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COMPARATIVE ANALYSIS OF WC-NICR, AL_2O_3-NICR, AND CR_3C_2-NICR METAL-CERAMIC COATINGS APPLIED BY HVOF AND DETONATION SPRAYING METHODS

The paper presents a comparative analysis of technologies for forming metal-ceramic coatings of WC-NiCr, Cr_3C_2-NiCr, and Al_2O_3-NiCr systems obtained by high-velocity oxygen fuel (HVOF) and detonation spraying methods. The aim of the study was to determine the influence of the coating technology on the microstructure, physical-mechanical and tribological properties of the coatings. The study included analysis of the morphology of the starting powders and the microstructure of the coatings using scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). Microhardness was determined using the FISCHERSCOPE HM 2000 system, and tribological characteristics were studied using the ball-on-disc method on an Anton Paar TRB^3 tribometer in accordance with ASTM G133-95 and ASTM G99 standards. It was found that the spraying method has a significant effect on the structure and performance characteristics of coatings. For carbide systems (Cr_3C_2-NiCr and WC-NiCr), the HVOF method is more effective, providing the formation of a dense, fine-grained structure, increased hardness, and a reduced friction coefficient. For the Al_2O_3-NiCr oxide system, detonation spraying proved to be preferable, providing higher hardness and stable tribological characteristics. The results obtained allow for a reasonable choice of coating formation technology depending on their composition and operating conditions.

Keywords: HVOF, detonation spraying, metal-ceramic coatings, microstructure, friction coefficient, hardness.

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WC-NiCr, Al_2O_3-NiCr және Cr_3C_2-NiCr металлокерамикалық жабындарының HVOF және детонациялық бүрку әдістерімен алынған жабындарының салыстырмалы талдауы

Жұмыста жоғары жылдамдықты газотермиялық (HVOF) және детонациялық бүрку әдістері арқылы алынған WC-NiCr, Cr_3C_2-NiCr және Al_2O_3-NiCr жүйелеріндегі металлокерамикалық жабындарды қалыптастыру технологияларына салыстырмалы талдау жүргізілді. Зерттеудің мақсаты-жабынды жағу технологиясының жабындардың микроқұрылымына, физика-механикалық және трибологиялық қасиеттеріне әсерін анықтау. Зерттеу барысында бастапқы ұнтақтардың морфологиясы мен жабындардың микроқұрылымы растарлық электрондық микроскопия (РЭМ) және энергиядисперсиялық спектроскопия (EDS) әдістерімен талданды. Микроқаттылық FISCHERSCOPE HM 2000 жүйесінде анықталды, ал трибологиялық сипаттамалар ASTM G133-95 және ASTM G99 стандарттарына сәйкес Anton Paar TRB^3 трибометрінде «шар–диск» әдісі арқылы зерттелді. Бүрку әдісінің жабындардың құрылымы мен пайдалану сипаттамаларына елеулі әсер ететіні анықталды. Карбидті жүйелер (Cr_3C_2-NiCr және WC-NiCr) үшін HVOF әдісі тиімдірек болып табылады, себебі ол тығыз, ұсақдисперсті құрылымның қалыптасуын, қаттылықтың артуын және үйкеліс коэффициентінің төмендеуін қамтамасыз етеді. Ал Al_2O_3-NiCr оксидті жүйесі үшін детонациялық бүрку әдісі анағұрлым тиімді болып, жоғары қаттылық пен тұрақты трибологиялық сипаттамаларды қамтамасыз етеді. Алынған нәтижелер жабындардың құрамы мен пайдалану жағдайларына байланысты оларды қалыптастыру технологиясын ғылыми негізде таңдауға мүмкіндік береді.

Түйін сөздер: HVOF, детонациялық бүрку, металлокерамикалық жабындар, микроқұрылым, үйкеліс коэффициенті, қаттылық.

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Сравнительный анализ металлокерамических покрытий WC-NiCr, Al_2O_3-NiCr и Cr_3C_2-NiCr, нанесённых методами HVOF и детонационного напыления

В работе выполнен сравнительный анализ технологий формирования металлокерамических покрытий систем WC-NiCr, Cr_3C_2-NiCr и Al_2O_3-NiCr, полученных методами высокоскоростного газопламенного (HVOF) и детонационного напыления. Цель исследования заключалась в установлении влияния технологии нанесения на микроструктуру, физико-механические и трибологические свойства покрытий. Исследование включало анализ морфологии исходных порошков, микроструктуры покрытий методом растровой электронной микроскопии (РЭМ) и энергодисперсионной спектроскопии (EDS). Микротвёрдость определяли на системе FISCHERSCOPE HM 2000, трибологические характеристики исследовали методом «шар–диск» на трибометре Anton Paar TRB^3 в соответствии со стандартами ASTM G133-95 и ASTM G99. Установлено, что метод напыления оказывает существенное влияние на структуру и эксплуатационные характеристики покрытий. Для карбидных систем (Cr_3C_2-NiCr и WC-NiCr) более эффективным является метод HVOF, обеспечивающий формирование плотной мелкодисперсной структуры, повышение твёрдости и снижение коэффициента трения. Для оксидной системы Al_2O_3-NiCr предпочтительным оказалось детонационное напыление, обеспечивающее более высокую твёрдость и стабильные трибологические характеристики. Полученные результаты позволяют обоснованно выбирать технологию формирования покрытий в зависимости от их состава и условий эксплуатации.

Ключевые слова: HVOF, детонационное напыление, металлокерамические покрытия, микроструктура, коэффициент трения, твёрдость.

Introduction

Ensuring the operational reliability and durability of machine components operating under conditions of intense abrasive wear, erosion, and high-temperature corrosion is one of the priority tasks of modern materials science. In industries such as aircraft manufacturing, oil and gas, and thermal power engineering, traditional structural materials often reach their limits. Surface engineering using metal-ceramic coatings is recognized as the most effective technological solution in this field. Combining a nickel-chromium (NiCr) matrix with strengthening phases in the form of tungsten carbides WC, chromium Cr_3C_2, or aluminum oxide Al_2O_3, they are of particular interest due to their unique balance of high microhardness of ceramics and fracture toughness of the metal matrix [1-3].

WC–NiCr is traditionally considered the benchmark for wear resistance under low-temperature abrasive conditions. Recent studies have focused on the microstructural characteristics of such coatings when sprayed onto various substrates, including magnesium and aluminum alloys [4,5]. However, the problem of thermal decomposition of carbides during high-energy spraying remains relevant for preserving operational properties [6,7].

Cr_3C_2-NiCr is positioned in the literature as a key material for wear protection at temperatures up to 850–900°C. Its advantage lies in its ability to form dense self-healing oxide films, which is critical for power plants and pumping equipment [8-10].

Al_2O_3-NiCr is distinguished by its exceptional chemical inertness and corrosion resistance. The use of a NiCr matrix compensates for the brittleness of aluminum oxide, creating multilayer and gradient structures that can operate effectively in aggressive environments [11-13].

The properties of coatings are fundamentally determined by the velocity and temperature of the sprayed particles. The high-velocity oxygen fuel (HVOF) method is characterized by a continuous supersonic flow, ensuring high productivity and uniformity of the layer. In the HVOF spraying process, powder particles are in a continuous high-speed flow of combustion products, which ensures uniform heating and high process productivity. However, prolonged exposure of the material to a high-temperature gas jet increases the risk of oxidation of the metal matrix and decomposition of carbide inclusions [14-16].

In contrast, detonation spraying (Det. s.) is based on cyclic explosive action. Thanks to the pulsed nature of the process and brief thermal contact at ultra-high speeds (up to 1000-1200 m/s), it is possible to minimize thermal degradation of the powder. Studies [12,17,18] show that the detonation method allows the formation of unique gradient transitions and nanocrystalline structures, providing adhesive strength at the level of 80–110 MPa and high corrosion resistance when exposed to salt solutions.

Despite a significant number of publications on layer thickness optimization [19], there is a lack of systematic comparative data obtained under identical experimental conditions for carbide and oxide systems in the current literature. The tribological mechanisms of wear during the transition from traditional [20] have not been sufficiently studied. The question of the correlation between the method of transferring kinetic energy to particles and the completeness of preservation of strengthening phases in the NiCr matrix for all three systems simultaneously remains open [21-25]. Despite the availability of a significant number of publications on each of the systems separately, there is still a lack of systematic comparative data obtained under identical experimental conditions for all three compositions (WC, Cr_3C_2, Al_2O_3) when comparing HVOF and detonation methods in the modern world literature.

The aim of this work is to conduct a comprehensive comparative analysis of the microstructure and tribological characteristics of WC-NiCr, Cr_3C_2,-NiCr, and Al_2O_3-NiCr coatings applied by HVOF and detonation spraying methods.

Materials and Methods (or Research Methodology)

WC-NiCr, Al_2O_3-NiCr, and Cr_3C_2-NiCr metal-ceramic powders were used to obtain coatings, the composition of which is given in Table 1. Low-alloy steel 20GL was used as the substrate material, the chemical composition of which is presented in Table 2. The study examined the tribological properties of the coatings, their hardness, and morphology.

HVOF coatings were obtained using a high-velocity oxy-fuel (HVOF) spraying system. The HVOF spraying modes are shown in Table 3. The distance to the substrate was 200 mm. Detonation coatings were obtained using a CCDS2000 detonation spraying system (LIH SO RAN, Novosibirsk, Russia).

The morphological characteristics of the powder particles and the coating surfaces were studied using scanning electron microscopy (SEM) on a TESCAN VEGA4 LMH microscope (TESCAN, Brno, Czech Republic). Energy dispersive analysis was performed using the Xplore 30 system (Oxford Instruments, Oxford, UK). The hardness of the coatings was measured using the FISCHER-SCOPE HM 2000 system (Helmut Fischer GmbH, Sindelfingen, Germany) controlled by WIN-HCU software version 7.1. In all tests, the exposure time was 10 s at a load of 300 mN. Tribological studies were performed on an Anton Paar TRB[3] tribometer (Anton Paar, Buchs, Switzerland) using a ball-on-disc test method in accordance with international standards ASTM G133-95 and ASTM G99. A ball with a radius of 6 mm made of 100Cr6 material was used as the counterbody.

Table 1. Powder composition

	WC-NiCr		
W	C	Ni	Cr
base	5%	6%	8%
	Cr_3C_2-NiCr		
Cr	C	Ni	Cr
base	9,2%	12%	4,5%
	Al_2O_3-NiCr		
Al2O3	Ni	Cr	
base	6,2%	8,3%	

Table 2. Chemical composition of 20GL steels

Element	Designation	Mass fraction in 20GL (%) (GOST 977-88)
Carbon	C	0,15-0,25
Silicon	Si	0,20-0,40
Manganese	Mn	1,20-1,60
Sulfur	S	до 0,040
Phosphorus	P	до 0,040
Iron	Fe	~97

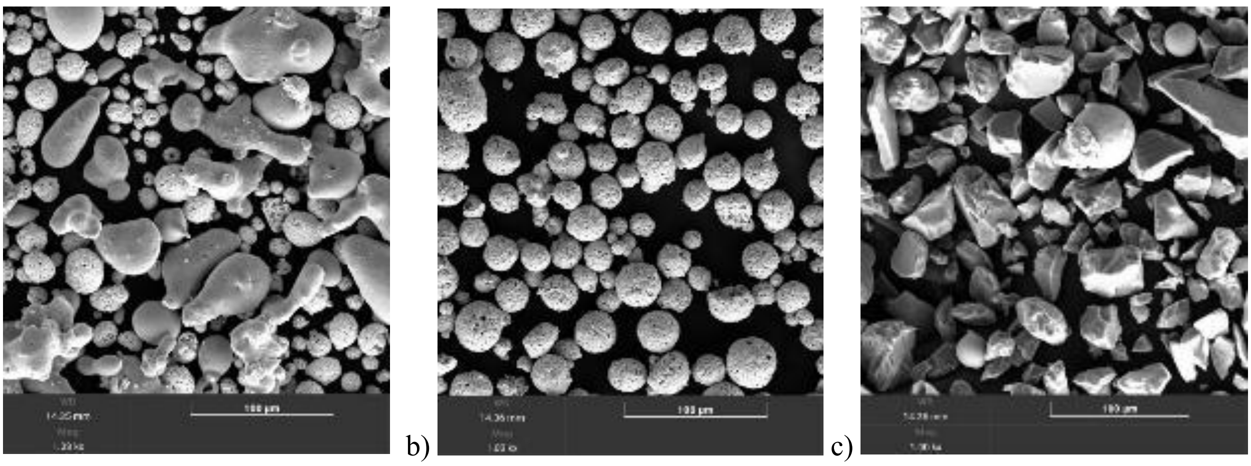
Table 3. HVOF Spraying Parameters

Gas Control Panel Parameter Settings	Pressure
Propane	2,9 bar
Oxygen	5 bar
Compressed Air	3,2 bar

Results and discussion

The study compared two high-energy coating methods: detonation spraying and high-velocity oxygen fuel (HVOF) spraying. This section presents the results of a study of the structure, mechanical and tribological properties of WC-NiCr, Cr_3C_2-NiCr and Al_2O_3-NiCr metal-ceramic coatings obtained by detonation and high-velocity oxygen fuel (HVOF) spraying methods.

The morphological characteristics of the particles are shown in Figure 1.



a) b) c)

Figure 1-SEM images of powders a)WC-NiCr, б) Cr_3C_2-NiCr, c) Al_2O_3-NiCr

Figure 1 shows SEM images of the morphology of WC-NiCr, Cr_3C_2-NiCr, and Al_2O_3-NiCr powders. It has been established that WC–NiCr powder is characterized by predominantly irregular angular particle shapes and pronounced surface roughness. Cr_3C_2-NiCr powder has predominantly spherical particles and a more uniform particle size distribution. Al_2O_3-NiCr powder is characterized by sharply angular, fragmented particle shapes due to the brittleness of the oxide phase. The results obtained show significant differences in the morphology of powders depending on their composition.

Table 4. Comparative analysis of powders using different spraying technologies

Characteristics	WC-NiCr	Cr_3C_2-NiCr	Al_2O_3-NiCr
Primary purpose	Extreme wear resistance, abrasion protection.	Corrosion resistance and wear at high temperatures.	Electrical insulation, wear at high temperatures, chemical resistance.
Max. operating T	Up to 500°C (further oxidation occurs).	Up to 850-900°C.	Up to 900-1000°C (depending on the bundle).

Figures 2 show the results of EDS analysis of WC-NiCr, Cr_3C_2-NiCr, and Al_2O_3-NiCr coatings. Elemental mapping shows a uniform distribution of the main elements across the thickness of the coatings and confirms the formation of a characteristic compositional structure of the layers. It was found that WC and Cr_3C_2 carbide particles, as well as the Al_2O_3 oxide phase, are uniformly dispersed in the NiCr metal matrix. No pronounced local segregation of elements was detected, which indicates the homogeneity of the composition and structure of the coatings obtained.

After analyzing the coatings obtained by detonation spraying, the coatings formed by high-velocity oxygen fuel (HVOF) spraying were studied. The results of EDS mapping of the HVOF coatings are shown in Figures 2.

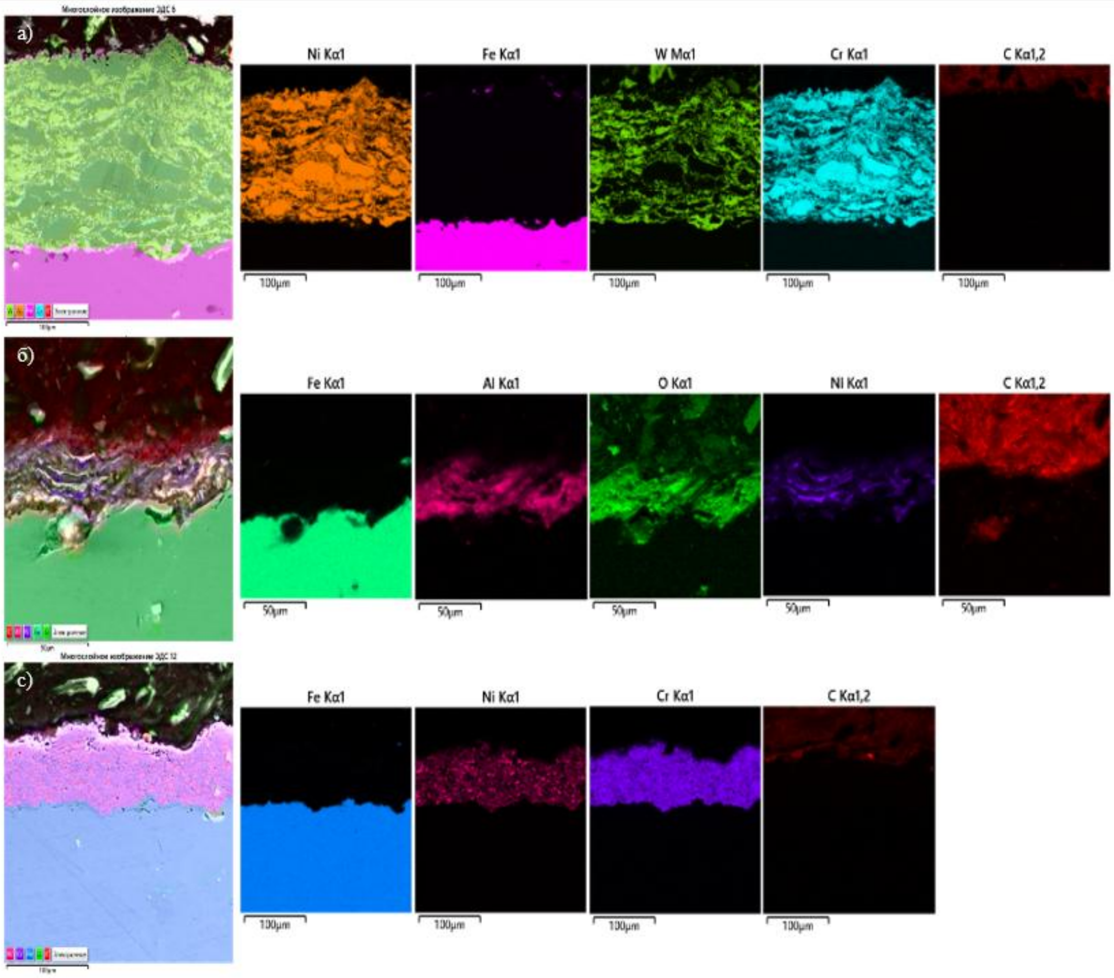


Figure 2-EMF analysis of detonation coatings a) WC-NiCr, b) Al_2O_3-NiCr, c) Cr_3C_2-NiCr

The results of EDS mapping indicate the formation of a composite structure of the Al_2O_3-NiCr coating typical for metal-ceramic systems: the NiCr metal binder provides the viscosity and adhesion of the layer to the substrate, while the dispersed Al_2O_3 particles act as a strengthening phase. For the Cr_3C_2-NiCr coating, a uniform distribution of Cr_3C_2 carbide particles in the NiCr metal matrix was established, indicating a homogeneous structure and the absence of pronounced phase segregation. A characteristic compositional structure was revealed in WC-NiCr, represented by uniformly distributed WC carbide inclusions in a nickel-chromium binder forming a continuous metal matrix of the coating.

At the next stage of the study, tribological tests were carried out on coatings obtained by detonation spraying and HVOF. The results are shown in Figure 4. The tests were carried out at room temperature without lubricants, using a 6 mm radius ball made of 100Cr6 material as the counterbody. Tribological tests were carried out under a load of 6 N at a linear speed of 3 cm/s, with a wear radius of 3 mm and a total wear length of 60 m.

Figure 4 shows the friction coefficient values for WC–NiCr, Cr_3C_2-NiCr, and Al_2O_3-NiCr coatings, as well as the friction coefficient variation curves during testing. The hardness values of the coatings, determined by cross-section, are shown in Figure 5.

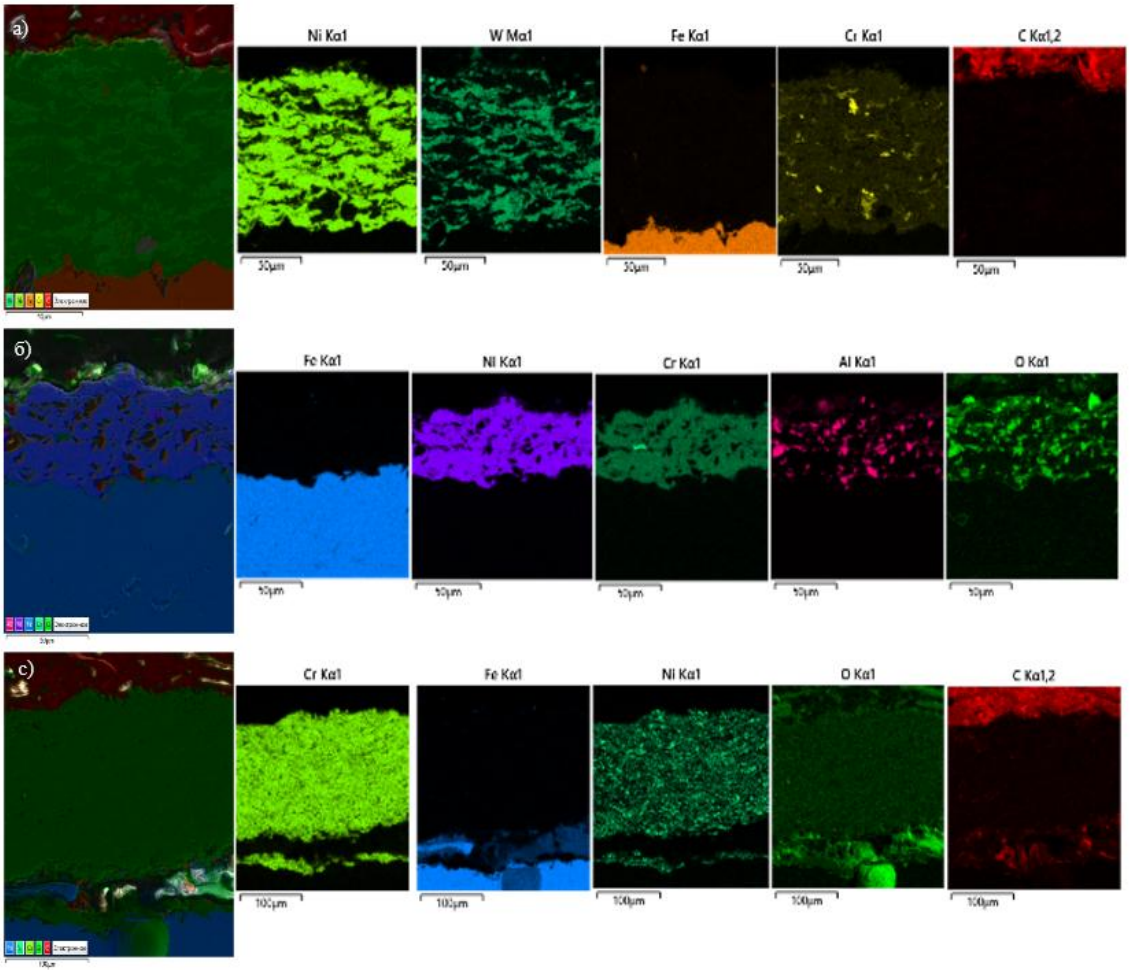


Figure 3-Results of EDS mapping of coatings obtained by the HVOF method a) Cr_3C_2-NiCr, б) Al_2O_3 -NiCr, c)WC-NiCr

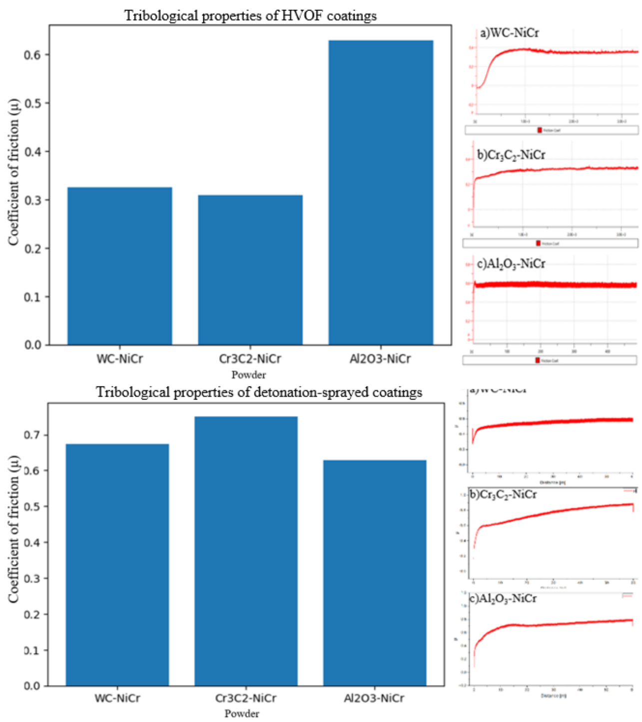


Figure 4-Friction coefficient graph WC-NiCr(a), Cr_3C_2-NiCr(b), Al_2O_3-NiCr(c)

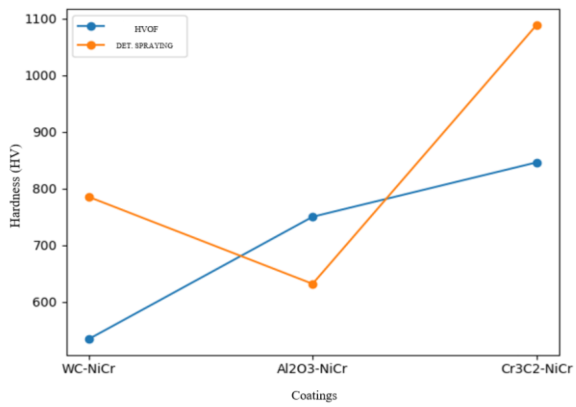


Figure 5-Graph of coating hardness determined by cross-section

Table 5. Comparative characteristics of coatings obtained by detonation and HVOF spraying methods

Powder Composition	Spraying Method	Microhardness (HV)	Coefficient of Friction (μ)
WC-NiCr	Detonation spraying	534	0.673
	HVOF	785.2	0.326
Cr_3C_2-NiCr	Detonation spraying	846	0.751
	HVOF	1088.6	0.310
Al_2O_3-NiCr	Detonation spraying	750	0.629
	HVOF	631.6	0.630

Hardness measurement results (Fig. 5) revealed a significant advantage of the HVOF technology for carbide systems, including WC–NiCr, Cr_3C_2–NiCr, and Al_2O_3–NiCr coatings.

For the Cr_3C_2-NiCr coating, the HVOF method achieved a hardness of 1088.6 HV, which is 28.6% higher than that obtained by detonation spraying (846 HV). A similar trend was observed for WC-NiCr, where the hardness increased from 534 HV (detonation spraying) to 785.2 HV (HVOF). The high kinetic energy of particles during the HVOF process (up to 900 m/s) ensures extreme coating densification, which minimizes porosity and improves cohesive strength. In the case of detonation spraying, the lower hardness values of WC-NiCr (534 HV) can be explained by partial decarburization of the carbide phase and structural heterogeneity.

For the oxide-based Al_2O_3-NiCr coating, detonation spraying demonstrated superior performance (750 HV compared to 631.6 HV for HVOF). This is attributed to the fact that under HVOF conditions the load is mainly carried by the more ductile metallic matrix, while aluminum oxide is present as discrete inclusions, reducing the overall hardness of the coating.

Tribological tests (Fig. 5) showed qualitative differences in coating behavior. The HVOF method significantly reduces the coefficient of friction for carbide coatings. For Cr_3C_2-NiCr, the friction coefficient decreased from 0.751 (detonation spraying) to 0.310 (HVOF), while for WC-NiCr it decreased from 0.673 to 0.326. During the HVOF process, a finer and more homogeneous microstructure is formed, as confirmed by EDS mapping (Fig. 4), which provides a stable contact area and reduces adhesive interaction.

In contrast, under detonation spraying conditions the best tribological performance was observed for the Al_2O_3-NiCr coating (μ=0.629). This is attributed to the formation of a smoother contact surface and the characteristics of the hard oxide phase, which reduces seizure in the friction zone.

Conclusion

The results of the study of microstructure, physicomechanical, and tribological properties of WC-NiCr, Cr_3C_2-NiCr, and Al_2O_3-NiCr metal-ceramic coatings indicate a significant influence of the spraying method on the performance characteristics of the layers. Comparative analysis showed that the high-velocity oxy-fuel (HVOF) spraying method is the most effective for carbide systems. Due to the high kinetic energy of particles (up to 900 m/s), extreme coating densification and the formation of a fine-dispersed homogeneous structure are achieved (confirmed by SEM and EDS mapping), which minimizes porosity and increases cohesive strength. Thus, for the Cr_3C_2–NiCr system, the HVOF method made it possible to achieve a hardness of 1088.6 HV (28.6% higher than that of the detonation method) and significantly reduce the coefficient of friction from 0.751 to 0.310. Similarly, for WC–NiCr, the hardness increased from 534 HV to 785.2 HV, while the coefficient of friction decreased from 0.673 to 0.326. In the case of detonation spraying, the lower performance of carbide coatings is explained by partial decarburization of phases and structural heterogeneity. However, for the oxide system Al_2O_3–NiCr, detonation spraying proved to be more preferable, demonstrating a hardness of 750 HV compared to 631.6 HV for HVOF and a stable coefficient of friction of 0.629. This is attributed to the fact that during HVOF spraying of aluminum oxide, the load is predominantly carried by the ductile NiCr matrix, whereas the detonation method ensures the formation of a more rigid framework and a smoother contact surface, reducing seizure. Thus, the HVOF technology is recommended for producing ultra-hard wear-resistant carbide coatings, while detonation spraying is advisable for optimizing the properties of oxide systems.

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Author Contributions

A.E. Kussainov: Conceptualization, Methodology; **M.T. Kaliaskarova**: Formal Analysis, Data Curation, Writing – Review & Editing; **I.K. Abizhanova**: Investigation, Data Curation, Visualization; **E.S. Molbosynov**: Formal Analysis, Resources, Validation; **L.B. Bayatanova**: Supervision, Funding Acquisition, Project Administration; **G.Zh. Zhunisova**: Investigation, Data Curation, Visualization.

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