ТЕХНИКАЛЫҚ ФИЗИКА
ТЕХНИЧЕСКАЯ ФИЗИКА
TECHNICAL PHYSICS

Article

UDC 620.18

https://doi.org/10.31489/2025PH3/31-40

Received: 19.03.2025
Accepted: 07.06.2025

Sh.R. Kurbanbekov[1], A. Kizatov[2], N. Musakhan[1],
P.A. Saidakhmetov[3], S.Kh. Kambarbekov[1]✉, B. Kaldar[4]

[1]*Research Institute Natural Sciences, Nanotechnologies and New materials, Khoja Akhmet Yassawi International Kazakh-Turkish University, Turkestan, Kazakhstan;*
[2]*Researcher of Scientific Research Center "Veritas", D. Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk, Kazakhstan;*
[3]*Researcher Department of Physics, M. Auezov South Kazakhstan University, Shymkent, Kazakhstan;*
[4]*Yasavi International Kazakh-Turkish University, Turkestan, Kazakhstan*

Effect of HVOF spraying parameters on the structural-phase composition and mechanical properties of ZrCN coating

The article presents the results of a study on the influence of HVOF spraying parameters on the phase composition, mechanical properties, and adhesion characteristics of zirconium carbonitride (ZrCN) coatings. X-ray diffraction analysis of the ZrCN coatings revealed the presence of ZrCN, ZrC, ZrN, ZrO, Fe, and FeN phases, indicating a complex coating structure and possible oxidation and elemental diffusion processes. The formation of ZrC and ZrN is attributed to the thermal decomposition of ZrCN powder during the coating process, while the presence of the oxide phase ZrO is explained by the use of an oxygen-containing gas mixture during HVOF spraying. The microhardness of the ZrCN coatings reaches values in the range of 1500–1800 HV, depending on the spraying parameters. Adhesion test results showed that the maximum coating bond strength under tensile load was 7.49 MPa. Optimal coating characteristics were achieved at the following spraying parameters: substrate distance of 35–40 cm, propane pressure of 1.7 bar, air pressure of 2.6 bar, and oxygen pressure of 2.8 bar. These conditions allow the formation of a dense, wear-resistant coating structure with enhanced performance characteristics.

Keywords: HVOF, microhardness, adhesion, structure, phase composition, ZrCN coating, X-ray diffraction

✉*Corresponding author*: Kambarbekov, Sardor, sardor.kambarbekov@mail.ru

Introduction

Currently, ensuring high wear resistance and durability of cutting tools of technological equipment is one of the key tasks in mechanical engineering and metalworking. Cutting tools and parts operating under conditions of intensive wear and high mechanical loads require the use of wear-resistant protective coatings [1]. Both physical and chemical deposition methods are actively used to form protective and functional coatings. Physical processing methods include physical vapor deposition, plasma spraying, and magnetron sputtering, which provide dense, wear-resistant coatings with high adhesion to the substrate [2–6]. Additionally, to increase wear resistance and corrosion resistance of materials, sol-gel technologies and laser coating methods are actively used, ensuring control over the composition and structure of the formed layers [7, 8].

Among the above methods, the most promising is the HVOF technology, which allows obtaining nanostructured coatings. HVOF technology has become widespread in many industries due to its flexibility and cost-effectiveness in obtaining high-quality coatings [9–11]. The physical and mechanical properties of HVOF sprayed coatings largely depend on the nano- or microstructure of the coating, which in turn largely depends on the physical and chemical state of the particles at the point of impact on the substrate, such as speed, temperature, degree of melting and oxidizer content [12–14]. In particular, coatings that can withstand wear, high mechanical loads and chemically aggressive influences are of particular importance. In this regard, ZrCN coatings demonstrate excellent characteristics under such conditions [15, 16]. It has been proven that ZrCN-based ceramics have high thermal stability and resistance to physical and chemical environments, which makes them an excellent candidate for protective coatings of cutting tools and metal parts operating in extreme conditions [17–19]. It was found that the grains of ZrN/ZrCN coatings were denser, finer and more compact than those of Zr/ZrN coatings. Accordingly, higher values of hardness, modulus and H/E were demonstrated by ZrN/ZrCN coatings [20].

The aim of this study is to investigate the influence of HVOF spraying mode parameters on the phase composition and mechanical properties of ZrCN coating.

Materials and methods

The ZrCN coatings were deposited using the HVOF method on a Termika-3 system [21], which is equipped with a control panel that allows precise adjustment of the gas supply pressures. Figure 1 presents both a visual and schematic illustration of the equipment used. As the pressure increases, the gas components are mixed inside the chamber, after which the powder material with a metered feed enters the burner, where it is transported by compressed air supplied by the compressor.

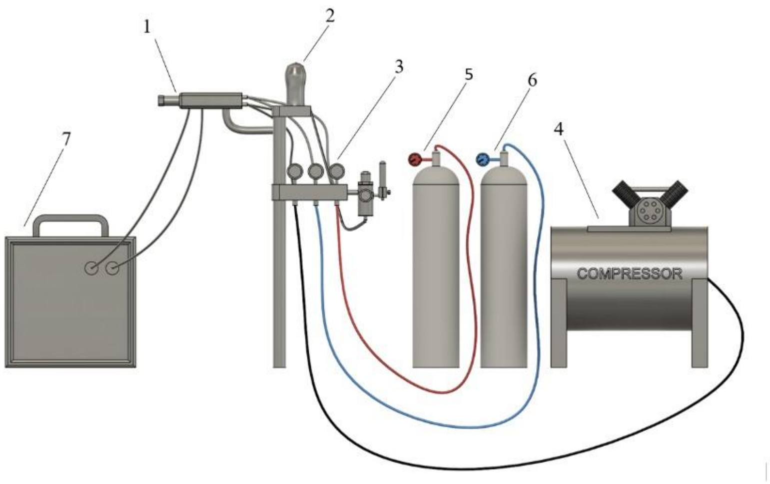


Figure 1. External view and structural diagram of the HVOF spraying system: *1*—torch; *2*— powder feeder; *3*—gas control panel; *4*—compressor; *5*—gas cylinder (C_3H_8); *6*—gas cylinder (O_2); and *7*—chiller

At the outlet of the burner, the powder particles enter the flame zone, where they are heated to a state that ensures their plastic deformation. Then the molten particles are directed to the pre-prepared surface of the substrate, forming a uniform protective coating. The ZrCN powder with a particle size range of 20–100 µm exhibits an irregular polyhedral fragmented morphology, which is known to have lower flowability compared to spherical particles. The main spraying parameters are given in Table 1. Steel grade 65G [22], which belongs to the group of high-carbon, alloyed steels, was used as a substrate.

Table 1

Coating application parameters

№	Distance	Propane	Air Pressure	Oxygen	Powder
Sample a	35–40 cm	1.7 bar	2.6 bar	2.8 bar	ZrCN
Sample b			2.8 bar		
Sample c			3 bar		

Table 2 shows the chemical composition of 65G steel. Before spraying, the substrate surface was mechanically processed (grinded) to remove oxide films, and then sandblasted to improve coating adhesion.

Table 2

Chemical composition of steel 65G [22]

Steelgrade	Mass fraction of elements, %			
	Carbon	Silicon	Manganese	Chromium
65G	0.62–0.70	0.17–0.37	0.90–1.20	0.25

The phase composition of the obtained ZrCN-based coatings was studied using an X'Pert PRO X-ray digraphometer with Cu-Kα radiation (λ = 1.5406 Å), a voltage of 40 kV and a current of 30 mA. The scanning angle range was from 20.01° to 89.99° with a step of 0.02° and a data accumulation time of 2 s. The diffraction patterns were processed using High Score Plus software.

Microhardness was investigated using the Vickers method in accordance with GOST 9450-76 on the HLV-1DT microhardness tester. A diamond tetrahedral pyramid with angles of 136° was used as an indenter in the study. During the measurement, a load of $HV_{0.5}$ was applied to the surface of the sample, and the indenter was held for 10 seconds. Then the diagonal dimensions of the input traces (d1 and d2) were determined with accuracy [24].

To study the adhesive properties of the coatings, tests were carried out in accordance with ASTM D4541-22. Using an Elcometer 510 hydraulic adhesion meter (Elcometer Instruments, Manchester, UK). The strength of the adhesive coatings was determined under the following conditions: hold time 0.50 s; target speed 1.00 MPa/s; backing size 20 mm.

Results and discussion

To study the phase composition of the ZrCN powder intended for spraying, X-ray phase analysis was carried out, the diffraction pattern of which is shown in Figure 2. It can be seen from the figure that the presence of the ZrCN peak next to the ZrC, ZrN peaks indicates its partial preservation [23] and confirms its decomposition with the formation of zirconium nitride. Zirconium carbonitride combines high hardness with good plasticity, which contributes to the increased resistance of the material to the formation and propagation of cracks.

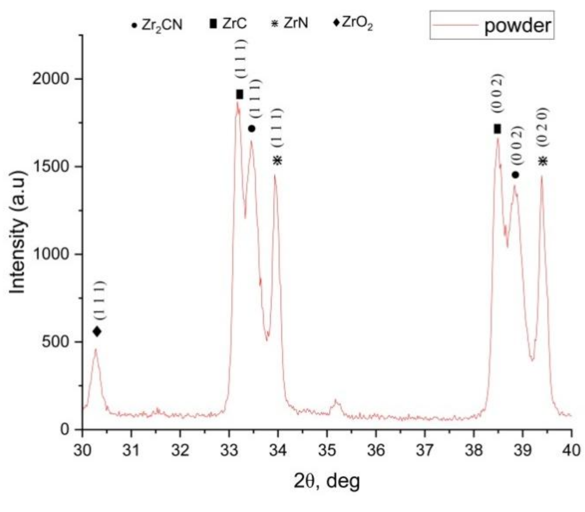


Figure 2. X-ray diffraction pattern of ZrCN powder

X-ray diffraction patterns of three coating samples are shown in Figure 3. The study of the phase composition of the sprayed coatings by the HVOF method showed the presence of the following phases: ZrCN, ZrC, ZrN, ZrO, Fe and FeN. The X-ray diffraction results confirmed that $ZrC_{1-x}N_x$ crystallizes in a face-centered cubic (FCC) structure, and its diffraction peak is located between the control peaks of ZrC and ZrN, which indicates complete mutual solubility of these phases [24], the parameters of the ZrCN crystal lattice are cubic system, space group Fm-3m. Compared to titanium and hafnium carbonitrides, ZrCN has greater plasticity, which has a positive effect on the crack resistance of ceramics made on its basis [25]. In works [26, 27], high values of hardness and critical intensity factors were revealed. In addition to high hardness, an important advantage of the coating is its relatively high thermal conductivity, which reduces the risk of thermal damage [28]. The formation of ZrC and ZrN phases is associated with thermal decomposition of ZrCN powder. Addition of large amounts of oxygen to the ZrN structure can distort its crystal structure, introduce defects and promote the formation of an amorphous structure. A decrease in grain size and an increase in the lattice constant are associated with the presence of oxygen in the coatings. These effects will manifest themselves as a broadening of peaks in X-ray diffraction patterns [29]. Many nitrides such as ZrN crystallize in sodium chloride type structures, and in an ideal perfect crystal first order Raman scattering is forbidden. However, it is known that deposited coatings contain vacancies which cause distortion of the structure [30], and as a consequence the Raman spectrum consists of broadened bands due to disorder and second order processes.

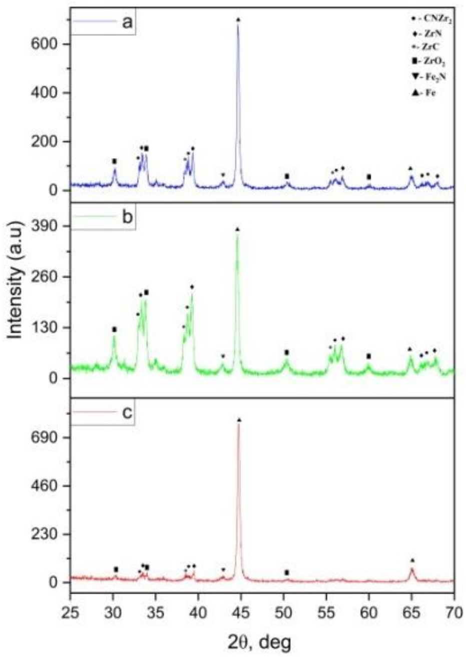


Figure 3. X-ray diffraction pattern after ZrCN coating HVOF modes:
sample *a* distance 35–40 cm, fuel pressure 1.7 bar, air pressure 2.6 bar, oxygen pressure 2.8 bar;
sample *b* 35–40 cm, fuel pressure 1.7 bar, air pressure 2.8 bar, oxygen pressure 2.8 bar
and sample *c* 35–40 cm, fuel pressure 1.7 bar, air pressure 3 bar, oxygen pressure 2.8 bar

It is known [31] that zirconium oxide can be found in mainly different phases: tetragonal ZrO_2, monoclinic ZrO_2 and cubic ZrO_2. Usually pure t-ZrO_2 in the tetragonal phase exists if Y_2O_3 yttrium oxide is present in the coatings [32]. HVOF promotes the formation of a mixture of c-ZrO_2 and t-ZrO_2, but if the cooling is very fast, more of the cubic phase remains. The formation of the ZrO phase, which possesses a similar cubic lattice structure with the space group Fm-3m, is attributed to the use of an oxygen–propane mixture as the oxidizing environment during high-velocity oxy-fuel spraying. This led to an active interaction of ZrCN with oxygen and a partial loss of carbon. Excess carbon released during the decomposition of ZrCN diffused into the metal matrix, promoting the formation of carbide (ZrC) and oxide (ZrO) phases. All samples exhibit low Zr/(C+N) ratio, $0.3 \leq Zr/(C+N) \leq 0.6$, which suggests the presence of an additional amorphous phase, most likely amorphous C or CNx. Indeed, these phases were also observed in the TiCN system [33]. The Fe phase was detected at an angle of 44.62°, its main parameters are: cubic system, space group—Im-3m. In addition, the FeN phase, space group P-3m1, with a cubic lattice was identified. At the same time, the main lines of this phase coincide in positions with the shifted lines of the (ZrC)(ZrN) type phases with cubic lattice parameters mentioned earlier. The peaks of the phase lines in sample 3 at angles of 38.76° have characteristic broadenings, indicating the presence of phases of transformed compositions. The microhardness of the coatings and the substrate is an important parameter determining their mechanical properties and performance characteristics. Figure 4 shows the obtained microhardness values for the substrate and ZrCN coatings. The initial microhardness values of the substrate are 400–500 HV, which corresponds to the typical characteristics of hardened steel 65G. This indicates a relatively low hardness of the base material compared to the applied coatings and emphasizes the need to use protective layers to improve wear resistance.

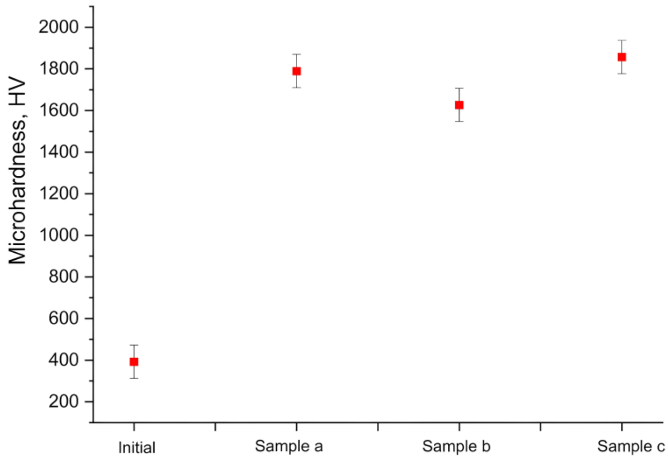
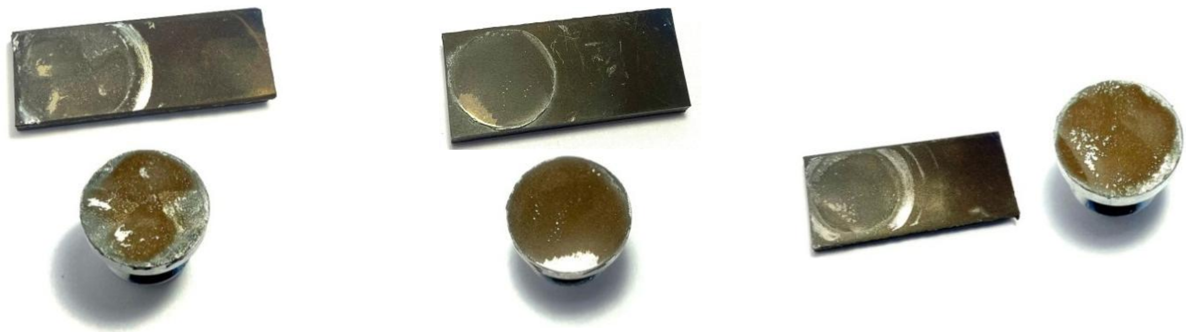


Figure 4. Microhardness values of 65G steel. HVOF modes:
sample *a* distance 35–40 cm, fuel pressure 1.7 bar, air pressure 2.6 bar, oxygen pressure 2.8 bar;
sample *b* 35–40 cm, fuel pressure 1.7 bar, air pressure 2.8 bar, oxygen pressure 2.8 bar
and sample *c* 35–40 cm, fuel pressure 1.7 bar, air pressure 3 bar, oxygen pressure 2.8 bar

After deposition of ZrCN coatings, a significant increase in microhardness is observed, with values varying depending on the sample. Sample *a* shows an increase in microhardness to 1600 HV, indicating the formation of a dense coating with a good degree of particle compaction. Sample *b* reaches a maximum hardness of 1800 HV, which can be associated with the optimal particle size of the coating, uniform phase distribution and minimal porosity. Sample *c* shows microhardness in the range of 1500–1600 HV, which is slightly lower than the second sample, but still indicates high coating strength. A smooth change in microhardness is observed at the coating-base interface, indicating possible diffusion of alloying elements and temperature effects during the spraying process.

Coating adhesion tests were carried out using the pull-off method in accordance with GOST 32299-2013 (ISO 4624: 2002) at a temperature of 20±5 °C no earlier than three days after coating application. To improve the adhesive bond, the coating surface at the gluing point of the “mushroom” was treated with sandpaper, provided and degreased with ethyl alcohol. The adhesive was applied according to the manufacturer’s instructions. Epoxy Adhesive 2214 was applied in an even layer to the surface of the “mushroom”, then the “mushroom” was pressed against the coating and kept until the adhesive hardened, ensuring the centering of the surfaces to be glued. If necessary, excess glue was removed. Using a cutting tool (annular cutter), the coating was cut to the metal around the “mushroom”. Saw cuts were made across the entire coating thickness until the metal appeared, with the cut width being at least 1 mm. Tests were conducted at least 24 hours after gluing the “mushrooms”. To measure adhesion, the “mushroom” was placed in a special adhesion meter device. The adhesion meter’s stop mechanism was hooked onto the “mushroom” and by pressing the handle, a normal tear-off force was applied, the value of which was recorded on the device scale. It should be noted that non-compliance of the coating with the operating conditions of its application (e.g., climatic conditions), insufficient quality of surface preparation and other violations of the application technology lead not only to a decrease in its efficiency and reliability, but also to defective coating.

In Figure 5, the final result was a maximum bond strength at break of 7.49 MPa per square centimeter. But even with such a break, the surface of the sample was not damaged. In sample *b*, we can see distinct places that were attached to the “mushrooms” and it is clear that the surface of the sample was not deformed during the break. When breaking, it was obvious that we only tore off the adhesive, not the surface of the sample. With such indicators, the surface of the sample was not affected in any way and no visual deformations were visible.



Statistics	
# Readings	1
Mean	2.750 MPa
Maximum	2.75 MPa
Minimum	2.75 MPa
Standard Deviation (σ)	
Mean + 3σ	
Mean — 3σ	
Coefficient of Variation	
# Readings < Limit	1 (100.0 %)

Sample a

Statistics	
# Readings	1
Mean	7.490 MPa
Maximum	7.49 MPa
Minimum	7.49 MPa
Standard Deviation (σ)	
Mean + 3σ	
Mean — 3σ	
Coefficient of Variation	
# Readings < Limit 1	(100.0 %)

Sample b

Statistics	
# Readings	1
Mean	4.240 MPa
Maximum	4.24 MPa
Minimum	4.24 MPa
Standard Deviation (σ)	
Mean + 3σ	
Mean — 3σ	
Coefficient of Variation	
# Readings < Limit 1	(100.0 %)

Sample c

Figure 5. Image of the sample surface and the results obtained after the adhesion test

Conclusion

This research paper presents the results of structural-phase, microhardness and adhesion of ZrCN coatings applied by the HVOF method on 65G steel. The study showed that ZrCN coatings applied by the HVOF method form a complex phase structure including ZrCN, ZrC, ZrN, ZrO phases. The best formation of ZrCN and ZrC phases is achieved at moderate values of atmospheric pressure, which minimizes oxidation and increases the coating density. Sample (b) demonstrates the most favorable phase composition, which confirms its best mechanical properties, such as high hardness, wear resistance and chemical resistance. ZrCN-based coatings have significantly higher microhardness compared to the substrate, which is largely due to the formation of ZrC, ZrN. Sample (*b*) demonstrates the greatest strength, having a microhardness of 1800 HV, which makes it the most suitable for use under high loads. In addition, the maximum adhesion at adhesion failure is 7.49 MPa per square centimeter, which shows that sample (*b*) of the coating has high adhesion and has a layered structure characteristic of thermal spraying. The results obtained confirm that HVOF spraying can form coatings with high wear resistance and heat resistance, ensuring reliable operation under extreme conditions.

Acknowledgments

This research is funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (grant No. AP22787358).

References

1 Исламкулов К.М. Разработка инновационной технологии упрочнения дисковых пил хлопкоочистительных машин / К.М. Исламкулов // Международный журнал прикладных и фундаментальных исследований. — 2015. — 6-1. — 25–30.

2 Тулина А.А. Исследование свойств оксидных покрытий, полученных методом вакуумно-дугового осаждения / А.А. Тулина, А.Ю. Назаров, В.Р. Мухамадеев // Вестник УГАТУ. — 2023. — Т. 27. — № 4 (102). — С. 144–151.

3 Компаниец Д.Ю. Разработка оборудования для формирования ИМ-покрытий на оконных стёклах магнетронным методом. Магистерская диссертация / Д.Ю. Компаниец. — Минск, 2024. — 77 с.

4 Rakhadilov B.K. Obtaining functional gradient coatings based on Al_2O_3 by detonation spraying / B.K. Rakhadilov, A.B. Nugumanova, P. Kowalewski, M.K. Kylyshkanov, L.B. Bayatanova, D.N. Kakimzhanov // Bulletin of the University of Karaganda–Physics. — 2020. — 100(4). — 22–27. https://doi.org/10.31489/2020Ph4/22-27

5 Vorobyova M. PVD for decorative applications: A review / M. Vorobyova, F. Biffoli, W. Giurlani, S. M. Martinuzzi, M. Linser, A. Caneschi, M. Innocenti // Materials. — 2023. — 16(14). — 4919. https://doi.org/10.3390/ma16144919

6 Frank F. ZrN-based hard coatings deposited by chemical and physical vapor deposition [Doctoral dissertation, Technical University of Leoben] / F. Frank. — 2022.

7 Нургазина Г.М. Синтез металлсодержащих нанокомпозитов и их применение в катализе: дис. ... д-ра философии (PhD). Спец. 6D060600 — Химия. / Г.М. Нургазина. — Астана, 2013. — 300 с.

8 Ahmed T. Tribology Behaviour in High-performance Coatings for Bike Chains Deposited by PVD. Master's thesis / T. Ahmed. — Coimbra, July 2024.

9 Rakhadilov B. Preparation and characterization of NiCr/NiCr-Al_2O_3/Al_2O_3 multilayer gradient coatings by gas detonation spraying / B. Rakhadilov, D. Buitkenov, Z. Sagdoldina, Z. Idrisheva, M. Zhamanbayeva, D. Kakimzhanov // Coatings. — 2021. — 11(12). — 1524. https://doi.org/10.3390/coatings11121524

10 Kantay N. Influence of detonation-spraying parameters on the phase composition and tribological properties of Al_2O_3 coatings / N. Kantay, B. Rakhadilov, S. Kurbanbekov, D. Yeskermessov, G. Yerbolatova, A. Apsezhanova // Coatings. — 2021. — 11(7). — 793. https://doi.org/10.3390/coatings11070793

11 Rakhadilov B.K. Effect of HVOF method spraying parameters on phase composition and mechanical and tribological properties of 86WC-10Co-4Cr coating / B.K. Rakhadilov, N. Muktanova, D.N. Kakimzhanov, P. Kowalewski // Bulletin of the University of Karaganda-Physics. — 2024. — 11529(3). — 71–83. https://doi.org/10.31489/2024ph3/71-83

12 Skakov M. Development and Studying of the Technology for Thermal Spraying of Coatings Made from Ultra-High-Molecular-Weight Polyethylene / M. Skakov, I. Ocheredko, B. Tuyakbayev, M. Bayandinova, M. Nurizinova // Coatings. — 2023. — 13. — 698. https://doi.org/10.3390/coatings13040698

13 Рахадилов Б.К. Теоретические исследования и решения оптимальных режимов процесса термического напыления HVOF для покрытия Cr_3C_2-NiCr. / Б.К. Рахадилов, Ш. Р. Курбанбеков, Б. Сейтов, Н. Муктанова, Д.Э. Балтабаева, К. Катпаева // Вестник НЯЦ РК. — 2023. — № 4. — С. 22–31. https://doi.org/10.52676/1729-7885-2023-4-22-31

14 Рахадилов Б.К. Влияние варьирования расстояния напыления на структурно-фазовое состояние и механотрибологические свойства покрытий на основе 86WC-10Co-4Cr, полученных методом HVOF / Б.К. Рахадилов, Н. Муктанова, Д.Н. Какимжанов // Вестник НЯЦ РК. — 2024. — № 3. — С. 91–104. https://doi.org/10.52676/1729-7885-2024-3-91-104

15 Larijani M.M. The effect of carbon fraction in Zr(C, N) films on the nano-structure properties and hardness / M.M. Larijani, M.B. Zanjanbar, A. Majdabadi // Journal of Alloys and Compounds. — 2010. — 492. — 735–738. https://doi.org/10.1016/j.jallcom.2009.12.035

16 Kolchev S. Structure and mechanical properties of TiCN-ZrCN multilayer coatings / S. Kolchev, T. Cholakova, L. Kolaklieva, R. Kakanakov, G. Bahchedjiev, V. Chitanov, E. Zlatareva // Journal of Physics: Conference Series. — 2024. — 2710(1). — 012025. IOP Publishing.

17 Silva E. Structure-property relations in ZrCN coatings for tribological applications / E. Silva, M.R. de Figueriredo, R. Franz, R.E. Galindo, C. Palacio, A. Espinosa, V.S. Calderon, C. Mitterer, S. Carvalho // Surface and Coatings Technology. — 2010. — 205. — 2134–2141. https://doi.org/10.1016/j.surfcoat.2010.08.126

18 Fominov E.V. The influence of zirconium and titanium nitride based coatings on tribodeformation processes of friction while cutting with carbide inserts / E.V. Fominov, M.M. Aliev, K.G. Shuchev, A.V. Fomenko // Journal of Friction and Wear. — 2024. — 45(1). — 18–23. https://doi.org/10.3103/S106836662470003X

19 Dorkar N.V. Friction and wear mechanisms of hot-pressed SiC – in situ Zr_2CN composites in extreme conditions of humidity and temperature / N.V. Dorkar, Y.W. Kim, B.V.M. Kumar // Wear. — 2025. — 564. — 205718.

20 Ul-Hamid, A. Deposition, microstructure and nanoindentation of multilayer Zr nitride and carbonitride nanostructured coatings / A. Ul-Hamid // Scientific Reports. — 2022. — 12. — 5591. https://doi.org/10.1038/s41598-022-09449-6

21 Kurbanbekov S. Research on the structural–phase and physical–mechanical characteristics of the Cr_3C_2–NiCr composite coating deposited by the HVOF method on E110 zirconium alloy / S. Kurbanbekov, B. Rakhadilov, D. Kakimzhanov, B. Seitov, K. Katpaeva, A. Kurmantayev, ... A. Kengesbekov // Coatings. — 2024. — 14(8). — 1030. https://doi.org/10.3390/coatings14081030

22 Прокат из рессорно-пружинной углеродистой и легированной стали. Технические условия. ГОСТ 14959-79. — Введ. 01.01.1981. — Москва: Изд-во Стандартинформ, 2006. — 21 с.

23 Löbel M. Microstructure and corrosion properties of AlCrFeCoNi high-entropy alloy coatings prepared by HVAF and HVOF / M. Löbel, T. Lindner, T. Mehner, L.M. Rymer, S. Björklund, S. Joshi, T. Lampke // Journal of Thermal Spray Technology. — 2022. https://doi.org/10.1007/s11666-021-01255-2

24 Harrison R. Processing and characterisation of ZrCxNy ceramics as a function of stoichiometry via carbothermic reduction-nitridation (Doctoral dissertation, Imperial College London) / R. Harrison. — 2015.

25 Jonda E. Microstructure and selected properties of Cr_3C_2–NiCr coatings obtained by HVOF on magnesium alloy substrates / E. Jonda, L. Łatka, W. Pakieła // Materials. —2020. — 13(12). — 2775. https://doi.org/10.3390/ma13122775

26 Марков Ю.М. Получение карбонитрида циркония в режиме СВС-Аз / Ю.М. Марков // Современные материалы, техника и технологии. — 2017. — 6(14). — С. 88–93.

27 Матренин С.В. Структура и физико-механические свойства керамики на основе ZrCN / С.В. Матренин, Е.Д. Кузьменко // В Инновационные технологии в машиностроении: Сборник трудов XV Международной научно-практической конференции. — Томский политехнический университет. — 2024. — С. 13-15.

28 Кузьменко Е.Д. Исследование механических свойств керамики на основе ZrCN / Е.Д. Кузьменко // Исследования и разработки в области машиностроения, энергетики и управления : материалы XXIV Междунар. науч.-техн. конф. студентов, аспирантов и молодых ученых [в 2-х ч.] (25-26 апреля 2024). — Гомель, 2024. — Часть 1. — С. 76–78.

29 Крутский Ю.Л. Карбиды некоторых переходных металлов: Свойства, области применения и методы получения. Часть 2. Карбиды хрома и циркония (обзор) / Ю.Л. Крутский, Т.С. Гудыма, Т.М. Крутская, А.О. Семенов, А.В. Уткин // Известия вузов. Черная металлургия. — 2023. — 66(4). — 445–458. https://doi.org/10.17073/0368-0797-2023-4-445-458

30 Ul-Hamid A. Synthesis, microstructural characterization and nanoindentation of Zr, Zr-nitride and Zr-carbonitride coatings deposited using magnetron sputtering / A. Ul-Hamid // Journal of Advanced Research. — 2021. — 29. — 107–119. https://doi.org/10.1016/j.jare.2020.11.010

31 Vaz F. Property change in ZrN_xO_y, thin films: effect of the oxygen fraction and bias voltage / F. Vaz, P. Carvalho, L. Cunha, L. Rebouta, C. Moura, E. Alves, A.R. Ramos, A. Cavaleiro, Ph. Goudeau, J.P. Rivière // Thin Solid Films. — 2004. — 469–470. — 11-17.

32 Kim D.J. Effect of Ta_2O_5, Nb_2O_5, and HfO_2 alloying on the transformability of Y_2O_3-stabilized tetragonal ZrO_2 / D.J. Kim // Journal of the American Ceramic Society. — 1990. — 73(1). — 115–120. https://doi.org/10.1111/j.1151-2916.1990.tb05100.x

33 Manninen N.K. Ag–Ti(C, N)-based coatings for biomedical applications: Influence of silver content on the structural properties / N. K. Manninen, R. E. Galindo, N. Benito, N. M. Figueiredo, A. Cavaleiro, C. Palacio, S. Carvalho // Journal of Physics D: Applied Physics. — 2011. — 44(37). — 375501. https://doi.org/10.1088/0022-3727/44/37/375501

Ш.Р. Курбанбеков, А. Кизатов, Н. Мусахан,
П.А. Саидахметов, С.Х. Камбарбеков, Б. Қалдар

HVOF бүрку параметрлерінің ZrCN жабындарының құрылымдық-фазалық құрамына және механикалық қасиеттеріне әсері

Мақалада HVOF бүрку параметрлерінің цирконий карбонитриді (ZrCN) жабынының фазалық құрамына, механикалық қасиеттеріне және адгезиялық сипаттамаларына әсерін зерттеу нәтижелері берілген. ZrCN жабындарының рентгендік дифракциялық талдауы ZrCN, ZrC, ZrN, ZrO, Fe және FeN фазаларының болуын анықтады, бұл күрделі жабын құрылымын және элементтердің ықтимал тотығу және диффузиялық процестерін көрсетеді. ZrC және ZrN түзілуі жабу процесінде ZrCN ұнтағының термиялық ыдырауымен байланысты, ал ZrO оксид фазасының пайда болуы HVOF шашу кезінде оттегі қоспасы қолданылғанымен түсіндіріледі. ZrCN жабындарының микроқаттылығы бүрку параметрлеріне байланысты 1500–1800 HV диапазонындағы мәндерге жетеді. Адгезия сынауларының нәтижелері үзілу кезінде жабынның максималды байланыс беріктігі 7,49 МПа болғанын көрсетті. Оңтайлы сипаттамаларға келесі бүрку параметрлері арқылы қол жеткізілді: субстратқа дейінгі қашықтық 35–40 см, пропан қысымы 1,7 бар, ауа — 2,6 бар, оттегі 2,8 бар. Белгіленген шарттар өнімділік қасиеттері жақсартылған тығыз, тозуға төзімді жабын құрылымын қалыптастыруға мүмкіндік береді.

Кілт сөздер: HVOF, микроқаттылық, адгезия, құрылым, фазалық құрамы, ZrCN жабындары, рентгендік дифракция

Ш.Р. Курбанбеков, А. Кизатов, Н. Мусахан,
П.А. Саидахметов, С.Х. Камбарбеков, Б. Қалдар

Влияние параметров напыления HVOF на структурно-фазовый состав и механические свойства покрытий ZrCN

В статье представлены результаты исследования влияния параметров высокоскоростного газопламенного напыления (HVOF) на фазовый состав, механические свойства и адгезионные характеристики покрытия карбонитрида циркония (ZrCN). Рентгеноструктурный анализ покрытий ZrCN выявил присутствие ZrCN, ZrC, ZrN, ZrO, Fe и FeN фаз, что свидетельствует о сложной структуре покрытия и возможных процессах окисления и диффузии элементов. Формирование ZrC и ZrN связано с термическим разложением порошка ZrCN в процессе получения покрытия, а образование оксидной фазы ZrO объясняется тем, что при HVOF напылении использовалась смесь кислорода. Микротвердость ZrCN покрытий достигает значений в диапазоне 1500–1800 HV в зависимости от параметров напыления. Результаты испытаний на адгезию показали, что максимальная прочность сцепления покрытия при разрыве составила 7,49 МПа. Оптимальные характеристики достигнуты при параметрах напыления: расстояние до подложки 35–40 см, давление пропана 1,7 бар, воздуха — 2,6 бар, кислорода 2,8 бар. Установленные условия позволяют сформировать плотную, износостойкую структуру покрытия с улучшенными эксплуатационными свойствами.

Ключевые слова: HVOF, микротвёрдость, адгезия, структура, фазовый состав, покрытия ZrCN, рентгеновская дифракция.

References

1 Islamkulov, K.M. (2015). Razrabotka innovatsionnoi tekhnologii uprochneniia diskovykh pil khlopkoochistitelnykh mashin [Development of an innovative technology for hardening circular saws of cotton gins]. *Mezhdunarodnyi zhurnal prikladnykh i fundamentalnykh issledovanii — International Journal of Applied and Fundamental Research, (6-1)*, 25–30 [in Russian].

2 Tulina, A.A., Nazarov, A.Yu., & Mukhamadeev, V.R. (2023). Issledovanie svoistv oksidnykh pokrytii, poluchennykh metodom vakuumno-dugovogo osazhdeniia [Investigation of the properties of oxide coatings obtained by vacuum-arc deposition]. *Vestnik Ufimskogo gosudarstvennogo aviatsionnogo tekhnicheskogo universiteta — Bulletin of Ufa State Aviation Technical University, 27,* 4(102), 144–151 [in Russian].

3 Kompaniets, D.Yu. (2024). Razrabotka oborudovaniia dlia formirovaniia IM-pokrytii na okonnykh steklakh magnetronnym metodom [Development of equipment for the formation of IM coatings on window panes by the magnetron method]. *Master's thesis.* Minsk [in Russian].

4 Rakhadilov, B.K., Nugumanova, A.B., Kowalewski, P., Kylyshkanov, M.K., Bayatanova, L.B., & Kakimzhanov, D.N. (2020). Obtaining functional gradient coatings based on Al_2O_3 by detonation spraying. *Bulletin of the University of Karaganda – Physics, 100*(4), 22–27. https://doi.org/10.31489/2020Ph4/22-27

5 Vorobyova, M., Biffoli, F., Giurlani, W., Martinuzzi, S.M., Linser, M., Caneschi, A., & Innocenti, M. (2023). PVD for decorative applications: A review. *Materials, 16*(14), 4919. https://doi.org/10.3390/ma16144919

6 Frank, F. (2022). ZrN-based hard coatings deposited by chemical and physical vapor deposition. *Doctor's thesis*.

7 Nurgazina, G.M. Sintez metallsoderzhashchikh nanokompozitov i ikh primenenie v katalize [Syntesis of metal nanocomposites and their application in catalysis]. *Doctor`s thesis.* Astana [in Russian].

8 Ahmed, T. (2024). Tribology Behaviour in High-performance Coatings for Bike Chains Deposited by PVD. *Master's thesis.* Coimbra.

9 Rakhadilov, B., Buitkenov, D., Sagdoldina, Z., Idrisheva, Z., Zhamanbayeva, M., & Kakimzhanov, D. (2021). Preparation and characterization of NiCr/NiCr-Al_2O_3/Al_2O_3 multilayer gradient coatings by gas detonation spraying. *Coatings, 11*(12), 1524. https://doi.org/10.3390/coatings11121524

10 Kantay, N., Rakhadilov, B., Kurbanbekov, S., Yeskermessov, D., Yerbolatova, G., & Apsezhanova, A. (2021). Influence of detonation-spraying parameters on the phase composition and tribological properties of Al_2O_3 coatings. *Coatings, 11*(7), 793. https://doi.org/10.3390/coatings11070793

11 Rakhadilov, B.K., Muktanova, N., Kakimzhanov, D.N., & Kowalewski, P. (2024). Effect of HVOF method spraying parameters on phase composition and mechanical and tribological properties of 86WC-10Co-4Cr coating. *Bulletin of the University of Karaganda – Physics, 29*, 3(115), 71–83. https://doi.org/10.31489/2024ph3/71-83

12 Skakov, M., Ocheredko, I., Tuyakbayev, B., Bayandinova, M., & Nurizinova, M. (2023). Development and studying of the technology for thermal spraying of coatings made from ultra-high-molecular-weight polyethylene. *Coatings, 13*(4), 698. https://doi.org/10.3390/coatings13040698

13 Rakhadilov, B.K., Kurbanbekov, Sh.R., Seitov, B., Muktanova, N., Baltabaeva, D.E., & Katpaeva, K. (2023). Teoreticheskie issledovaniia i resheniia optimalnykh rezhimov protsessa termicheskogo napyleniia HVOF dlia pokrytiia Cr_3C_2-NiCr [Spraying Process for Cr_3C_2-NiCr Coating]. *Vestnik Natsionalnogo Yadernogo Tsentra Respubliki Kazakhstan — Bulletin National Nuclear center of the Republic of Kazakhstan,* 4, 22–31. https://doi.org/10.52676/1729-7885-2023-4-22-31 [in Russian]

14 Rakhadilov, B.K., Muktanova, N., & Kakimzhanov, D.N. (2024). Vliianie varirovaniia rasstoianiia napyleniia na strukturno-fazovoe sostoianie i mekhanotribologicheskie svoistva pokrytii na osnove 86WC-10Co-4Cr, poluchennykh metodom HVOF [Influence of Varying the Spraying Distance on the Structural-phase State and Mechanotribological Properties of 86WC-10Co-4Cr-based Coatings Obtained by the hvof Method]. *Vestnik Natsionalnogo Yadernogo Tsentra Respubliki Kazakhstan — Bulletin National Nuclear center of the Republic of Kazakhstan,* 3, 91–104. https://doi.org/10.52676/1729-7885-2024-3-91-104 [in Russian]

15 Larijani, M.M., Zanjanbar, M.B., & Majdabadi, A. (2010). The effect of carbon fraction in Zr(C, N) films on the nano-structure properties and hardness. *Journal of Alloys and Compounds, 492*, 735–738. https://doi.org/10.1016/j.jallcom.2009.12.035

16 Kolchev, S., Cholakova, T., Kolaklieva, L., Kakanakov, R., Bahchedjiev, C., Chitanov, V., & Zlatareva, E. (2024). Structure and mechanical properties of TiCN-ZrCN multilayer coatings. In *Journal of Physics: Conference Series* (Vol. 2710, No. 1, p. 012025). IOP Publishing.

17 Silva, E., de Figueriredo, M.R., Franz, R., Galindo, R.E., Palacio, C., Espinosa, A., Calderon, V.S., Mitterer, C., & Carvalho, S. (2010). Structure-property relations in ZrCN coatings for tribological applications. *Surface and Coatings Technology, 205*, 2134–2141. https://doi.org/10.1016/j.surfcoat.2010.08.126

18 Fominov, E.V., Aliev, M.M., Shuchev, K.G., & Fomenko, A.V. (2024). The influence of zirconium and titanium nitride based coatings on tribodeformation processes of friction while cutting with carbide inserts. *Journal of Friction and Wear, 45*(1), 18–23. https://doi.org/10.3103/S106836662470003X

19 Dorkar, N.V., Kim, Y.W., & Kumar, B.V.M. (2025). Friction and wear mechanisms of hot-pressed SiC-in situ Zr_2CN composites in extreme conditions of humidity and temperature. *Wear, 564*, 205718.

20 Ul-Hamid, A. (2022). Deposition, microstructure and nanoindentation of multilayer Zr nitride and carbonitride nanostructured coatings. *Scientific Reports, 12*, 5591. https://doi.org/10.1038/s41598-022-09449-6

21 Kurbanbekov, S., Rakhadilov, B., Kakimzhanov, D., Seitov, B., Katpaeva, K., Kurmantayev, A., ... & Kengesbekov, A. (2024). Research on the structural–phase and physical–mechanical characteristics of the Cr_3C_2-NiCr composite coating deposited by the HVOF method on E110 zirconium alloy. *Coatings, 14*(8), 1030. https://doi.org/10.3390/coatings14081030

22 (2006). Prokat iz ressorno-pruzhinnoi uglerodistoi i legirovannoi stali. Tekhnicheskie usloviia [Rolled products made of spring-loaded carbon steel and alloy steel. Technical specifications]. GOST 14959-79. From: 01.01.1981. Moscow: Izdatelstvo Standartinform [in Russian].

23 Löbel, M., Lindner, T., Mehner, T., Rymer, L.M., Björklund, S., Joshi, S., & Lampke, T. (2022). Microstructure and corrosion properties of AlCrFeCoNi high-entropy alloy coatings prepared by HVAF and HVOF. *Journal of Thermal Spray Technology*. https://doi.org/10.1007/s11666-021-01255-2

24 Harrison, R. (2015). Processing and characterisation of ZrCxNy ceramics as a function of stoichiometry via carbothermic reduction-nitridation (Doctoral dissertation, Imperial College London).

25 Jonda, E., Łatka, L., & Pakieła, W. (2020). Microstructure and Selected Properties of Cr_3C_2–NiCr Coatings Obtained by HVOF on Magnesium Alloy Substrates. *Materials, 13*(12), 2775. https://doi.org/10.3390/ma13122775

26 Markov, Yu.M. (2017). Poluchenie karbonitrida tsirkoniia v rezhime SVS-Az [Production of zirconium carbonitride in the SHS-Az mode]. *Sovremennye materialy, tekhnika i tekhnologii — Modern materials, machinery and technologies, 6*(14), 88–93 [in Russian].

27 Matrenin, S.V., & Kuzmenko, E.D. (2024). Struktura i fiziko-mekhanicheskie svoistva keramiki na osnove ZrCN [Structure and physico-mechanical properties of ceramics based on ZrCN]. *Innovatsionnye tekhnologii v mashinostroenii: sbornik trudov XV Mezhdunarodnoi nauchno-prakticheskoi konferentsii —Innovative technologies in mechanical engineering: Proceedings of the 15th International Scientific and Practical Conference* (pp. 13–15). Tomskii politekhnicheskii universitet [in Russian].

28 Kuzmenko, E.D. (2024). Issledovanie mekhanicheskikh svoistv keramiki na osnove ZrCN [Investigation of the mechanical properties of ceramics based on ZrCN]. *Issledovaniia i razrabotki v oblasti mashinostroeniia, energetiki i upravleniia: materialy XXIV Mezhdunarodnoi nauchno-tekhnicheskoi konferentsii studentov, aspirantov i molodykh uchenykh — Research and development in the field of mechanical engineering, energy and management: proceedings of the 24th International Scientific and Technical Conference of Students, Postgraduates and Young Scientists* (pp. 76–78). In two parts. Part 1 [in Russian].

29 Krutskii, Yu.L., Gudyma, T.S., Krutskaya, T.M., Semenov, A.O., & Utkin, A.V. (2023). Karbidy nekotorykh perekhodnykh metallov: Svoistva, oblasti primeneniia i metody polucheniia. Chast 2. Karbidy khroma i tsirkoniia (obzor) [Carbides of transition metals: Properties, application and production. Review. Part 2. Chromium and zirconium carbides]. *Izvestiia vuzov. Chernaia metallurgiia — News. Ferrous Metallurgy, 66*(4), 445–458. https://doi.org/10.17073/0368-0797-2023-4-445-458 [in Russian].

30 Ul-Hamid, A. (2021). Synthesis, microstructural characterization and nanoindentation of Zr, Zr-nitride and Zr-carbonitride coatings deposited using magnetron sputtering. *Journal of Advanced Research, 29*, 107–119. https://doi.org/10.1016/j.jare.2020.11.010

31 Vaz, F., Carvalho, P., Cunha, L., Rebouta, L., Moura, C., Alves, E., ... & Rivière, J.P. (2004). Property change in ZrN_xO_y, thin films: effect of the oxygen fraction and bias voltage. *Thin Solid Films,* 469–470, 11–17.

32 Kim, D.J. (1990). Effect of Ta_2O_5, Nb_2O_5, and HfO_2 alloying on the transformability of Y_2O_3-stabilized tetragonal ZrO_2. *Journal of the American Ceramic Society, 73*(1), 115–120. https://doi.org/10.1111/j.1151-2916.1990.tb05100.x

33 Manninen, N.K., Galindo, R.E., Benito, N., Figueiredo, N.M., Cavaleiro, A., Palacio, C., & Carvalho, S. (2011). Ag–Ti(C, N)-based coatings for biomedical applications: Influence of silver content on the structural properties. *Journal of Physics D: Applied Physics, 44*(37), 375501. https://doi.org/10.1088/0022-3727/44/37/375501

Information about the authors

Kurbanbekov, Sherzod — PhD, Associate Professor, Director of the Research Institute Natural Sciences, Nanotechnologies and New materials, Khoja Akhmet Yassawi International Kazakh-Turkish University, Turkestan, Kazakhstan; e-mail: sherzod.kurbanbekov@ayu.edu.kz; ORCID ID: https://orcid.org/0000-0001-5510-0568

Kizatov, Aibar — Researcher of Scientific Research Center “Veritas”, D. Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk, Kazakhstan; e-mail: AKizatov@ektu.kz; ORCID ID: https://orcid.org/0009-0004-6627-9742

Musakhan, Nurken — Research Institute Natural Sciences, Nanotechnologies and New materials, Khoja Akhmet Yassawi International Kazakh-Turkish University, Turkestan, Kazakhstan; e-mail: nurken.mussakhan@ayu.edu.kz; ORCID ID: https://orcid.org/0000-0003-4154-0356

Saidakhmetov, Polat — Candidate of Science (Physics), Assistant professor, Department of Physics, M. Auezov South Kazakhstan University, Shymkent, Kazakhstan; e-mail: timpf_ukgu@mail.ru

Kambarbekov, Sardor (*contact person*) — Research Institute Natural Sciences, Nanotechnologies and New materials, Khoja Akhmet Yassawi International Kazakh-Turkish University, Turkestan, Kazakhstan; e-mail: sardor.kambarbekov@mail.ru; ORCID ID: https://orcid.org/0009-0001-6794-1281

Kaldar, Berik — Bachelor student, Yasavi International Kazakh-Turkish University, Turkestan, Kazakhstan; e-mail: Berik2002Berik@gmail.com; ORCID ID: https://orcid.org/0009-0002-9267-7029