is distributed uniformly and does not exceed 2.1 % (Fig. 4). The intensity of porosity manifestation along the coating thickness increases towards the base of the material.

Table 3 presents the results of comparative mechanical tests of the original rod material and the selected AISI 4140 analogue after heat treatment.

Based on the data of reverse engineering studies, the main technological principles for the production of rods, for booster compressor station by the foreign Dresser-Rand Group company were determined. The authors identified that for trouble-free operation of these products of oil and gas engineering at a contact load on the rod of 0.7 kg/mm^2, a pressure within 68 kgf/cm^2, at a working medium temperature of up to 150 °C, the composition of associated oil-containing gases: H_2S – 2 %, CO_2 – 2 %, water vapour – up to 1 %, the working coating must have a dispersed tungsten-based carbide structure and an adhesion strength of the coating of at least 50 MPa.

Fig. 5 shows the results of metallographic studies with the research of the WC dimension in the coating of a prototype, with a 20 % content of a hardening carbide phase.

The structure analysis follows that the tungsten carbide in the coating is a spherical granule with a size identical to the original powder composition. This indicates that the sprayed particles are not subjected to serious mechanical stresses during high-speed impact with the substrate, as a result of which their shape and dimensions remain unchanged; they do not prevent the free formation of lamellas of the coating viscous nickel component, they are evenly distributed in the binder without forming free cavities at the boundary of WC and Ni–Cr–B-based binder. Fig. 6 and Table 4 show the results of spectral analysis of individual WC carbide inclusions.

At the stage of adjusting the technology for deposition of a tungsten-based coating, the coating adhesion strength corresponded to the values of the original and varied within 45–55 MPa. The surface layer porosity was recorded within 6.1 % (with a permissible value of pores up to 10 %) [17], the micro-hardness of the coating base (Ni–Cr–B) was about 700 $HV_{0.1}$, and the micro-hardness of tungsten carbide inclusions was 2000 $HV_{0.1}$.

The data in Table 5 demonstrate that with an increase in the percentage ratio of tungsten carbide from 20 to 70 %, the overall wear resistance of the coating increases as well.

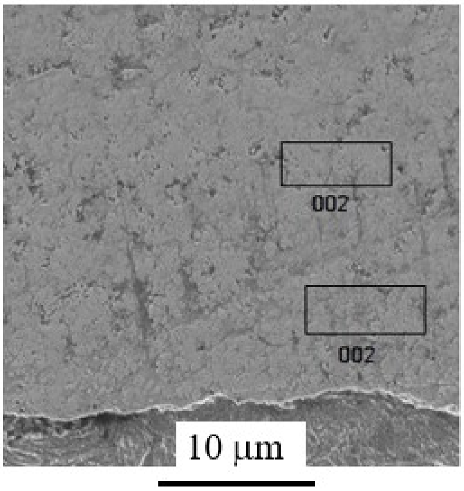
Based on the conducted metallographic studies and wear resistance tests, the Ni–Cr–B–WC composition with a tungsten carbide content of 70 % is the optimal composition for hardening the surface layer of the "compressor rod" item. This coating, with a lower WC content in the volume, ensures satisfactory and comparable to the original micro-hardness values, meets or exceeds the original in the wear resistance of the working surface due to the application of a combined Ni–Cr–B metal base instead of the original cobalt binder, which provides additional attractiveness of the development in economic terms.

The results of PMSD measurements obtained using the STRESSVISION mechanical stress scanner (indicator) are shown in Fig. 7.

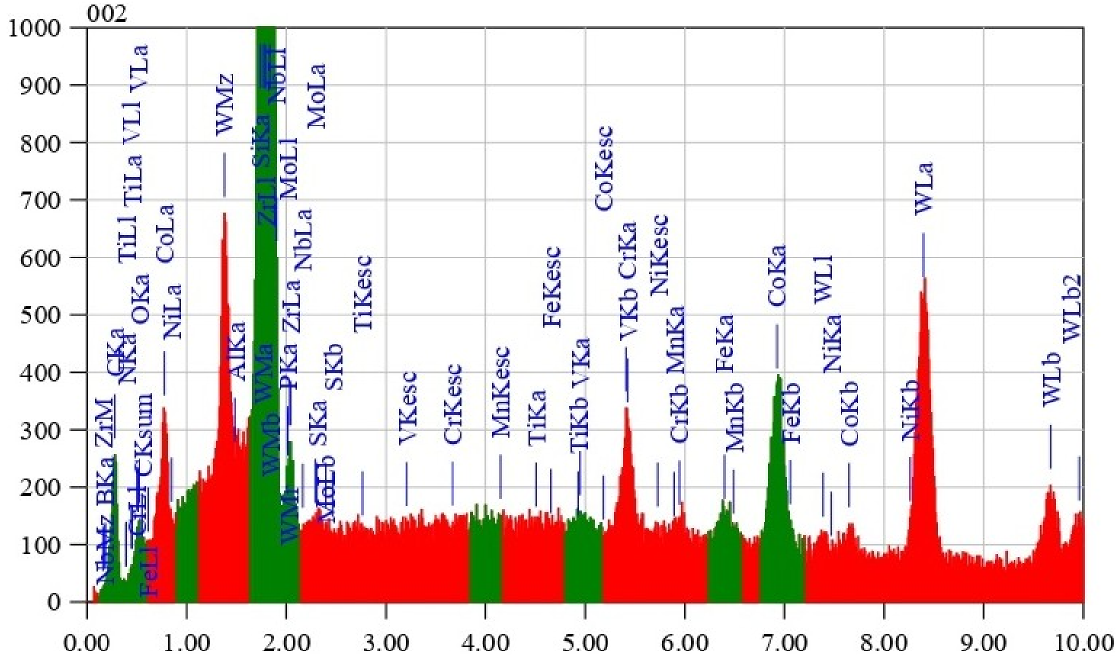
The numerical characteristics obtained by mathematical processing of the maps of the PMSD distribution in the original rod and the prototype are summarized in Table 6.

The analysis of distribution cartograms of residual mechanical stresses showed that the cold flame spraying technique, which allows obtaining the thickness of the developed coating corresponding to the original product (in the range from 0.2 to 0.25 mm), is optimal in terms of internal stresses at the metal-coating boundary. (Fig. 6). Fig. 8 presents the numerical characteristics obtained by mathematical processing of PMSD distribution maps, which reflect the comparative distribution of maximum stresses over the zones of scanning.

The analysis of the data (Fig. 6, Fig. 7) shows that the PMSD distribution over the surface of the experimental sprayed sample is uniform and does not exceed 10 c. u. after manufacturing. Stress state analysis data were obtained from the original product at the stage of reverse engineering of the compressor rod used for 4 thousand hours. The original product has two local stress state zones: zone 8, where the PMSD maximum value is 346.84 c. u.,



a



b

Fig. 3. *Elemental composition of the specific coating area:*
a *– an analyzed fragment of the coating (002 spectrum);* ***b*** *– a spectrogram of the respective analysis area*

Table 2. *Chemical composition of the coating in the 002 spectrum area, % by weight*

C	V	Cr	Mn	Fe	Co	W
2.27	0.06	2.81	0.03	0.92	7.82	86.09

and zone 6, where the PMSD maximum value is 225.5 c. u. However, the average background of stress distribution is also stable and lies within 10–20 c. u. The existence of zones with the increased PMSD values is explained by the cumulative effect of stresses in local friction zones during operation. The obtained data show that in the experimental sample with surface hardening by cold flame spraying, in the process of coating and its subsequent mechanical processing, insignificant uniform residual mechanical stresses are formed in the coating zone not exceeding the PMSD values compared to the foreign manufacturer technology. This makes it possible to recommend, reasonably, the developed coating composition and its application method for testing on a pilot item.

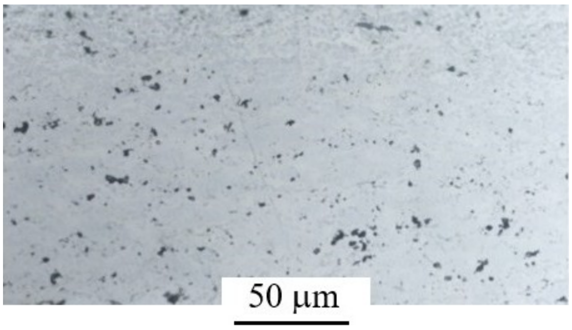
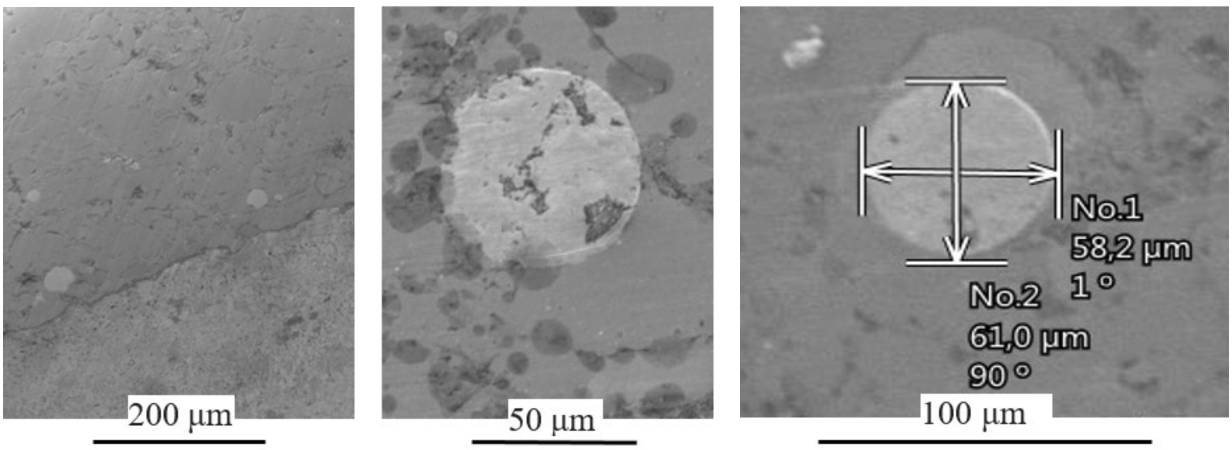


Fig. 4. *Microphotographs of the coating section when measuring porosity*

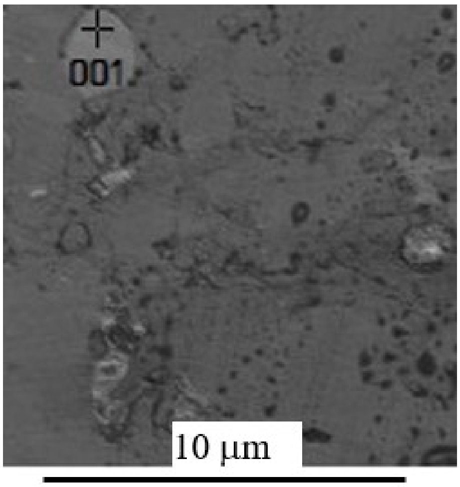
Table 3. *Mechanical properties of the base metal of the product*

Characteristics	An original	A material – AISI 4140 analogue
Yield strength $\sigma_{0.2}$, Mpa	347	563
Ultimate stress limit $\sigma_{в}$, MPa	728	784
Percentage elongation δ_5, %	23.2	17.1
Percentage reduction ψ, %	63.1	67.9
Impact resistance KCU^{+20}, J/sm^2	62.5	176
Hardness, HB	215	226

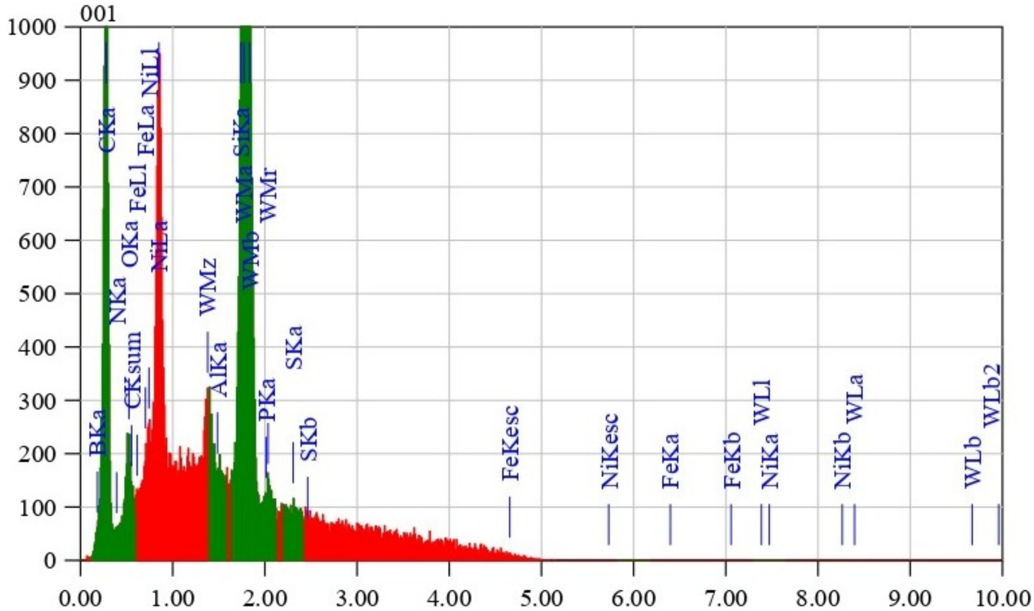


a ***b*** ***c***

Fig. 5. *The structure of the coating surface layer produced by cold gas flame spraying:*
a, b *– structure general view;* ***c*** *– dimensions and shape of the tungsten carbide particles (×500)*



a



b

Fig. 6. *The results of X-ray microanalysis of spherical tungsten carbide:*
a *– an analyzed fragment of the coating (001 spectrum);* ***b*** *– a spectrogram of the analyzed fragment of the coating (001 spectrum)*

Table 4. *WC chemical composition in the 001 spectrum, % by weight*

C	B	Ni	O	W
32.23	2.54	1.05	1.40	62.78

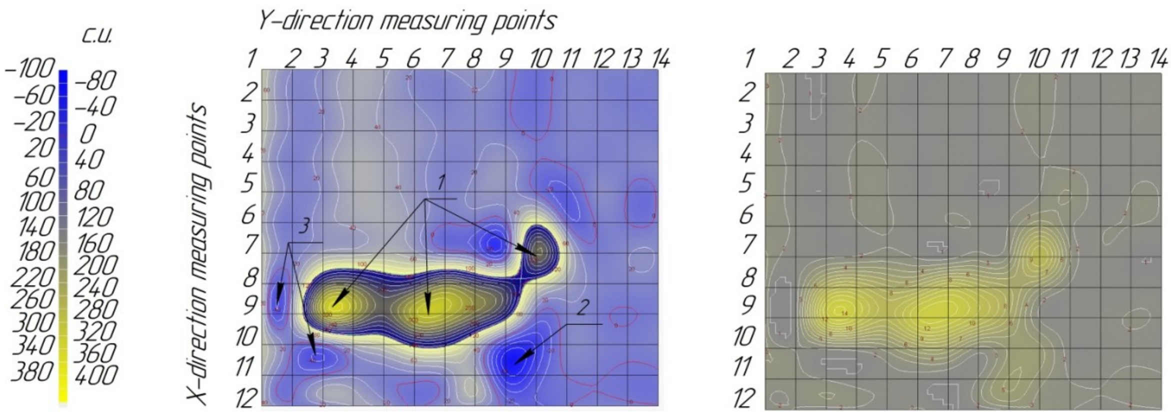
DISCUSSION

The development of manufacturing technology for the import-substituting “compressor rod” item included: the development of the design-engineering documentation, metallographic studies, engineering and technical experiments [18; 19].

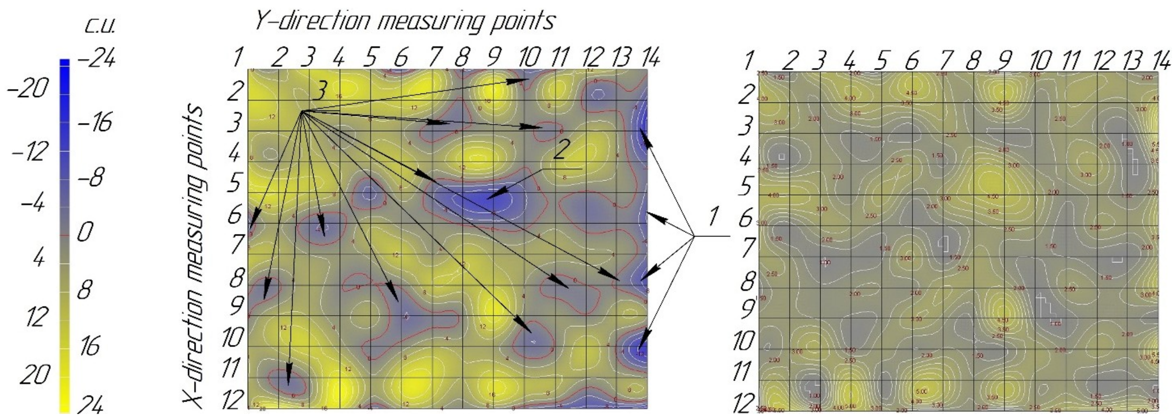
In the process of coating formation by flame spraying, at the stage of plasticisation and deformation of refractory particles during high-speed impact, typical defects and free cavities inevitably form in the zone of contact of the previously applied layers of lamellas with the surface. Their interaction with the atmosphere during the precipitation of dust fractions up to 80 μm in size, as well as the adsorption of gases on freshly formed coating layers, significantly worsen the structure and, consequently, the properties of the interlayer coating zone. Reducing the size of the sprayed particles can significantly improve the layer-by-layer filling of the coating through the formation of a more homogeneous structure,

Table 5. *The dependence of the wear value on the carbide phase amount in the coating*

Tungsten carbide amount in the coating, %	Specimen weight, g		Wear, g
	before tests	after tests	
Experimental spraying			
20	11.45	11.38	0.07
30	11.50	11.43	0.07
50	11.49	11.44	0.05
70	14.65	14.64	0.01
Original rod			
90	14.57	14.56	0.01



a



b

Fig. 7. *Cartograms of PMSD distribution:*
a *– of an experimental specimen;* ***b*** *– of an original compressor rod:*
1 – edge defect zone, 2 – compressive stress zone, 3 – compensation zones

increasing its density while reducing the volume of microvoids. In this regard, the choice of fractional composition and shape of powder particles takes on special significance.

Thus, powder compositions for the formation of the working layers of pumping and compressor equipment should ensure high adhesive strength (more than 50 MPa), wear resistance, and minimal coating porosity. These requirements can be fully met by spraying powder compositions, with tungsten carbide inclusions, in a working layer. In early works [18; 19], the authors paid attention to comparing the efficiency of introducing tungsten carbide particles of different morphology and granulometry into the nickel

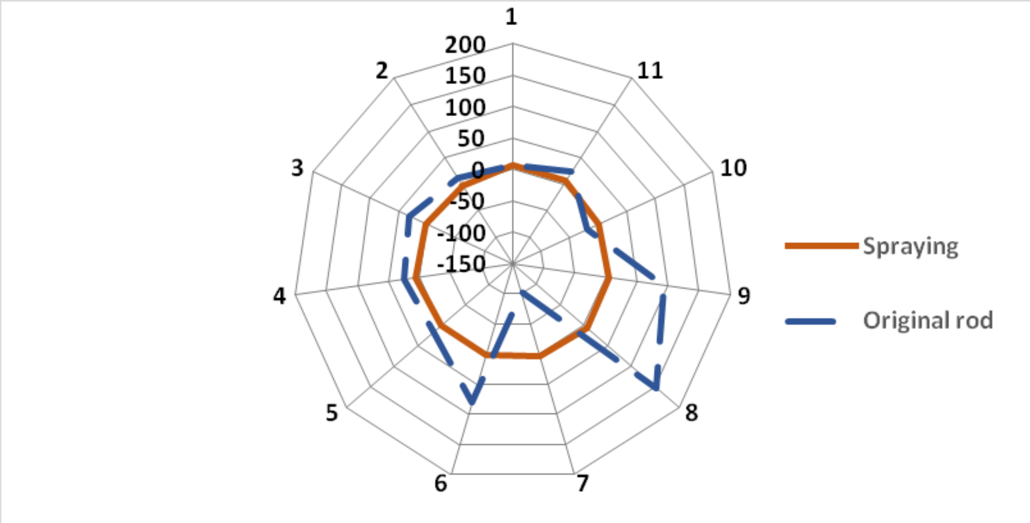


Fig. 8. *Comparative analysis of the distribution of average residual stresses in the test sample and the original product*

matrix, showed the advantage of introducing dispersed spherical particles with regard to the formation of a monolithic surface layer that excludes cracking, coarse pores, and tears under load. Based on the studies performed, it was found that particles of spherical tungsten carbide (WC) up to 50 µm in size [17–19] contained in the matrix in the range of 60–70 vol. % provide the best result of carbide hardening, which is confirmed by the present results.

The research showed that a nickel matrix existing in the form of a γ-solid solution in the deposited layer contributes to increasing the coating fracture toughness and abrasive resistance, and the presence of dispersed high-strength spherical carbide phases in the metal base provides the coating increased strength and wear resistance in the context of boundary friction and friction without lubrication. Comparative studies of wear resistance showed that due to the elastic-plastic properties of the coating composite material, the wear rate decreases by 1.2–1.3 times. The increase in wear resistance at a constant friction coefficient is associated with hardening through the structure refinement and the targeted formation of a significant number of hardening phases in the working layer.

CONCLUSIONS

1. Based on the data of the reverse engineering studies of a booster compressor station rod, the original product of the Dresser-Rand Group company (Siemens, Germany), the grade of the main material – AISI 4140 steel (chemical composition, wt. %: 0.38–0.43 C; 0.15–0.30 Si; 0.75–1.0 Mn; 0.80–1.10 Cr; 0.15–0.25 Mo; 0.04 S; 0.035 P; the rest is Fe) and technological features of the working surface manufacturing, and hardening by applying a wear-resistant tungsten-containing coating using the cold gas-thermal spraying technique were determined.

2. A composition of a wear-resistant powder coating based on the Ni–Cr–B metal system with the spherical tungsten carbide (WC) inclusions was developed. The proposed technology of its application using the cold gas-thermal spraying method allowed obtaining a surface wear-resistant layer of 0.2–0.25 mm having a base micro-hardness in the range of 700 $HV_{0.1}$ with a uniform distribution of strengthening carbide phases with a micro-hardness of up to 2000 $HV_{0.1}$.

3. It is established that the nickel matrix carbide hardening by the dispersed spherical tungsten carbide WC particles within 60–70 vol. % allows improving the layer-by-layer formation of coating lamellae, increasing the density and uniformity of the structure, reducing the volume of free microvoids at the "WC – binder" boundary from 10 to 6 %, according to the coating porosity analysis.

4. The proposed Ni-Cr-B-WC coating compares with the original product in wear resistance, has a certain economic attractiveness, while ensuring accurate geometric dimensions and a minimum stress state gradient not exceeding 10 MPa. These technological advantages made it possible to start implementing the technology of surface hardening of compressor equipment rods under production conditions.

REFERENCES

1. Barvinok V.A., Shitarev I.L., Bogdanovich V.I., Dokukina I.A., Karasev V.M. Wearability, wearproof and heat-shielding coverings for details of the gas path of the turbine, the compressor and the chamber of combustion of gas turbine engine. *Vestnik Samarskogo gosudarstvennogo aerokosmicheskogo universiteta im. akademika S.P. Koroleva*, 2009, no. 3-1, pp. 11–28. EDN: LADTXX.
2. Yao H.-L., Yang Ch., Yi D.-L., Zhang M.-X., Wang H.-T., Chen Q.-Yu., Bai X.-B., Ji G.-Ch. Microstructure and mechanical property of high velocity oxy-fuel sprayed WC-Cr3C2-Ni coatings. *Surface and Coatings Technology*, 2020, vol. 397, article number 126010. DOI: 10.1016/j.surfcoat.2020.126010.
3. Testa V., Morelli S., Bolelli G., Benedetti B., Puddu P., Sassatelli P., Lusvarghi L. Alternative metallic matrices for WC-based HVOF coatings. *Surface and Coatings Technology*, 2020, vol. 402, article number 126308. DOI: 10.1016/j.surfcoat.2020.126308.

4. Rakhadilov B.K., Muktanova N., Zhurerova L.G. Application of HVOF technology for WC-based wear-resistant coatings – an overview. *Vestnik NYaTs RK*, 2023, no. 1, pp. 4–14. DOI: 10.52676/1729-7885-2023-1-4-14.
5. Pereira P., Vilhena L.M., Sacramento J., Senos A.M.R., Malheiros L.F., Ramalho A. Abrasive wear resistance of WC-based composites, produced with Co or Ni-rich binders. *Wear*, 2021, vol. 482-483, article number 203924. DOI: 10.1016/j.wear.2021.203924.
6. Santos R.F., Ferro Rocha A.M., Bastos A.C., Cardoso J.P., Rodrigues F., Fernandes C.M., Sacramento J., Ferreira M.G.S., Senos A.M.R., Fonseca C., Vieira M.F., Malheiros L.F. The effect of Cr content on the corrosion resistance of WC-Ni-Cr-Mo composites. *International Journal of Refractory Metals and Hard Materials*, 2021, vol. 95, article number 105434. DOI: 10.1016/j.ijrmhm.2020.105434.
7. Santos R.F., Ferro Rocha A.M., Bastos A.C., Cardoso J.P., Rodrigues F., Fernandes C.M., Sacramento J., Ferreira M.G.S., Senos A.M.R., Fonseca C., Vieira M.F., Malheiros Luís F. Microstructural characterization and corrosion resistance of WC-Ni-Cr-Mo composite – The effect of Mo. *International Journal of Refractory Metals and Hard Materials*, 2020, vol. 86, article number 105090. DOI: 10.1016/j.ijrmhm.2019.105090.
8. Wang D., Zhang B., Jia Ch., Gao F., Yu Yu., Chu K., Zhang M., Zhao X. Influence of carbide grain size and crystal characteristics on the microstructure and mechanical properties of HVOF-sprayed WC-CoCr coatings. *International Journal of Refractory Metals and Hard Materials*, 2017, vol. 69, pp. 138–152. DOI: 10.1016/j.ijrmhm.2017.08.008.
9. Chivavibul P., Watanabe M., Kuroda S., Shinoda K. Effects of carbide size and Co content on the microstructure and mechanical properties of HVOF-sprayed WC–Co coatings. *Surface and Coatings Technology*, 2007, vol. 202, no. 3, pp. 509–521. DOI: 10.1016/j.surfcoat.2007.06.026.
10. Yuan J., Ma Ch., Yang Sh., Yu Zh., Li H. Improving the wear resistance of HVOF sprayed WC-Co coatings by adding submicron-sized WC particles at the splats' interfaces. *Surface and Coatings Technology*, 2016, vol. 285, pp. 17–23. DOI: 10.1016/j.surfcoat.2015.11.017.
11. Ma N., Guo L., Cheng Zh., Wu H., Ye F., Zhang K. Improvement on mechanical properties and wear resistance of HVOF sprayed WC-12Co coatings by optimizing feedstock structure. *Applied Surface Science*, 2014, vol. 320, pp. 364–371. DOI: 10.1016/j.apsusc.2014.09.081.
12. Katranidis V., Gu S., Allcock B., Kamnis S. Experimental study of high velocity oxy-fuel sprayed WC-17Co coatings applied on complex geometries. Part A: Influence of kinematic spray parameters on thickness, porosity, residual stresses and microhardness. *Surface and Coatings Technology*, 2017, vol. 311, pp. 206–215. DOI: 10.1016/j.surfcoat.2017.01.015.
13. La Barbera-Sosa J.G., Santana Y.Y., Moreno E., Cuadrado N., Caro J., Renault P.O., Le Bourhis E., Staia M.H., Puchi-Cabrera E.S. Effect of spraying distance on the microstructure and mechanical properties of a Colmonoy 88 alloy deposited by HVOF thermal spraying. *Surface and Coatings Technology*, 2010, vol. 205, no. 7, pp. 1799–1806. DOI: 10.1016/j.surfcoat.2010.01.017.
14. Wang Q., Zhang Sh., Cheng Y., Xiang J., Zhao X., Yang G. Wear and corrosion performance of WC-10Co4Cr coatings deposited by different HVOF and HVAF spraying processes. *Surface and Coatings Technology*, 2013, vol. 218, pp. 127–136. DOI: 10.1016/j.surfcoat.2012.12.041.
15. Varis T., Suhonen T., Jokipii M., Vuoristo P. Influence of powder properties on residual stresses formed in high-pressure liquid fuel HVOF sprayed WC-CoCr coatings. *Surface and Coatings Technology*, 2020, vol. 388, article number 125604. DOI: 10.1016/j.surfcoat.2020.125604.
16. Santana Y.Y., La Barbera-Sosa J.G., Staia M.H., Lesage J., Puchi-Cabrera E.S., Chicot D., Bemporad E. Measurement of residual stress in thermal spray coatings by the incremental hole drilling method. *Surface and Coatings Technology*, vol. 201, no. 5, pp. 2092–2098. DOI: 10.1016/j.surfcoat.2006.04.056.
17. Krylova S.E., Plesovskikh A.Yu., Kurnoskin I.A., Tavtilov I.Sh. Influence of heat treatment on the structure and properties of the tungsten-containing coating of the working part of oil and gas equipment. *Chernye metally*, 2022, no. 12, pp. 36–42. DOI: 10.17580/chm.2022.12.05.
18. Plesovskikh A.Yu., Krylova S.E., Oplesnin S.P. Import-substituting technology for manufacturing parts of the oil and gas industry with the application of wear-resistant coatings based on tungsten. *Vestnik sovremennykh tekhnologiy*, 2019, no. 2, pp. 9–14. EDN: WJOBJF.
19. Plesovskikh A.Y., Krylova S.E., Oplesnin S.P., Kurnoskin I.A. Import-substituting technology for manufacturing parts of the oil and gas industry with the application of tungsten based wear-resistant coatings. *Materials Today: Proceedings*, 2021, vol. 38, part 4, pp. 1595–1598. DOI: 10.1016/j.matpr.2020.08.161.